



## Is there evidence for an aerosol indirect effect during the recent aerosol optical depth decline in Europe?

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[1] Aerosol indirect effects are some of the largest uncertainties of anthropogenic climate change. To estimate the first aerosol indirect radiative effect (or cloud albedo effect), we analyzed global solar irradiance measurements under completely overcast skies during the recent period of aerosol optical depth decline in Europe. Although measurements from 15 Swiss and 8 northern German sites show clear evidence for an aerosol direct radiative effect under cloud-free skies, trends of transmitted solar irradiance ( $SW_{\text{tran}}$ ) under overcast skies are ambiguous. Time series from 1981 to 2005 of  $SW_{\text{tran}}$  for all overcast conditions show slightly negative, but nonsignificant trends.  $SW_{\text{tran}}$  under overcast conditions with “thick” clouds ( $SW_{\text{tran}}$  smaller than the long-term mean) exhibit on average an increasing trend of  $+0.29$  [ $+0.01$  to  $+0.57$ ]  $W\ m^{-2}/$  decade. The increase of  $SW_{\text{tran}}$  under “thick” overcast skies, however, is about nine times smaller than the increase under cloud-free skies. Since cirrus clouds are generally excluded from and low-level stratiform clouds are more frequently represented by “thick” overcast skies, the slight increase in  $SW_{\text{tran}}$  may possibly result from a weak aerosol indirect effect. Alternatively, the increase in  $SW_{\text{tran}}$  may be due to a decreasing trend in low-level stratiform cloud amount under overcast conditions observed for these sites. We further find that solar irradiance changes caused by decreasing aerosol direct effect and increasing sunshine duration can account for most of the observed increasing all-sky solar radiation trend. This suggests that the first aerosol indirect effect makes little contribution to surface solar radiation changes over Europe.

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### 1. Introduction

[2] Global solar irradiance changes at the Earth’s surface have been widely observed, known popularly as solar “dimming” and “brightening” [e.g., Gilgen *et al.*, 1998; Wild *et al.*, 2005; Wild, 2009, and references therein]. Such decadal variations have been related to changes in atmospheric cloud-free transmittance, cloud cover, and cloud optical depth. In Europe, the decadal variations have been mainly observed under cloud-free skies [Ruckstuhl *et al.*, 2008] or after removing radiative effects of cloud cover changes on solar irradiance [Norris and Wild, 2007]. As the European cloud-free solar irradiance trends coincide with increasing and decreasing clear-sky visibility [Wang *et al.*, 2009] and declining aerosol optical depth (AOD) since 1986 [Ruckstuhl *et al.*, 2008], the observations provide strong evidence of the aerosol direct radiative effect (scattering and absorption of solar radiation by aerosols).

[3] Unlike the aerosol direct effect, the effects of aerosols on clouds, called aerosol indirect radiative effects (AIE),

remain rather uncertain. These include the first AIE or cloud albedo effect [Twomey *et al.*, 1984], the second AIE or cloud lifetime effect [Albrecht, 1989], and the semi-direct effect [Hansen *et al.*, 1997]. The cloud albedo effect is defined as the increase in cloud albedo caused by an enhancement in the number of cloud droplets with fixed water amount due to more cloud condensation nuclei (CCN). The cloud lifetime effect is caused by smaller cloud particles due to more CCN and hence, a decrease in precipitation and a prolonging of cloud lifetime. The semi-direct aerosol effect describes the absorption of solar radiation by soot, thereby causing evaporation of cloud particles. In the IPCC-AR4 [Forster *et al.*, 2007], the magnitude of the first AIE is estimated by global climate models (GCMs) to be  $-0.7$  [ $-1.8$  to  $-0.3$ ]  $W\ m^{-2}$  at top of the atmosphere (TOA). Some recent studies, however, indicate that the first AIE could be overestimated [e.g., Quaas *et al.*, 2008; Murphy *et al.*, 2009]. Estimates of AIE on the surface radiation budget are scarce, but they are thought to have about the same magnitude as the forcings at TOA [Ramanathan *et al.*, 2001; Lohmann and Feichter, 2005]. Norris and Wild [2007] found no evidence for the existence of the second AIE in Europe, where low-frequency cloud cover variations were correlated with the North Atlantic Oscillation rather than long-term changes in aerosol amount.

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[4] Although several experimental case studies have reported changes in cloud albedo and other physical cloud properties due to enhanced CCN [e.g., *Wilcox et al.*, 2006; *Roberts et al.*, 2008], there is still a lack of observational research on the effects of aerosol on clouds over longer time scales and in larger geographical areas. The main reasons for this are the absence of long-term monitoring systems (i.e., multidecadal high-time resolution measurements of AOD, solar irradiance, and cloud properties) and difficulties in eliminating the large confounding impact of natural cloud variability.

[5] One way to reduce the impact of natural cloud cover variability on the surface radiation budget is to consider only those cases of completely overcast skies. Such studies were performed in Germany for periods when the European anthropogenic aerosol burden was increasing. According to *Liepert* [1997, 2002] and *Liepert and Kukla* [1997], global solar irradiance under completely overcast skies decreased by about  $-2.5$  to  $-8 \text{ W m}^{-2}$  per decade (dec) in Germany between the mid-1960s and 1990. The reduction in solar irradiance has been attributed to a decrease in cloud transmissivity due either to changing cloud types or AIEs. *Krüger and Grassl* [2002] reported that cloud albedo decreased over Europe by about  $-2.5\%$  between a period in the late 1980s and a period in the late 1990s, corresponding to a reduction in cloud radiative forcing of about  $1.5 \text{ W m}^{-2}$ .

[6] Because of the strong AOD decrease in Europe during the past two decades, a change in cloud albedo should be apparent in surface global solar irradiance measurements if the first AIE is non-negligible. This study uses surface solar irradiance measurements under completely overcast skies to investigate whether transmission through clouds over Switzerland and northern Germany was increasing when AOD and hypothesized AIE-influenced cloud albedo were decreasing. We also examine whether the aerosol direct effect and changes in sunshine duration can account for the trend in all-sky solar irradiance measurements.

## 2. Observational Data and Methods

[7] We use global solar irradiance measurements from the MeteSwiss Automatic Meteorological Network (ANETZ) [*Moesch and Zelenka*, 2004] where synoptic cloud observations are also available. This reduces the number of lowland sites from 25 originally used by *Ruckstuhl et al.* [2008] to 15 sites. In northern Germany, synoptic total cloud cover reports from the German Weather Service (DWD) are used, which are available for all of the eight DWD sites reported in *Ruckstuhl et al.* [2008]. Synoptic cloud-type reports for the 1981–1996 time period were obtained from the NDP-026C archive [*Hahn and Warren*, 1999] for five of the eight German sites.

[8] Monthly mean anomalies of transmitted solar irradiance ( $SW_{\text{tran}}$ ) under overcast skies were calculated in order to estimate decadal trends of cloud properties. It is not possible from surface measurements to distinguish the impacts of cloud absorption or reflection on transmission, but it has been shown that reflection is about an order of magnitude larger than absorption [*Stephens*, 1978].  $SW_{\text{tran}}$  variations thus represent mainly changes in cloud albedo. We used synoptic cloud reports to identify overcast situa-

tions. In Germany, cloud observations are made during the 10 min time window before the synoptic hour according to the rules for Weather Service ground observations. In Switzerland, the time window is set to 30–40 min before the synoptic time, in order to provide enough time for the observer to transmit the data to the data center. For the German sites, we calculated the fraction of transmitted solar radiation,  $R_{\text{tran}}$ , as the average of the hour before and after the reported total cloud cover was 8 octas. For the Swiss sites, we calculated  $R_{\text{tran}}$  for the specific synoptic hour.

[9] For overcast daytime hours with solar zenith angle (SZA)  $\leq 85^\circ$ , we calculated  $R_{\text{tran}}$  according to equation (1)

$$R_{\text{tran}}(i) = \frac{\text{SDR}_{\text{ovc}}(i)}{\text{SDR}_{\text{TOA}}(i)}, \quad (1)$$

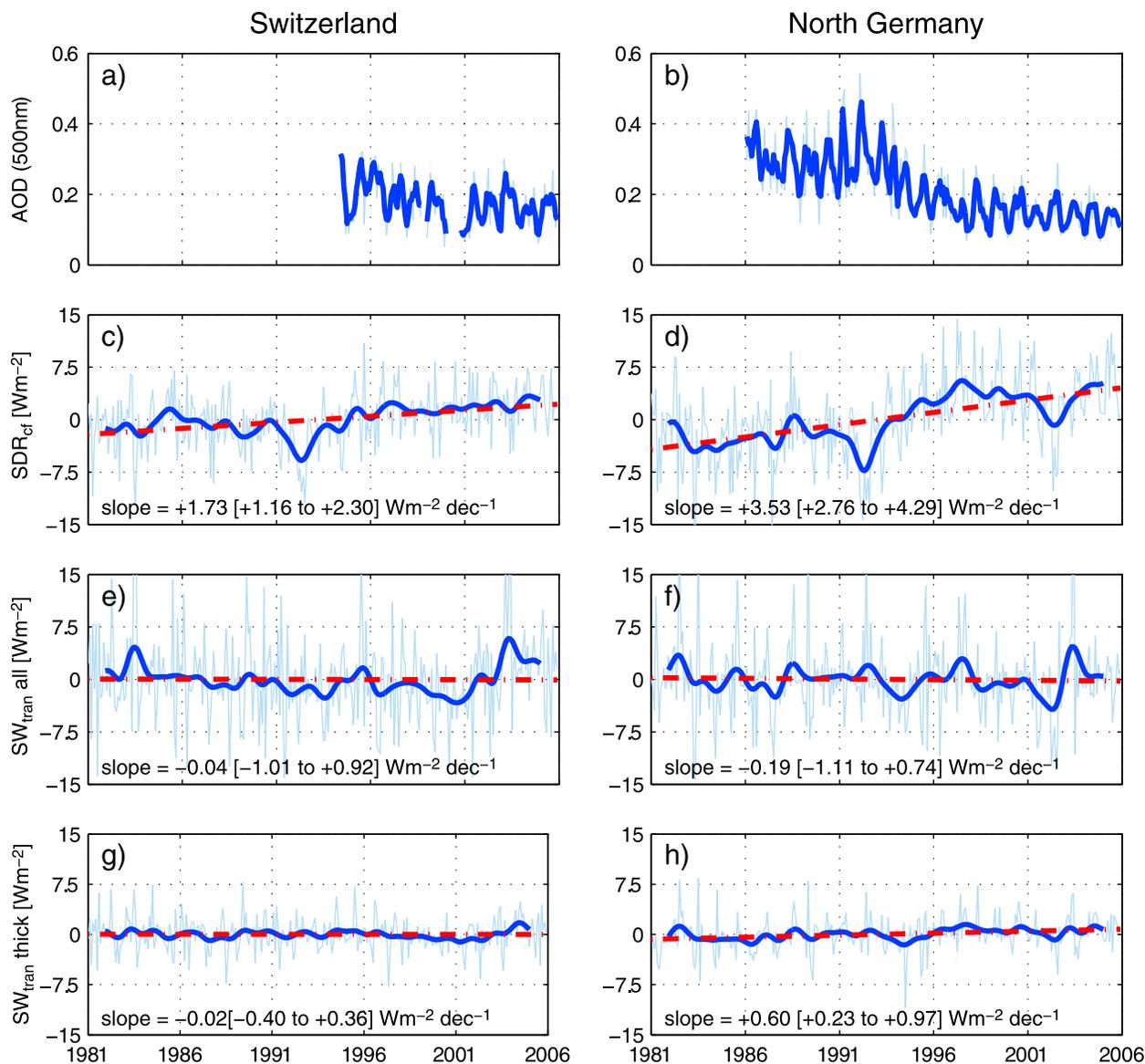
where  $\text{SDR}_{\text{TOA}}$  is shortwave downward radiation at TOA,  $\text{SDR}_{\text{ovc}}$  is solar irradiance at the surface measured under overcast skies, and the index  $i$  stands for 1- or 2-h average values.  $R_{\text{tran}}(i)$  exhibits a slight linear dependence on SZA, caused by the cloud albedo dependency on SZA, and this dependence was removed by applying a site-dependent empirically derived linear correction formula. We then averaged hourly values of SZA corrected  $R_{\text{tran}}(i)$  during each month (mo) and year (yr) to monthly values of cloud transmission  $R_{\text{tran}}(\text{yr}, \text{mo})$ . Monthly absolute transmission anomalies in  $\text{W m}^{-2}$ ,  $SW_{\text{tran}}(\text{yr}, \text{mo})$ , were obtained according to equation (2), assuming perpetual overcast skies

$$SW_{\text{tran}}(\text{yr}, \text{mo}) = R_{\text{tran}}(\text{yr}, \text{mo}) \times \text{SDR}_{\text{TOA}}(\text{yr}, \text{mo}), \quad (2)$$

where  $\text{SDR}_{\text{TOA}}$  is the monthly mean solar irradiance at TOA for a particular month and year, averaged over 24 h each day. With this procedure, we ensure that  $SW_{\text{tran}}(\text{yr}, \text{mo})$  values are independent of SZA at the time of the occurrence of overcast skies, of the frequency of overcast skies during a particular period, and of the decreasing trend in the occurrence of overcast skies trends as reported by *Vautard et al.* [2009]. Additionally, we distinguish between “all” and “thick” overcast conditions by defining the latter as hourly  $R_{\text{tran}}(i)$  values that are smaller than the climatological monthly mean  $R_{\text{tran}}(1981-2005, \text{mo})$  of the respective site.

## 3. Results: Aerosol Direct Versus Indirect Effect

[10] With exception of the Mt. Pinatubo affected years (1991–1994), AOD decreased steadily in Central Europe during the last two decades [*Ruckstuhl et al.*, 2008]. The AOD decrease coincides with declining anthropogenic aerosol emission [*Streets et al.*, 2006] and is therefore most pronounced at lower elevation sites. Figure 1 shows time series of AOD at 500 nm for the lowland site Payerne, Switzerland (Figure 1a) and as the average of two northern German sites, Zingst and Lindenberg (Figure 1b). Congruent with the decrease in AOD, there is a statistically significant increase in shortwave downward radiation observed under cloud-free skies ( $\text{SDR}_{\text{cf}}$ ). In Figures 1c and 1d, we show  $\text{SDR}_{\text{cf}}$  time series averaged over the 15 Swiss and the 8 northern German sites, respectively.  $\text{SDR}_{\text{cf}}$  was calculated by applying the method described in *Ruckstuhl and Philipona* [2008], but assuming perpetual cloud-free skies.  $\text{SDR}_{\text{cf}}$  increased by  $+1.73$  [ $+1.16$  to  $+2.30$ ]  $\text{W m}^{-2}$



**Figure 1.** Time series of aerosol optical depth (AOD) (a) at the lowland site Payerne, Switzerland and (b) as average of the two northern German sites Zingst and Lindenberg after the application of a 3-month running mean. Monthly deseasonalized anomalies of (c and d) cloud-free shortwave downward radiation, (e and f) transmitted shortwave radiation under “all” overcast sky conditions, and (g and h) under “thick” overcast sky conditions. See text for details how between “all” and “thick” overcast skies are distinguished. Figures 1c, 1e, and 1g represent an average of 15 Swiss lowland sites, and Figures 1d, 1f, and 1h represent the average of 8 northern German sites, respectively. Dark blue lines are time series after applying a 23-point Lanczos lowpass filter and red dashed lines represent linear trends from 1981 to 2005. Slopes of the trends per decade are given with their 95% confidence intervals in brackets.

$\text{dec}^{-1}$  in Switzerland and by  $+3.53 [+2.76 \text{ to } +4.29] \text{ W m}^{-2} \text{ dec}^{-1}$  in northern Germany. The number in brackets indicate the 95% confidence interval of the linear regression. The coherence between increasing  $\text{SDR}_{\text{cf}}$  and decreasing AOD is likely to represent the aerosol direct radiative effect.

[11] Changes in transmitted solar radiation under completely overcast skies are contrastingly rather small. Figures 1e and 1f show time series of  $\text{SW}_{\text{tran}}$  for “all” overcast cases. In both countries, a slight statistically nonsignificant decrease of  $\text{SW}_{\text{tran}}$  is observed ( $-0.04 [-1.01 \text{ to } +0.92] \text{ W m}^{-2} \text{ dec}^{-1}$  for Switzerland and  $-0.19 [-1.11 \text{ to } +0.74] \text{ W$

$\text{m}^{-2} \text{ dec}^{-1}$  for northern Germany). Variability between monthly  $\text{SW}_{\text{tran}}$  anomalies for “all” overcast cases is relatively large and is caused by natural variability in the occurrence of different cloud types. For this reason, we also investigated  $\text{SW}_{\text{tran}}$  for “thick” overcast cloud to avoid the possibility that trends in the frequency of overcast optically thin clouds, such as cirrus, could have a dominant impact on the  $\text{SW}_{\text{tran}}$  trends. Note that variability in  $\text{SW}_{\text{tran}}$  for “thick” overcast is weaker than that for all overcast and cloud-free conditions because cloud albedo has less sensitivity to optical thickness changes at large values. We found a

**Table 1.** Daytime Cloud Amount and Overcast Frequency Trends and Their Average Amount and Frequency of Occurrence<sup>a</sup>

	Switzerland 1981–2005 (7 Sites)		North–West Germany 1981–1996 (5 Sites)	
	Trend	Average	Trend	Average
Cloud amount	−0.66 [−2.00 to +0.69]	63.9	−0.35 [−2.71 to +2.00]	69.9
Overcast frequency	−2.37 [−3.64 to −1.10]	30.3	−1.96 [−4.17 to +0.24]	27.4

<sup>a</sup>The daytime cloud amount trends are given in % sky cover dec<sup>−1</sup> and overcast frequency trends are given in % dec<sup>−1</sup>. The 95% confidence interval is given in brackets.

positive correlation ( $R^2 = 0.091$ , slope = +0.62 [+0.53 to +0.70] W m<sup>−2</sup> %<sup>−1</sup>) between monthly anomalies of the occurrence of high clouds and SW<sub>tran</sub> for “all” overcast conditions, but not for “thick” overcast conditions ( $R^2 = 0.0003$ , slope = −0.02 [−0.06 to +0.03] W m<sup>−2</sup> %<sup>−1</sup>). The absence of a correlation shows that limiting the analysis to “thick” overcast skies effectively reduces the uncertainty due to trends in the occurrence of different cloud types. We found a negative correlation between the occurrence of low-level stratiform clouds and SW<sub>tran</sub>, indicating that these clouds typically correspond to “thick” overcast conditions. Low-level stratiform clouds (cloud types four through eight according to the World Meteorological Organization code [World Meteorological Organization, 1974], nontechnical descriptions are given by Norris [1998, Table 1]) are furthermore more likely to be influenced by the first AIE. Figures 1g and 1h show that SW<sub>tran</sub> trends under “thick” overcast sky situations are also relatively small (between −0.02 [−0.40 to +0.36] W m<sup>−2</sup> dec<sup>−1</sup> in Switzerland and +0.60 [+0.23 to +0.97] W m<sup>−2</sup> dec<sup>−1</sup> in northern Germany). Increasing “thick” SW<sub>tran</sub> and decreasing AOD over Germany may represent the first AIE, but on average, the “thick” SW<sub>tran</sub> trends are about nine times smaller than the cloud-free trends.

[12] One important question is whether the SW<sub>tran</sub> trends are likely to be primarily caused by the first AIE, by a change in the frequency of occurrence or amount of different cloud types, or any changes in liquid water path. To answer this, we investigated time series of cloud amount under all-sky and overcast conditions using daytime synoptic reports. German cloud-type data are limited to five

former West-German sites and the period 1981–1996. Table 1 lists daytime all-sky cloud amount trends and overcast frequency trends. Although the trends are mostly not statistically significant, cloud amount and overcast frequency have been declining in Switzerland as well as in northern Germany. Table 2 displays cloud amount trends for different cloud types and their average amount under daytime all-sky and overcast conditions. Swiss cloud amount trends from 1981 to 2005 are calculated without the year 2004 due to missing cloud-type data in that year. In northwestern Germany, the amount of low-level stratiform clouds under overcast conditions decreased by a nonsignificant −0.17 [−2.06 to +1.72]%sky-cover dec<sup>−1</sup>. The Swiss synoptic observations (7 out of the 15 Swiss sites report detailed cloud observations) also show a decrease of stratiform cloud amount (−2.80 [−3.96 to −1.64]%sky-cover dec<sup>−1</sup> for “all” overcast and −2.56 [−3.74 to −1.38]% dec<sup>−1</sup> for “thick” overcast). Considering these negative trends and the abovementioned negative correlation between monthly anomalies of stratiform cloud occurrence and SW<sub>tran</sub>, we conclude that the decrease in stratiform clouds under overcast conditions contributed to the increase in SW<sub>tran</sub>. Without the reduction in low-level stratiform clouds, SW<sub>tran</sub> trends would have been less positive. Changes in other cloud types have smaller impacts on SW<sub>tran</sub> trends as they either exhibit much smaller trends or no correlation between their monthly cloud occurrence anomalies and SW<sub>tran</sub> anomalies.

[13] It is possible that the observed SW<sub>tran</sub> trends might be affected by changes in cloud liquid water content. Unfortunately, no high-time resolution long-term measurements of cloud liquid water path are available to test this hypothesis.

**Table 2.** Daytime Cloud Amount Trends Under All-Sky and Overcast Conditions and Their Average Cloud Amount<sup>a</sup>

	Switzerland 1981–2005 (7 Sites)				North–West Germany 1981–1996 (5 Sites)			
	All-Sky		Overcast		All-Sky		Overcast	
	Trend	Average	Trend	Average	Trend	Average	Trend	Average
Cumulus amount	−0.12 [−0.30 to +0.06]	4.3	−0.34 [−0.57 to −0.10]	1.9	−0.06 [−0.83 to +0.71]	7.2	+0.42 [−0.10 to +0.93]	2.1
Stratus amount	−2.50 [−3.49 to −1.51]	31.3	−2.80 [−3.96 to −1.64]	51.1	−0.67 [−3.32 to +1.99]	43.9	−0.17 [−2.06 to +1.72]	77.1
Mid amount	+0.98 [+0.56 to +1.39]	11.5	+2.36 [+1.72 to +3.01]	11.6	+0.09 [−0.55 to +0.73]	6.5	+1.04 [−0.29 to +2.37]	11.1
Mid and high amount	+0.06 [−0.13 to +0.25]	3.0	−0.38 [−0.64 to −0.12]	0.9	+0.68 [+0.36 to +1.01]	2.8	+0.34 [+0.17 to +0.51]	0.5
High amount	+0.43 [+0.24 to +0.63]	3.9	+0.36 [+0.10 to +0.61]	1.7	+0.40 [−0.40 to +1.20]	6.7	+0.04 [−0.17 to +0.26]	0.7
Fog amount	−0.81 [−1.26 to −0.36]	3.6	−1.19 [−2.11 to −0.28]	8.5	−0.94 [−1.53 to −0.34]	2.1	−2.45 [−3.97 to −0.94]	6.0

<sup>a</sup>The daytime cloud amount trends are given in % sky cover dec<sup>−1</sup> and the average cloud amount is given in % sky cover. The 95% confidence interval is given in brackets.

**Table 3.** Surface Solar Radiation Trends From 1981 to 2005<sup>a</sup>

	Switzerland (15 Sites)		Northern Germany (8 Sites)	
	1981–2005	1981–2005 Without 2003	1981–2005	1981–2005 Without 2003
SDR <sub>all-sky</sub>	+2.66 [+0.44 to +4.89]	+1.59 [−0.69 to +3.86]	+3.33 [+0.87 to +5.80]	+2.35 [−0.22 to +4.90]
SDR <sub>cloud-free</sub>	+0.81 [+0.53 to +1.09]	+0.84 [+0.55 to +1.13]	+1.48 [+1.13 to +1.84]	+1.49 [+1.12 to +1.86]
SDR <sub>cloud</sub>	+1.86 [−0.46 to +4.18]	+0.74 [−1.62 to +3.11]	+1.85 [−0.57 to +4.27]	+0.86 [−1.66 to +3.37]
SDR <sub>SSD</sub>	+1.44 [+0.68 to +2.20]	+1.09 [+0.31 to +1.86]	+0.69 [−0.20 to +1.58]	+0.37 [−0.55 to +1.30]
SDR <sub>thickness</sub>	+0.42 [−1.18 to +2.01]	−0.34 [−1.97 to +1.28]	+1.16 [−0.41 to +2.73]	+0.48 [−1.14 to +2.10]

<sup>a</sup>Surface solar radiation trends are given in  $\text{W m}^{-2} \text{dec}^{-1}$  and the 95% confidence interval is given in brackets. Trends for cloud-free conditions have been weighted by climatological monthly SSD for better comparability to all-sky trends.

We instead analyzed surface humidity measurements under overcast skies and found decreasing tendencies in relative humidity for both “all” and “thick” cloud conditions in Switzerland and slightly increasing tendencies for northern Germany. Considering that no correlation ( $R^2 < 0.003$ ) is seen between monthly anomalies of  $\text{SW}_{\text{tran}}$  and relative humidity under overcast conditions, it is unlikely that the surface humidity trends significantly affected  $\text{SW}_{\text{tran}}$ .

[14] We additionally investigated the importance of the first AIE to trends in all-sky solar irradiance ( $\text{SDR}_{\text{all-sky}}$ ) by comparing changes in  $\text{SW}_{\text{tran}}$ ,  $\text{SDR}_{\text{cf}}$ , and sunshine duration (SSD). Trends for Switzerland (15 sites) and northern Germany (8 sites) are listed in  $\text{W m}^{-2} \text{dec}^{-1}$  in Table 3. Since  $\text{SDR}_{\text{all-sky}}$  trends in Europe are substantially affected by the extraordinary cloud reduction during the drought summer of 2003, we calculate trends with and without the year 2003. When  $\text{SDR}_{\text{cf}}$  (weighted with the observed climatological SSD) is subtracted from  $\text{SDR}_{\text{all-sky}}$  we obtain  $\text{SDR}_{\text{cloud}}$ , the total change in solar irradiance due to changes in cloud optical thickness and cloud cover. The change in solar radiation irradiance due to a change in SSD ( $\text{SDR}_{\text{SSD}}$ ) is obtained by multiplying the climatological mean of  $\text{SDR}$  under overcast conditions by monthly anomalies in SSD. The remaining flux after removing  $\text{SDR}_{\text{SSD}}$  from  $\text{SDR}_{\text{cloud}}$  is the solar irradiance change due to changes in cloud optical thickness, referred to as  $\text{SDR}_{\text{thickness}}$ . Trends in  $\text{SDR}_{\text{thickness}}$  are either due to the first aerosol indirect effect or changes in the occurrence of certain cloud types.

[15] All-sky irradiance exhibits positive trends from 1981 to 2005, but they are statistically significant only if the year 2003 is included. SSD-weighted  $\text{SDR}_{\text{cf}}$  trends are significantly positive irrespective of whether 2003 data are included.  $\text{SDR}_{\text{cloud}}$  fluxes show nonsignificant positive trends. The increase in SSD over the 25 years, which is in accordance with the reported total cloud amount decrease, produces a significant positive trend over Switzerland and a nonsignificant positive trend over northern Germany. When the positive  $\text{SDR}_{\text{SSD}}$  trends are subtracted from  $\text{SDR}_{\text{cloud}}$  and 2003 data are excluded, the remaining  $\text{SDR}_{\text{thickness}}$  fluxes are  $-0.34$  [ $-1.97$  to  $+1.28$ ]  $\text{W m}^{-2} \text{dec}^{-1}$  for Switzerland and  $+0.48$  [ $-1.14$  to  $+2.10$ ]  $\text{W m}^{-2} \text{dec}^{-1}$  for northern Germany. If 2003 data are included,  $\text{SDR}_{\text{thickness}}$  trends have larger but nonsignificant values. The fact that  $\text{SDR}_{\text{cf}}$  and  $\text{SDR}_{\text{SSD}}$  trends can account for most of the  $\text{SDR}_{\text{all-sky}}$  trends, particularly if the meteorologically unusual year of 2003 is excluded, suggests that the first AIE has made little contribution to solar brightening over Europe. Note that the dominance of the aerosol direct effect over the indirect effect may be less at the TOA than it is at

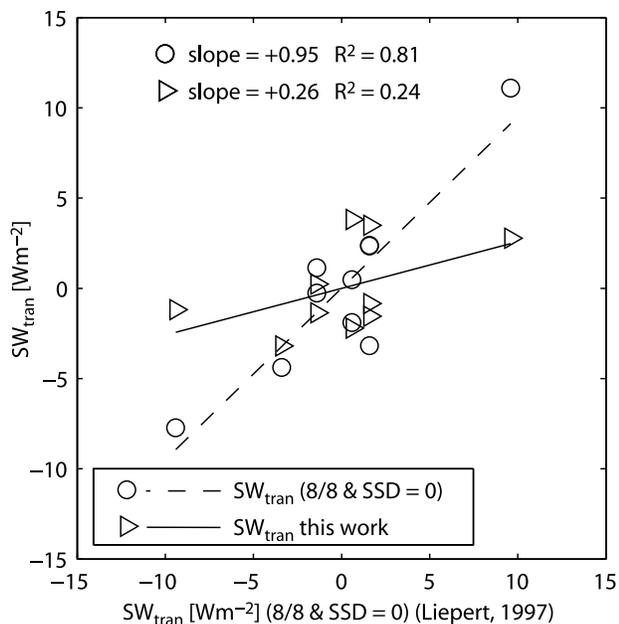
the surface due to aerosol absorption of solar radiation. For single-scattering albedo on the order of 0.9–0.97 as found in Europe [Tombette *et al.*, 2008], the TOA aerosol direct effect is about 2–1.1 times smaller than the surface effect [Gonzi *et al.*, 2007].

#### 4. Discussion and Conclusions

[16] The observed trends from 1981 to 2005 in downward solar radiation at the surface averaged over 15 Swiss lowland sites and 8 northern German sites are  $+2.63$  [ $+2.10$  to  $+3.15$ ]  $\text{W m}^{-2} \text{dec}^{-1}$  for cloud-free conditions and  $+0.29$  [ $+0.01$  to  $+0.57$ ]  $\text{W m}^{-2} \text{dec}^{-1}$  for “thick” overcast conditions. Assuming no other effects have compensated the first AIE in the radiation budget, the surface measurements indicate that the first AIE under perpetual overcast skies is about nine times smaller than the aerosol direct radiative effect under perpetual cloud-free skies. If the observed decrease in low-level stratiform cloud amount under overcast conditions is considered, the first AIE would be even smaller. As a second approach, we subtracted the effects of increasing flux under cloud-free skies and increasing sunshine duration from all-sky irradiance. The resulting flux, associated with changes in cloud optical thickness, has an average trend of  $+0.79$  [ $-0.56$  to  $+2.14$ ]  $\text{W m}^{-2} \text{dec}^{-1}$  if all years are considered or  $+0.07$  [ $-1.31$  to  $+1.44$ ]  $\text{W m}^{-2} \text{dec}^{-1}$  if the extraordinary drought year of 2003 is left out of the trend analysis. Considering the large range of uncertainty, it is not possible to state that an AIE has had an appreciable influence on surface solar irradiance over Europe. Moreover, without the observed decreasing trends of low-level stratiform cloud amount, the  $\text{SDR}_{\text{thickness}}$  trends would be even smaller.

[17] Assuming clouds in fractionally cloud-covered skies are affected by aerosols in the same way as clouds under completely overcast sky conditions,  $\text{SW}_{\text{tran}}$  trends would be smaller by the fraction of the observed cloud cover. In Switzerland and northern Germany, the average daytime cloud fraction is 5.1 octas and 5.6 octas, respectively. Accordingly, the average  $\text{SW}_{\text{tran}}$  trend under “thick” overcast conditions would be reduced to about  $+0.20$   $\text{W m}^{-2} \text{dec}^{-1}$ . The preceding value is actually an upper limit for changes in cloud transmission because “thick” clouds are only partial contributors to average cloud fraction. For comparison, the average  $\text{SDR}_{\text{cf}}$  trend scaled by the average noncloud fraction would reduce to about  $+0.84$   $\text{W m}^{-2} \text{dec}^{-1}$ .

[18] Our results stand in contrast to the relatively large decreasing trends in global solar irradiance under overcast



**Figure 2.** Correlation between  $SW_{\text{tran}}$  from data used in this study and from Liepert [1997]. Annual mean  $SW_{\text{tran}}$  is calculated for overcast conditions and  $SSD = 0$  from all daytime values during a year (dashed line) and with the method described in this work (solid line).

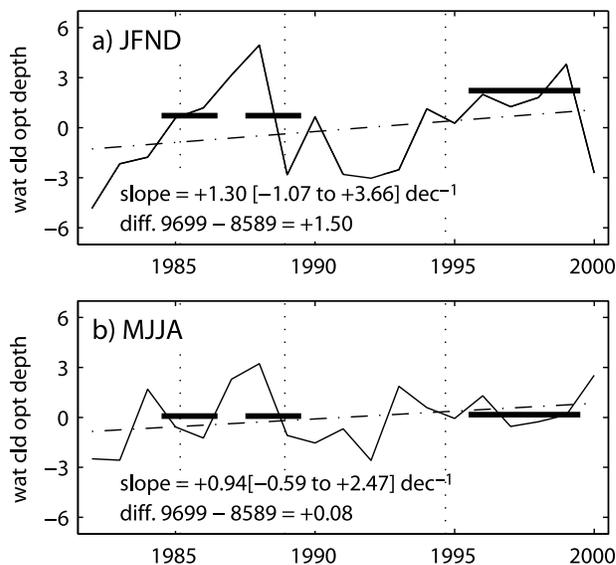
conditions reported by Liepert [1997, 2002] and Liepert and Kukla [1997] during the increasing AOD period of the 1960s–1990. Although we examine the period of time when AOD was decreasing, the results should be of the same order of magnitude. One reason for the difference is that annual means given by Liepert are calculated as average over only daytime measurements during a specific year. This artificially enlarges any trends by ignoring nighttime hours. Figure 2 shows the correlation of  $SW_{\text{tran}}$  anomalies for overcast skies and  $SSD = 0$  between Liepert [1997] Hamburg data, annual means of  $SW_{\text{tran}}$  calculated for Hamburg for the same conditions averaging all annual values (dashed line). The dotted line is from data calculated with the method used in this work. Note that our procedure results in much smaller  $SW_{\text{tran}}$  anomalies than the Liepert approach.

[19] Another reason for the difference is that Liepert calculated solar irradiance under overcast skies within relatively large SZA intervals. If a systematic change in average SZA for overcast conditions occurs over time, averaging hourly  $SDR_{\text{ovc}}$  values to monthly or annual values without first normalizing by  $SDR_{\text{TOA}}$  will produce a spurious change in  $SW_{\text{tran}}$  solely due to the variation of insolation with SZA. We calculated the radiative impacts of observed SZA changes for overcast skies within the SZA intervals used by Liepert and found artificial solar irradiance trends at Hamburg between  $-0.7$  and  $-2.2 \text{ W m}^{-2} \text{ dec}^{-1}$  for the 1971–1990 time period, depending on the method to average the intervals and whether all overcast or only low-level stratiform overcast conditions are considered.

[20] Krüger and Grassl [2002] also reported a relatively large AIE over Europe based on a decrease in the reflectance of liquid water clouds between 1985 and 1989 and

1996–1999 according to the Advanced Very High Resolution Radiometer Pathfinder Atmosphere (PATMOS) data set [Jacobowitz *et al.*, 2003]. Using the PATMOS-X data set, a next-generation version with improved algorithms [Pavolonis *et al.*, 2005], we found that long-term changes in the optical thickness of liquid water clouds contrastingly show a statistically nonsignificant increase irrespective of whether a trend was calculated over 1982–2000 or whether the 1985–1989 (excluding 1987) and 1996–1999 periods were differenced (Figure 3). Times series in Figure 3 are from the same area over land in parts of central Europe ( $48.5^{\circ}\text{N}$  to  $57.5^{\circ}\text{N}$  and  $5^{\circ}\text{W}$  to  $28.5^{\circ}\text{E}$ ) as used in Krüger and Grassl [2002]. The change of trend sign between older and newer versions of the PATMOS data set suggests that the Krüger and Grassl results are not robust. Furthermore, PATMOS cloud properties may suffer from spurious trends arising from systematic drifts in equatorial crossing time that alias the diurnal cycle [Jacobowitz *et al.*, 2003].

[21] Our results indicate that the first AIE is quite small and difficult to discern through surface solar irradiance measurements under overcast conditions, even in a region where aerosols drastically decreased by up to 63% within two decades. It is possible that changes in meteorological conditions or some other unidentified processes may have influenced trends in overcast solar irradiance, but we have no reason to expect that these effects have had the time characteristics to fortuitously cancel or diminish any AIE. Although our regional value cannot be directly compared to global estimates, we expect that the first AIE, where it is a



**Figure 3.** Anomalies of water cloud optical depth (wat cld opt depth) from 1982 to 2000 for (a) the winter months JFND and (b) the summer months MJJA averaged over land in parts of central Europe ( $48.5^{\circ}\text{N}$  to  $57.5^{\circ}\text{N}$  and  $5^{\circ}\text{W}$  to  $28.5^{\circ}\text{E}$ ). Linear trends with their 95% confidence intervals are given per decade. Difference 9699 – 8589 gives the differences between the time periods from 1985 to 1989 (excluding 1987) and 1996 to 1999. The averages of these time periods are illustrated with solid horizontal lines. The vertical lines stand for changes of satellites within the NOAA satellite series.

climatically significant mechanism, should be much more pronounced in Europe than in the global average. Similar long-term studies in other regions will help determine whether aerosol indirect effects are observable from surface.

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