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Aerosol and cloud effects on solar brightening and the recent rapid warming

Christian Ruckstuhl,[1] Rolf Philipona,[2] Klaus Behrens,[3] Martine Collaud Coen,[2]
Bruno Dürr,[4] Alain Heimo,[2] Christian Mätzler,[5] Stephan Nyeki,[6] Atsumu Ohmura,[1]
Laurent Vuilleumier,[2] Michael Weller,[3] Christoph Wehrli,[6] and Antoine Zelenka[4]

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[1] The rapid temperature increase of 1°C over mainland Europe since 1980 is considerably larger than the temperature rise expected from anthropogenic greenhouse gas increases. Here we present aerosol optical depth measurements from six specific locations and surface irradiance measurements from a large number of radiation sites in Northern Germany and Switzerland. The measurements show a decline in aerosol concentration of up to 60%, which have led to a statistically significant increase of solar irradiance under cloud-free skies since the 1980s. The measurements confirm solar brightening and show that the direct aerosol effect had an approximately five times larger impact on climate forcing than the indirect aerosol and other cloud effects. The overall aerosol and cloud induced surface climate forcing is $\sim$+1 W m^{-2} dec^{-1} and has most probably strongly contributed to the recent rapid warming in Europe. **Citation:** Ruckstuhl, C., et al. (2008), Aerosol and cloud effects on solar brightening and the recent rapid warming, *Geophys. Res. Lett.*, *35*, L12708, doi:10.1029/2008GL034228.

1. Introduction

[2] Continental- and global-scale surface temperatures have decreased slightly from the 1950s to the 1980s, but have since strongly increased, in particular over the northern continents [*Jones and Moberg*, 2003]. Solar irradiance measurements from various regions around the globe, exhibit similar behaviour with a decrease after the mid-1950s followed by an increasing trend as of the mid-1980s [*Ohmura*, 2006]. This solar dimming [*Ohmura and Lang*, 1989; *Stanhill and Cohen*, 2001; *Liepert*, 2002] and brightening [*Wild et al.*, 2005] cannot be explained by variations of the Sun's radiative output [*Foukal et al.*, 2006], and is therefore expected to be a consequence of changing atmospheric transmittance due to increases and subsequent decreases in anthropogenic aerosol concentrations [*Norris and Wild*, 2007], cloud mediated aerosol effects, and direct cloud effects.

[3] Aerosols are known to affect atmospheric transmittance and hence temperature via the direct aerosol effect (scattering and absorption of sunlight by aerosol particles). Modelling studies however, expect cloud mediated indirect aerosol effects, such as the cloud albedo effect (enhancement of cloud albedo due to smaller droplets) [*Twomey*, 1974] or the cloud lifetime effect (extension of cloud lifetime due to smaller droplets and less precipitation loss) [*Albrecht*, 1989] to have an even larger impact than the direct aerosol effect at the top of the atmosphere [*Lohmann and Feichter*, 2005].

[4] In this study, we present observational evidence of a strong decline in aerosol optical depth (*AOD*) over mainland Europe during the last two decades of rapid warming. Solar irradiance, concurrently measured at a large number of stations under cloud-free and cloudy conditions, has allowed direct and indirect aerosol radiative forcing to be investigated. A large direct but a small cloud radiative impact on surface climate was found.

2. Aerosol Optical Depth in Central Europe

[5] Aerosol optical depth, or the vertical integral of the aerosol direct radiation extinction as a measure of atmospheric transmittance, has been determined by sunphotometry since the 1960s [*Shaw*, 1983]. However, the first automated continuous *AOD* measurements in Europe did not begin until 1986 in Lindenberg (Germany) [*Weller and Leiterer*, 1988]. The longest series of spectral *AOD* measurements from the German Weather Service and MeteoSwiss are reported here from six sites covering mainland Europe from the Baltic Sea to the Alps. A BAS type Sun photometer [*Leiterer and Weller*, 1988] was used at the German sites Zingst (ZIN), Lindenberg (LIN) and Hohenpeissenberg (HOP), and SPM2000 Sun photometers [*Ingold et al.*, 2001] and PFR precision filter radiometers [*Wehrli*, 2000] were used at the Swiss sites Payerne (PAY), Davos (DAV), and Jungfraujoch (JUN). Figure 1 shows the *AOD* sites in orange (left) and *AOD* measurements at $\lambda = 500$ nm (right), ordered by increasing altitude from ZIN at sea level up to JUN at 3580 m above sea level (masl).

[6] The longest data series are from ZIN and LIN, with LIN showing an uninterrupted record from February 1986 to 2005. Continuous records are available at all stations

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[1] Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.

[2] Aerological Station, Federal Office of Meteorology and Climatology MeteoSwiss, Payerne, Switzerland.

[3] Meteorologisches Observatorium Lindenberg, Deutscher Wetterdienst, Lindenberg, Germany.

[4] Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland.

[5] Institute of Applied Physics, University of Bern, Bern, Switzerland.

[6] Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Davos, Switzerland.

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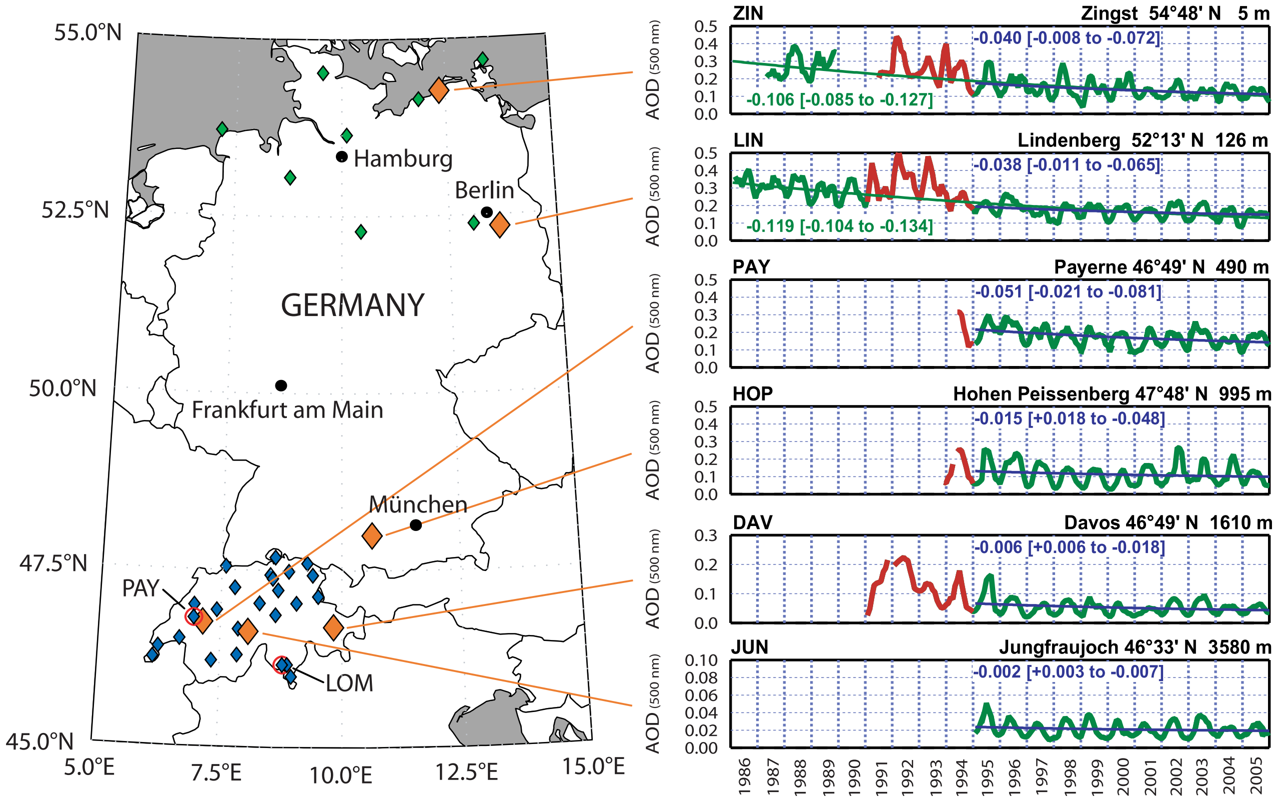

Figure 1. (left) Location of surface observation sites in Germany and Switzerland used in this study. *AOD* sites are shown in orange, DWD (German Weather Service) sites in green, MeteoSwiss sites in blue, and ASRB stations in red. (right) Monthly mean *AOD* are smoothed with a three month running mean and shown in green, except the Pinatubo affected years 1991–1994 that are not included in trend analyses and are shown in red. Trends in *AOD* are given per decade and are shown for different time periods (green 1986–2005, blue 1995–2005), while square brackets denote the 95% confidence interval.

since January 1995. Monthly values are shown with a three-month running mean to better illustrate *AOD* seasonality. Since *AOD* data are log-normally distributed, trends for different time periods were estimated by fitting the logarithm of the monthly mean *AOD* with a Least Mean Square (LMS) approximation [*Weatherhead et al.*, 1998]. *AOD* data are illustrated in green except for the Pinatubo affected years 1991 to 1994 that are shown in red and which have been discarded from trend analyses.

[7] A considerable decrease in *AOD* with a statistically significant trend is observed at ZIN and LIN over the 1986 to 2005 measurement period (green). A statistically significant reduction is also observed for the 1995 to 2005 period (blue) at the three lowland stations ZIN, LIN, PAY. In addition, a decrease in *AOD* occurred at the alpine stations HOP, DAV, and JUN over the same period, but the trends are not statistically significant due to lower absolute *AOD* and larger relative variability.

[8] ZIN and LIN show an overall *AOD* decrease of about 60% from 1986 to 2005 (see Table 1). From 1995 to 2005 *AOD* decreases between 20 and 30% at the three lowland stations and by 10 to 15% at the higher sites. The large decrease in aerosol concentration that is observed primarily at low altitude sites suggests a reduction in anthropogenic aerosol emissions [*Weller and Gericke*, 2005; *Streets et al.*, 2006]. *AOD* has stabilized since about 2000 at these low values.

3. Shortwave Radiation Flux Changes

[9] With decreasing *AOD*, solar global irradiance or shortwave downward radiation (*SDR*) as used here (vertical direct and diffuse shortwave downward radiation) is expected to increase mainly at low altitudes, where aerosol and hence solar transmittance changes are largest. *SDR* is measured at eight sites in Northern Germany (green dia-

Table 1. Aerosol Optical Depth Change Over Different Time Periods[a]

		AOD Change (%)	
Station	Alt (m)	86-05	95-05
ZIN	5	**−63**	**−27**
LIN	126	**−60**	**−21**
PAY	490		**−26**
HOP	995		−15
DAV	1610		−12
JUN	3580		−10

[a] Numbers in bold show *AOD* changes with significance at the 95% confidence level.

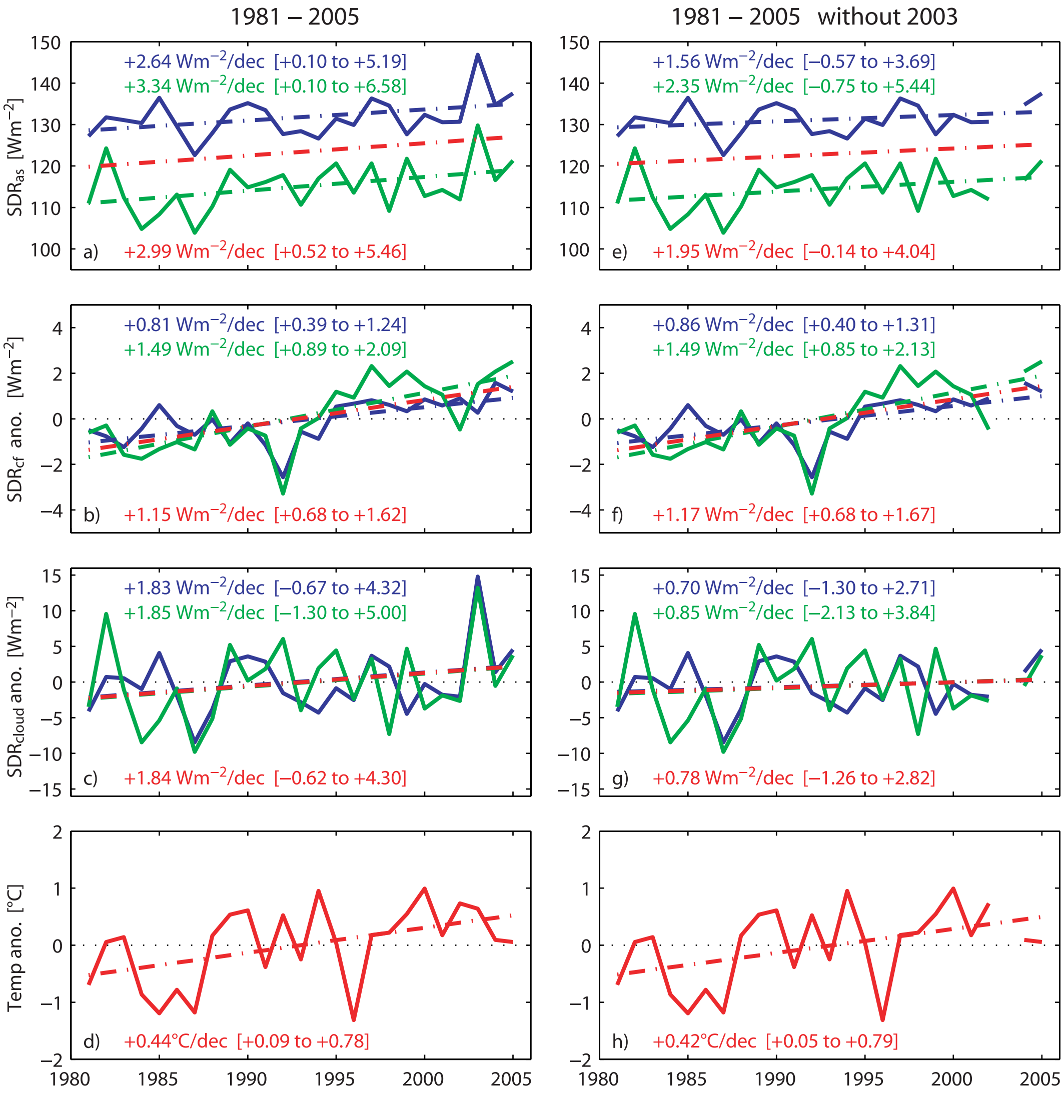

Figure 2. Time series of (a) and (e) all-sky *SDR*, (b) and (f) anomaly of cloud-free *SDR*, (c) and (g), anomaly of *SDR* for cloudy skies, and (d) and (h) the temperature anomaly. Figures 2a–2d indicate the times series of all years from 1981 to 2005. Figures 3e–2h illustrate the same time period but exclude the year 2003 with the exceptional summer. The blue lines and numbers represent average values for all 25 sites in Switzerland, green represents average values at all 8 sites in Northern Germany, and red represents the grand average and the temperature anomaly (Crutem2 data from CRU/UEA) for Central Europe (45°–55°N; 5°–15°E). Numbers indicate decadal trends in Wm^{-2} with 95 % confidence interval in square brackets.

monds in Figure 1 (left)) with PRM2 and CM11 Pyranometers, whereas sunshine duration (*SSD*) is measured with Campbell-Stokes and SONIe instruments. In Switzerland *SDR* is measured with CM6 Pyranometers and *SSD* with SOLAR 111B Heliometers at the 25 lowland (below 1000 masl) MeteoSwiss ANETZ (automatic meteorological network) sites (blue diamonds in Figure 1). The ANETZ dataset has been meticulously quality-checked and homogenized [*Moesch and Zelenka*, 2004]. This dataset is independent of the often-used Global Energy Balance Archive (GEBA) [*Gilgen and Ohmura*, 1999], which shows similar trends for all-sky and cloud removed solar irradiance [*Norris and Wild*, 2007].

[10] Sunshine duration is used to separate cloud-free from cloudy situations and is defined as the duration in minutes per hour, when the direct solar radiation exceeds a certain threshold. Cloud-free hours have been determined by applying the following procedure [*Ruckstuhl and Philipona*, 2008]: (1) *SSD* measurements show 60 minutes of sunshine during the specific hour. (2) The shortwave downward radiation transmittance $\tau_G = \left(\frac{SDR}{S_{TOA}\sin\gamma}\right)^{\frac{1}{m}}$ is calculated for these specific hours, where S_{TOA} is the insolation at top of the atmosphere (TOA) and γ the solar elevation angle. The inverse of m, the relative optical air mass, is used to normalize τ_G to normal incidence. (3) The difference between two neighbouring τ_G values has to be smaller than an empirically pre-defined value (i.e. 0.025). Large differences in τ_G between consecutive hours are interpreted as an indicator of cirrus clouds. Based on the cloud-free hourly τ_G values, monthly means of τ_G have been determined. Monthly mean τ_G values are then used to recalculate *SDR* for

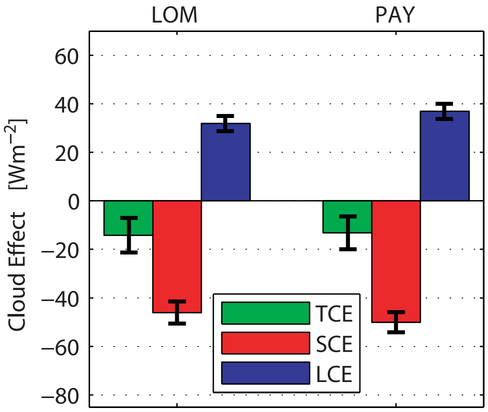

Figure 3. Total (*TCE*) in green, shortwave (*SCE*) in red, and longwave (*LCE*) cloud effect in blue (average from 1996 to 2005) at the ASRB sites Locarno Monti (LOM) and Payerne (PAY). The whiskers indicate ±1 standard deviation of the annual means. The net cloud effect is around 3.5 times smaller than the shortwave cloud effect.

cloud-free hours and monthly means of shortwave downward radiation under cloud-free situations (SDR_{cf}) are determined by averaging hourly SDR_{cf} values that are weighted with the observed *SSD*.

[11] Figure 2 shows *SDR* annual mean time series averaged over the eight German and the 25 Swiss sites for all-sky (all measured situations), cloud-free and cloudy periods. All-sky solar irradiance (SDR_{as}) (Figure 2a) shows positive trends from 1981 to 2005 at the German (green) and the Swiss sites (blue). The average increase in SDR_{as} at all stations is +2.99 [+0.52 to +5.46] Wm^{-2} dec^{-1} (red line in Figure 2a). All-sky radiation trends are largely affected by the year 2003, with strongly reduced cloudiness and hence increased shortwave radiation during the extreme summer.

[12] Anomalies, with respect to the mean irradiance from 1981 to 2005, of cloud-free shortwave downward radiation (SDR_{cf}) are shown in Figure 2b. The radiation increase under cloud-free skies of +1.15 [+0.68 to +1.62] Wm^{-2} dec^{-1} averaged over the Swiss and German sites is apparently strongly related to the observed 60 % decrease in *AOD* at low altitudes (i.e. direct aerosol effect) from 1986 to 2005. The large negative SDR_{cf} anomaly in 1992 is caused by the eruption of Mt. Pinatubo in June 1991, which does not noticeably affect the linear trends over the 1981 to 2005 period. By subtracting SDR_{cf} from SDR_{as} anomalies we obtain the changes in shortwave downward radiation anomalies that are due to changes in cloud cover and cloud characteristics (SDR_{cloud}) (Figure 2c). SDR_{cloud} anomalies show large year-to-year variability and the average trend of +1.84 [−0.62 to +4.30] Wm^{-2} dec^{-1} is again strongly affected by summer 2003.

[13] With the observed large *AOD* decrease SDR_{cloud} is expected to increase due to decreasing cloudiness related to the indirect aerosol effect. Trends in cloudiness though may also have been affected by long-term variations in large-scale atmospheric circulation. The extreme decrease in cloudiness during summer 2003 however, is caused by persisting high pressure systems and is clearly different from such long-term changes. Hence, in order to analyse long-term radiation changes between 1981 and 2005, time series of shortwave downward radiation fluxes are shown in Figures 2e–2g without the year 2003. The increasing trend in SDR_{as} is about one third lower and is no longer statistically significant. This reduction and hence the impact of 2003 is mainly observed in SDR_{cloud}, where the average trend decreases by more than a factor two from +1.84 to a non-significant value of +0.78 [−1.26 to +2.82] Wm^{-2} dec^{-1}. Trends in SDR_{cf} radiation fluxes however, show almost no change and remain statistically significant.

[14] The important question to ask now is: how have the observed changes in solar radiation (brightening) and specifically changes in SDR_{cf} and SDR_{cloud} affected the rapid temperature rise observed in Central Europe? Temperature anomalies (Crutem2 data from CRU/UEA) in Central Europe (45°–55°N; 5°–15°E; area shown in Figure 1), from 1981 to 2005 with and without 2003 (Figures 2d and 2h), show statistically significant trends of +0.44 [+0.09 to +0.78]°C dec^{-1} and +0.42 [+0.05 to +0.79]°C dec^{-1} respectively. The graphs show 2003 having negligible impact on temperature change, hence, it is appropriate to investigate long-term radiative forcings without it.

[15] With respect to temperature or climate change, the reflected radiation due to the surface albedo (*A)* has to be subtracted and only changes of the surface-absorbed or shortwave net radiation (*SNR*) apply. The observed changes or forcings of SDR_{cf} and SDR_{cloud} are therefore multiplied by $(1 - A)$. *A* has been deduced from measurements at the Baseline Surface Radiation Network (BSRN) station Payerne (490 masl). However, since measurements only started in 1993 we have no information about possible long-term changes and therefore consider albedo as constant over the investigated period. This assumption rather underestimates the effect of solar brightening, since with rising temperatures, snow amount and therefore albedo might have slightly decreased. With an average albedo for mainland Europe of $A = 0.28$ the net forcing SNR_{cf} under cloud-free skies becomes +0.84 [+0.49 to +1.20] Wm^{-2} dec^{-1}, whereas the shortwave net forcing from changing clouds SNR_{cloud} results in +0.56 [−0.91 to +2.00] Wm^{-2} dec^{-1}.

4. Short- and Longwave Cloud Effect

[16] Clouds simultaneously affect solar shortwave and thermal longwave radiation but with opposite sign. Cloud forcing effects [*Ramanathan et al.*, 1989] expressed here as cloud effect (*CE*), is defined as the net radiation flux under all-sky periods minus the net radiation flux under cloud-free skies. The total cloud effect (*TCE*) is the sum of the shortwave cloud effect (*SCE*) and the longwave cloud effect (*LCE*). Figure 3 shows measured *CEs* averaged from 1996 to 2005 at the ASRB lowland sites Locarno-Monti (LOM; 370 masl) and Payerne (PAY; 490 masl). The two stations show that a negative *SCE* is partly compensated by a positive *LCE* and that the resulting total cloud effect *TCE* is at low elevations about 3.5 times smaller than the negative *SCE*. Hence, with respect to surface temperature change or climate impact, the SNR_{cloud} forcing, which is due to declining clouds mainly in the lower troposphere where *AOD* changed, must be divided by 3.5 and results in a cloud forcing due to total net radiation (TNR_{cloud}) of only +0.16

[−0.26 to +0.57] Wm^{-2} dec^{-1}. This is about five times smaller than the SNR_{cf} forcing, which is due to the direct aerosol effect.

5. Strong Reductions in Air Pollutants

[17] A strong reduction in anthropogenic aerosol concentrations since the 1980s is not surprising given the tremendous efforts made to cut air pollutant emissions. In its recent 25 year report entitled "Clearing the Air", *Long-Range Transboundary Air Pollution (LRTAP)* [2004] reported a 60% reduction in annual SO_2 emissions in Europe from 1986 to 2000. Concentrations measured at rural sites in Switzerland and Germany [*European Monitoring Evaluation Programme*, 2004] show that amongst other gases and particles, SO_2 decreased by 80 to 90 % mainly during the first part of the 1990s. But LRTAP also reported a strong increase in SO_2 emissions before 1980. These facts and our measurements, as well as recent reports on aerosol reduction over western continents [*Streets et al.*, 2006] and the oceans [*Mishchenko et al.*, 2007] show that solar dimming and the subsequent brightening – or rather solar recovery – is very likely related to changes in anthropogenic aerosols. With respect to the temperature evolution in central Europe, increasing aerosols were apparently effective in masking greenhouse warming after the 1950s [*Wild et al.*, 2007], whereas the observed direct solar forcing due to the strong aerosol decline since the mid-1980s has reinforced greenhouse warming, although the reduction of absorbing aerosols (such as black carbon) might have dampened the reinforcement.

6. Discussion and Conclusions

[18] Our analyses show that *AOD* in the lower troposphere over mainland Europe has drastically decreased since 1986, and it is virtually certain that this is due to the strong reduction in anthropogenic aerosol emissions. MODTRAN™ simulations have adequately confirmed the relationship between decreasing *AOD* and increasing SDR_{cf} [*Ruckstuhl*, 2008]. Surface radiation measurements show that solar brightening is more related to direct aerosol effects under cloud-free skies than to indirect aerosol cloud effects. The fact that indirect aerosol cloud effects remain small despite the 60% decline in aerosol concentrations is very surprising. However, it is possible that part of the cloud mediated aerosol effect has been compensated by increasing cloudiness due to changing large-scale atmospheric circulation. With respect to the impact on climate or surface temperature, the forcing due to the direct aerosol effect under cloud-free skies SNR_{cf} of +0.84 [+0.49 to +1.20] Wm^{-2} dec^{-1} is about five times larger than the total net forcing TNR_{cloud} due to changing cloudiness, which to a large part is compensated by longwave cloud effects and results in a week climate forcing of +0.16 [−0.26 to +0.57] Wm^{-2} dec^{-1}. Overall, the aerosol and cloud induced radiative surface climate forcing over mainland Europe has been ~+1 Wm^{-2} dec^{-1} since the 1980s, and has very likely strongly contributed to the recent rapid warming in Europe.

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K. Behrens and M. Weller, Meteorologisches Observatorium Lindenberg, Deutscher Wetterdienst, D-15848 Lindenberg, Germany.

M. Collaud Coen, A. Heimo, R. Philipona, and L. Vuilleumier, Aerological Station, Federal Office of Meteorology and Climatology MeteoSwiss, CH-1530 Payerne, Switzerland. (rolf.philipona@meteoswiss.ch)

B. Dürr and A. Zelenka, Federal Office of Meteorology and Climatology MeteoSwiss, CH-8044 Zurich, Switzerland.

C. Mätzler, Institute of Applied Physics, University of Bern, CH-3012 Bern, Switzerland.

S. Nyeki and C. Wehrli, Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, CH-7260 Davos, Switzerland.

A. Ohmura and C. Ruckstuhl, Institute for Atmospheric and Climate Science, ETH Zurich, CH-8057 Zurich, Switzerland.