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Department of Geography, University of South Carolina, Columbia SC, USA

Trends in solar radiation over Germany and an assessment of the role of aerosols and sunshine duration

H. C. Power

With 13 Figures

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Summary

Global, diffuse, and horizontal direct (beam) irradiances have been evaluated for 13 stations in Germany where the time series vary between 11 and 48 years. Global irradiance has decreased significantly at two stations and increased at four stations. The mean trend in global is an increase of 1.94 Wm^{-2} or 1.83% per decade. Diffuse irradiance has decreased at five stations, with a mean reduction of 2.44 Wm^{-2} or 3.46% per decade, while horizontal direct irradiance has increased an average of 4.86 Wm^{-2} or 10.40% per decade at five stations. Increases in global and direct are most common at stations in the southwest region of Germany, decreases in global were observed in the southeast, and there was an absence of spatial homogeneity in the diffuse trends. Spatial variability in irradiance over Germany is higher in the direct component compared to variability in global and diffuse.

Trend analyses of concomitant time series of radiation, bright sunshine duration, and modeled estimates of Ångström's turbidity coefficient suggest that long-term decreases in aerosols are the most likely cause of increases in global irradiance observed at Mannheim, Norderney, and Trier; decreases in diffuse at Hohenpeissenberg, Kassel, Mannheim, and Trier; and increases in direct irradiance at Bocholt, Kassel, Mannheim, and Trier. An increase in sunshine duration at Freiburg likely contributed to an increase in global and direct irradiance observed at that station.

1. Introduction

Analyzing and documenting past climate change is necessary in order to understand the full range of variability in the climate system and to predict future climates more accurately. Solar radiation received by the earth is the primary source of energy that drives the climate system. Natural and anthropogenic change in the amount of insolation therefore has important implications for climate change studies as well as agriculture, water resources, and solar energy applications.

Solar radiation received at the earth's surface is conditioned by the radiation received at the top of the atmosphere and by absorption and scattering due to clouds, aerosols, and gases including carbon dioxide, ozone, water vapor, oxygen, and nitrogen dioxide. Aerosols also affect the radiation budget indirectly by altering the formation and precipitation efficiency of clouds. Radiative forcing of climate by aerosols is thought to be comparable in magnitude, but opposite in sign, to that of greenhouse gases (IPCC, 2001). Unlike greenhouse gases, however, the radiative effects of aerosols are usually expressed nonuniformly since aerosols exhibit high temporal and spatial variability (Ramaswamy et al., 2001).

Radiation reaching the ground after being scattered by the atmosphere is diffuse radiation while radiation received directly from the solar disk is direct or beam radiation; the sum of the diffuse and horizontal direct components is global or total radiation. There have been a number of studies that have reported a decline in global (total) insolation over the last 50 years. These include stations in Antarctica (Stanhill and Cohen, 1997), the Arctic (Dutton et al., 1991; Stanhill and Moreshet, 1994; Stanhill, 1995), Asia (Stanhill and Moreshet, 1994; Stanhill and Kalma, 1995), Egypt (Omran, 2000), Germany (Grabbe and Grassl, 1994; Liepert et al., 1994; Stanhill and Moreshet, 1994; Liepert, 1997; Liepert and Kukla, 1997), Israel (Stanhill and Moreshet, 1992; Stanhill and Ianetz, 1997), Namibia (Stanhill and Moreshet, 1994), the former Soviet Union (Russak, 1990; Stanhill and Moreshet, 1994; Abakumova et al., 1996; Liepert, 2002), the United Kingdom (Stanhill and Moreshet, 1994; Stanhill, 1998), and the United States (Liepert, 2002). Although a small number of studies have shown no significant change in global insolation (e.g. in Australia (Stanhill and Kalma, 1994) and the Netherlands (De Bruin et al., 1995)), Stanhill and Cohen (2001) evaluated a total of 1,114 years of annual global irradiance data from 854 sites worldwide and calculated a globally-averaged reduction of $0.51\,\mathrm{Wm}^{-2}$ or 2.7% per decade over the last 50 years.

In contrast to global insolation, there have been relatively few studies evaluating long-term variability in the diffuse and direct components of solar radiation, in large part due to the paucity of data. Decreases in diffuse radiation have been reported for Germany (Grabbe and Grassl, 1994; Liepert, 1997; Liepert and Kukla, 1997) and Ireland (Stanhill, 1998). At two stations in Germany, concomitant decreases in diffuse and global irradiation suggested that variability in diffuse, rather than the direct component, was responsible for the trends in global (Liepert, 1997). Decreases in direct radiation have been reported in Egypt (Omran, 2000) and in the former Soviet Union (Russak, 1990; Abakumova et al., 1996) while Stanhill (1998) reported an absence of trends in direct radiation at a station in Ireland. Similarly, Liepert and Kukla (1994) and Liepert (1997) reported no significant trends in direct radiation at two stations in Germany.

Any change in the amount of aerosol in the atmosphere will influence the amount of global, diffuse, and direct radiation received at the surface. Although the relative amounts of each radiation component vary with the type and size of aerosol, the wavelength of radiation, as well as humidity (d'Almeida et al., 1991; Penner et al., 2001), in general, an increase in the amount of aerosol in the atmosphere will typically decrease direct irradiance but increase diffuse irradiance. The decrease in direct is usually much larger than the increase in diffuse, however, and therefore any increase in aerosols will likely result in a decrease in global radiation at the surface (Iqbal, 1983).

Given the role of aerosols as agents of radiative forcing, variability in aerosols may be responsible for the observed changes in solar radiation received at the earth's surface. Indeed, Stanhill and Cohen (2001) considered possible causes of the "global dimming" reported by so many investigators and speculated that the two most probable causes are changes in the amount of aerosol and in cloud cover. They note that further research on the history of the aerosol content of the atmosphere is necessary in order to determine if aerosols can explain the observed decreases in radiation.

The goal of this research, therefore, was to determine whether trends in solar radiation can be attributed to variability in total column aerosols and bright sunshine duration.[1] Accordingly, this paper evaluates temporal and spatial variability in concomitant time series of global, diffuse, and direct horizontal irradiance, bright sunshine duration, and modeled estimates of total column aerosol over Germany. The German network of climate data was deemed particularly suitable for this analysis due to the standardized instrumentation and calibration procedures adopted by the German Weather Service, the long time series of available climate data, as well as the relatively high density of the station network. To date, radiation and sunshine duration trend analyses for Germany appear to only include data up until 1990. Here, radiation and sunshine duration data as recent as 2000 are evaluated.

2. Quantifying total column aerosol

Total column aerosol can be quantified by measuring either spectral (wavelength-specific) or

[1] Bright sunshine duration is defined as the number of hours per day that the sunshine intensity exceeds some predetermined threshold of brightness.

broadband solar radiation under clear sky conditions, accounting for attenuation of the extraterrestrial radiation by nonaerosol atmospheric constituents, and then "solving" for the contribution of aerosols to the total attenuation (Power, 2003). The spectral method is the most accurate. However, this approach requires sophisticated and expensive spectroradiometers that can measure solar radiation at discrete wavelengths. Consequently, exact measurements of atmospheric turbidity–the total column amount of aerosol–are scarce. The broadband approach is less accurate but it is appealing in that broadband solar radiation data are more readily available than spectral data. Turbidity can therefore be estimated at more sites, and for longer time series, than with the spectral method. Traditionally, both methods of quantifying aerosols have been constrained by the need for clear sky conditions, resulting in gaps in the turbidity record.

Atmospheric turbidity is most accurately represented by the spectral aerosol optical depth (Paltridge and Platt, 1976) but it can also be characterized by four turbidity indices (Ångström, 1929, 1930; Linke, 1922; Schüepp, 1949; Unsworth and Monteith, 1972). Ångström's turbidity coefficient (β) is a dimensionless index defined as the aerosol optical depth at a wavelength of 1.0 μm (Ångström, 1929). Typical values of β range from 0.02, for a low aerosol load, to 0.4, for a very high aerosol load. This coefficient is typically quantified using the spectroradiometric approach. However, Power (2001a, 2001b, 2001c) used a physically based, high-resolution spectral radiation model (Gueymard, 1995) and a least-squares fitting procedure to provide a scheme for estimating monthly averages of Ångström's turbidity coefficient, regardless of cloud cover, from broadband irradiation and other climate data. The turbidity model development and its performance evaluation, using turbidity and climate data from five stations in North America and Europe, are described fully in Power (2001a, 2001b). Willmott's absolute-difference-based index of agreement (d) (Willmott et al., 1985)[2] was 0.70, while the mean-absolute error was 0.02 for a mean monthly-averaged β of 0.09.

In short, Power's turbidity model permits reliable estimates of monthly-averaged β ($\bar{\beta}_m$) from monthly averages of precipitable water (w), total column ozone (u_o), atmospheric pressure (p), total column nitrogen dioxide (u_n), daily beam irradiation at normal incidence (H_{bn}) or horizontal incidence (H_b), and bright sunshine duration (s). These climate data can be obtained or estimated from historical weather-station and satellite records. All other variables in the model, such as the extraterrestrial irradiance and the hour angle, can be calculated from established earth-sun astronomical relationships. The appeal of this model is that it provides monthly estimates of turbidity regardless of cloud cover, and, in turn, continuous time series of turbidity. However, the nature of the model, and its turbidity estimates, means that it is not possible to independently evaluate turbidity trends during cloudy and cloudless periods.

Application of the Power model to investigate temporal and spatial variability in aerosols over South Africa was presented in Power and Willmott (2001). Power and Goyal (2003) also used this model to examine aerosol variability over Germany. A subset of those data, together with some more recent analyses, are presented here to permit comparison with the radiation trend analyses for Germany.

3. Data

The lengths of the time series that could be used in the present analysis were determined by the periods for which there were concomitant observations of global and diffuse irradiation, bright sunshine duration, and the historical climate data necessary to force the turbidity model. Although the time series of climate data available at some stations are longer than what was evaluated here, the "common window" approach ensured consistent periods of record within each set of station data. This, in turn, permitted a more systematic assessment of the possible causes of trends in radiation. Under these constraints, the requisite climate data were available at 13 stations in Germany (Fig. 1), with periods of analysis at each station ranging between 11 and 48 years

[2] Willmott's index of agreement (d) is a dimensionless statistic that varies between 0.0 and 1.0. A value of 1.0 denotes perfect agreement between two variables and 0.0 indicates complete disagreement.

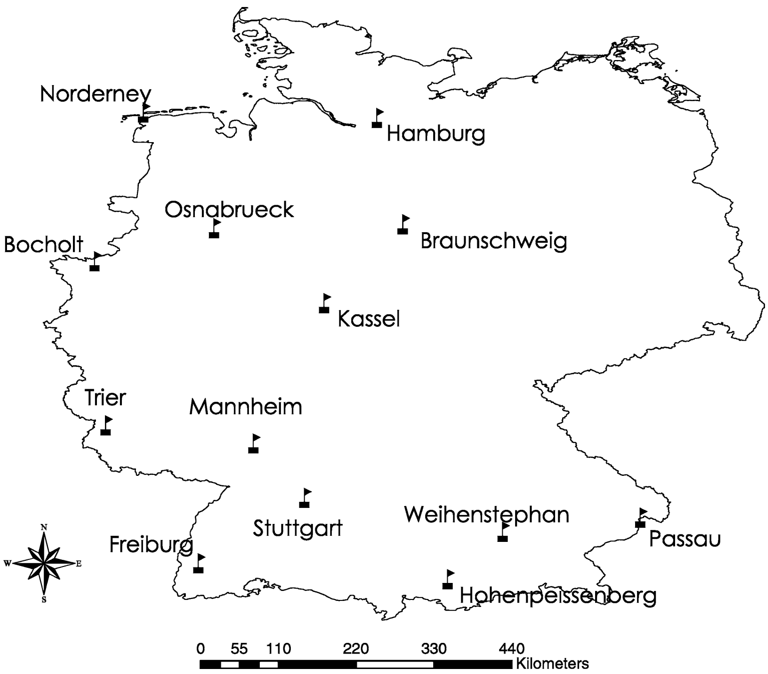

Fig. 1. Location of the German Weather Service (Deutscher Wetterdienst) climate stations for which the requisite data for radiation, sunshine, and aerosol trend analyses were available. Reprinted from *International Journal of Climatology* with permission from John Wiley & Sons, Limited

Table 1. Latitude, longitude, elevation, period and length of record, and population for each of the 13 climate stations in Germany for which trend analyses of total column aerosol, radiation, and bright sunshine duration were performed. Population figures are 1999 estimates (Bundesamtes für Bauwesen und Raumordnung, 2000). (Reprinted from International Journal of Climatology with permission from John Wiley & Sons, Limited)

	Lat (N)	Lon (E)	Elev (m)	Period	Length (yr)	Population
Bocholt	51.83	6.53	24	1977–2000	24	71,837
Braunschweig	52.30	10.45	81	1977–2000	24	246,322
Freiburg	48.00	7.85	308	1978–2000	23	202,455
Hamburg	53.65	10.12	49	1964–2000	37	1,704,735
Hohenpeissenberg	47.80	11.02	990	1953–2000	48	3,984
Kassel	51.30	9.45	237	1979–2000	22	196,211
Mannheim	49.52	8.55	106	1979–2000	22	307,730
Norderney	53.72	7.15	29	1977–2000	24	6,095
Osnabrueck	52.25	8.05	104	1979–2000	22	164,539
Passau	48.58	13.47	412	1979–1995	17	50,291
Stuttgart	48.83	9.20	318	1990–2000	11	582,443
Trier	49.75	6.67	278	1979–2000	22	99,891
Weihenstephan	48.40	11.72	469	1971–1996	26	40,300

(Table 1). Most records end in 2000, and all of the stations are located in the former West Germany.

The weather station network in Germany is maintained by the German Weather Service (Deutscher Wetterdienst; DWD). Global and diffuse radiation were measured by DWD using Kipp and Zonen pyranometers that have a spectral range of 0.3–2.7 µm. Bright sunshine duration was measured with Campbell-Stokes sunshine recorders. Both the pyranometers and the sunshine recorders were regularly calibrated and the DWD applied appropriate shadowband correction factors to the diffuse radiation data (Behrens, 2002). The DWD provided monthly-averaged global, diffuse, and sunshine data; monthly-averaged daily beam irradiation on a horizontal surface (H_b) was calculated as the difference between monthly-averaged observations of global (G) and diffuse (D) irradiation i.e. $H_b = G - D$. The source and/or calculation of all other turbidity model input variables (i.e. monthly values of w, u_n, u_o, p, and s) for Germany is detailed in Power and Goyal (2003). In short, w was calculated using Gueymard's (1994) algorithm as a function of air temperature and relative humidity; u_n was estimated as a function of the population of the station location (following Schroeder and Davies (1987) and Power and Willmott, 2001); and u_o was determined from either ground-based spectrophotometric ozone retrievals or from the National Aeronautics and Space Administration's merged ozone data set. The latter are retrievals from instruments on board the Nimbus-7, Earth Probe, and NOAA satellite platforms.

4. Methods

Having calculated H_b from global and diffuse, and estimated monthly values of Ångström's turbidity coefficient ($\bar{\beta}_m$) with the Power model, a least squares estimation method was used to explore long-term trends in the time series of global, diffuse, and direct radiation, bright sunshine duration, and turbidity. Although the climate data and the turbidity estimates were monthly averages, the trend analysis was performed on annual averages of these data in order to avoid autocorrelation that is typically present in monthly-averaged climate and turbidity data (see, for example, Pedrós et al., 1999; Holben et al., 2001; Power and Willmott, 2001; Power and Goyal, 2003). A t-test was used to determine whether the slope of the fitted trend model was significantly different from zero. Where the significance level reached 95% or greater, the trend was deemed statistically significant.

For each set of data, and where the trends were statistically significant, decadal trends were calculated in physical units and as a percentage change relative to the first modeled value i.e.

$$\text{Decadal change} = \frac{10(y(n) - y(1))}{n} \quad (1)$$

and

$$\text{Decadal percentage change} = \frac{1000(y(n) - y(1))}{n \times y(1)} \quad (2)$$

where n is the number of years in the time series, $y(n)$ is the modeled value (for a given climate variable) for the nth year, and $y(1)$ is the modeled value for the first year in the time series. The decadal percentage change was calculated relative to the first modeled value (i.e. $y(1)$), as opposed to the first observed value, since the latter may have been anomalous for any given climate variable. Other investigators have reported long-term trends relative to the first modeled value (e.g. Liepert et al., 1994), the first observed value (e.g. Stanhill and Moreshet, 1992), as well as the long-term mean (e.g. Stanhill and Ianetz, 1997). For trend analyses calculated using a least squares approach, the magnitude of a trend clearly depends on how the relative change is calculated; the sign of the trend, i.e. increasing or decreasing, does not.

Once the decadal trends were calculated for each set of station data, the trends among turbidity, bright sunshine duration, and radiation were evaluated.

5. Results and discussion

Statistical summaries and trend analyses for turbidity, bright sunshine duration, and global, diffuse, and direct radiation are provided in Tables 2–6, respectively. Table 7 presents a summary of the decadal percentage trends for each variable.

5.1 Turbidity

Long-term means of annual averages of β range from 0.064, at Hohenpeissenberg, to 0.116, at Bocholt (Table 2). Braunschweig exhibits the largest interannual variability, with a standard deviation in annually-averaged β ($\hat{\bar{\beta}}_a$) of 0.026, while Weihenstephan has the least variability, with a standard deviation of 0.014. As discussed by Power and Goyal (2003), there does not appear to be any consistency between the size (population) of the station location and the total column amount of aerosol. The low turbidity at the Hohenpeissenberg station, for example, may be explained by its small size (population, ~4000; see Table 1) and its relative isolation in the Bavarian mountains at an elevation of 990 m. However, Bocholt is also relatively small (population, ~72,000) yet has, on average, the highest amount of aerosol. The high turbidity at this

Table 2. Data and trend analyses of annual averages of Ångström's turbidity coefficient ($\hat{\bar{\beta}}_a$) for 13 stations in Germany. All values significant at $p \leq 0.05$ ("–" indicates no significant trend). The mean trends and significance levels (last row in table) only include data from stations where the trends were statistically significant. For Passau and Weihenstephan, the mean $\hat{\bar{\beta}}_a$ for the 1990s (column 7) are for 1991–1995 and 1991–1996, respectively

Station	Long-term annual mean	Std. dev. of annual mean	Trend (β per decade)	Trend (percent per decade)	Signif. level (%)	Long-term annual mean 1991–2000
Bocholt	0.116	0.016	−0.011	−8.42	97.5	0.111
Braunschweig	0.105	0.026	–	–	–	0.106
Freiburg	0.085	0.017	–	–	–	0.081
Hamburg	0.112	0.023	–	–	–	0.103
Hohenpeissenberg	0.064	0.015	−0.004	−5.62	99.5	0.053
Kassel	0.101	0.017	−0.015	−12.89	99.7	0.091
Mannheim	0.103	0.021	−0.019	−15.23	99.8	0.089
Norderney	0.086	0.022	−0.018	−16.56	99.5	0.076
Osnabrueck	0.100	0.018	−0.018	−14.90	100.0	0.087
Passau	0.096	0.015	–	–	–	0.098
Stuttgart	0.082	0.022	–	–	–	0.083
Trier	0.092	0.015	−0.012	−11.03	98.9	0.086
Weihenstephan	0.090	0.014	–	–	–	0.092
Mean	0.095	0.019	−0.014	−12.09	99.3	0.089

Table 3. Data and trend analyses of annual averages of daily bright sunshine duration for 13 stations in Germany. All values significant at $p \leq 0.05$ ("–" indicates no significant trend). The mean trends and significance levels (last row in table) only include data from stations where the trends were statistically significant. For Passau and Weihenstephan, the daily bright sunshine duration averaged for the 1990s (column 7) are for 1991–1995 and 1991–1996, respectively

Station	Long-term annual mean (hour)	Std. dev. of annual mean (hour)	Trend (hour per decade)	Trend (percent per decade)	Signif. level (%)	Long-term annual mean 1991–2000 (hour)
Bocholt	4.24	0.44	–	–	–	4.38
Braunschweig	4.29	0.48	0.32	8.22	98.6	4.51
Freiburg	4.77	0.40	0.24	5.41	96.1	4.87
Hamburg	4.30	0.37	–	–	–	4.30
Hohenpeissenberg	4.95	0.41	–	–	–	4.78
Kassel	4.02	0.41	–	–	–	4.13
Mannheim	4.56	0.37	–	–	–	4.52
Norderney	4.43	0.37	–	–	–	4.52
Osnabrueck	4.04	0.36	–	–	–	4.04
Passau	4.64	0.30	–	–	–	4.72
Stuttgart	4.65	0.32	–	–	–	4.61
Trier	4.26	0.36	–	–	–	4.36
Weihenstephan	4.59	0.30	–	–	–	4.52
Mean	4.44	0.38	0.28	6.81	97.4	4.48

location may be explained by its proximity to the Rhine-Ruhr industrial region, which is known for its high concentration of heavy industry such as iron- and steel-works, mines, and chemical plants (Berentsen et al., 1997; Power and Goyal, 2003).

The turbidity trend analyses indicate that annually-averaged values of Ångström's turbidity coefficient ($\hat{\bar{\beta}}_a$) have decreased at 11 of the 13 stations (all stations except Braunschweig and Weihenstephan). Statistically significant trends were observed at seven stations: Bocholt, Hohenpeissenberg, Kassel, Mannheim, Norderney, Osnabrueck, and Trier (Table 2, Figs. 2 and 3). The decreases in $\hat{\bar{\beta}}_a$ at these seven

Table 4. Data and trend analyses of annual averages of global irradiance for 13 stations in Germany. All values significant at $p \leq 0.05$ ("–" indicates no significant trend). The mean trends and significance levels (last row in table) only include data from stations where the trends were statistically significant. For Passau and Weihenstephan, the mean global irradiances for the 1990s (column 7) are for 1991–1995 and 1991–1996, respectively

Station	Long-term annual mean (Wm^{-2})	Std. dev. of annual mean (Wm^{-2})	Trend (Wm^{-2} per decade)	Trend (percent per decade)	Signif. level (%)	Long-term annual mean 1991–2000 (Wm^{-2})
Bocholt	113.59	5.81	–	–	–	115.18
Braunschweig	114.04	5.99	–	–	–	116.49
Freiburg	127.26	6.08	5.45	4.50	99.9	130.16
Hamburg	107.16	6.68	–	–	–	105.41
Hohenpeissenberg	137.19	7.88	−3.22	−2.22	100.0	132.18
Kassel	113.10	6.94	–	–	–	115.42
Mannheim	120.31	5.24	3.58	3.08	97.1	122.77
Norderney	116.31	7.23	4.92	4.46	98.8	120.03
Osnabrueck	111.21	5.75	–	–	–	113.40
Passau	126.01	4.90	–	–	–	126.47
Stuttgart	128.45	4.33	–	–	–	128.08
Trier	119.56	5.66	3.86	3.35	97.0	121.23
Weihenstephan	129.88	5.68	−2.92	−2.18	96.2	127.74
Mean	120.31	6.01	1.94	1.83	98.2	121.12

Table 5. Data and trend analyses of annual averages of diffuse irradiance for 13 stations in Germany. All values significant at $p \leq 0.05$ ("–" indicates no significant trend). The mean trends and significance levels (last row in table) only include data from stations where the trends were statistically significant. For Passau and Weihenstephan, the mean diffuse irradiances for the 1990s (column 7) are for 1991–1995 and 1991–1996, respectively

Station	Long-term annual mean (Wm^{-2})	Std. dev. of annual mean (Wm^{-2})	Trend (Wm^{-2} per decade)	Trend (percent per decade)	Signif. level (%)	Long-term annual mean 1991–2000 (Wm^{-2})
Bocholt	68.26	2.91	–	–	–	67.47
Braunschweig	66.46	1.93	–	–	–	66.04
Freiburg	64.83	2.95	–	–	–	64.80
Hamburg	62.21	4.64	−3.46	−5.05	100.0	57.92
Hohenpeissenberg	68.42	7.91	−3.64	−4.70	100.0	63.12
Kassel	65.41	2.60	−1.80	−2.67	97.3	64.36
Mannheim	66.00	2.52	−1.87	−2.75	98.4	65.23
Norderney	64.65	2.59	–	–	98.8	65.42
Osnabrueck	65.66	1.90	–	–	–	65.59
Passau	66.84	2.49	–	–	–	66.85
Stuttgart	66.40	1.77	–	–	–	66.61
Trier	65.76	1.86	−1.44	−2.14	98.8	64.59
Weihenstephan	69.99	2.10	–	–	–	70.14
Mean	66.22	2.94	−2.44	−3.46	98.9	65.24

stations range between 5.62% per decade, in Hohenpeissenberg, to 16.56% at Norderney. The average reduction is 12.09% per decade. This reduction in total column aerosol is consistent with decreases in mass concentrations of sulfate aerosols over Germany reported by others (e.g. Arends et al., 1994; Barrett et al., 2000). The reduction in aerosols can be attributed to increased environmental regulation across central and western Europe and a decline in heavy

Table 6. Data and trend analyses of annual averages of horizontal direct (beam) irradiance for 13 stations in Germany. All values significant at $p \leq 0.05$ ("–" indicates no significant trend). The mean trends and significance levels (last row in table) only include data from stations where the trends were statistically significant. For Passau and Weihenstephan, the mean direct irradiances for the 1990s (column 7) are for 1991–1995 and 1991–1996, respectively

Station	Long-term annual mean (Wm^{-2})	Std. dev. of annual mean (Wm^{-2})	Trend (Wm^{-2} per decade)	Trend (percent per decade)	Signif. level (%)	Long-term annual mean 1991–2000 (Wm^{-2})
Bocholt	45.15	5.66	4.67	11.69	99.3	47.48
Braunschweig	47.57	6.15	–	–	–	50.28
Freiburg	62.77	6.54	4.83	8.45	99.0	65.36
Hamburg	44.34	5.96	–	–	–	46.09
Hohenpeissenberg	67.82	6.49	–	–	–	69.64
Kassel	47.69	6.12	4.86	11.48	99.1	51.06
Mannheim	54.63	5.28	4.64	9.36	99.7	57.54
Norderney	51.98	6.80	–	–	–	54.61
Osnabrueck	45.84	5.24	–	–	–	47.81
Passau	59.17	4.99	–	–	–	59.62
Stuttgart	62.04	5.07	–	–	–	61.47
Trier	53.80	6.02	5.30	11.04	99.7	56.64
Weihenstephan	58.38	5.37	–	–	–	57.59
Mean	53.94	5.82	4.86	10.40	99.4	55.78

Table 7. Summary of trend analyses for annual averages of Ångström's turbidity coefficient, bright sunshine duration, global, diffuse, and direct irradiance for 13 stations in Germany. All values show the percent per decade trend in each variable. Trends are significant at $p \leq 0.05$ ("–" indicates no significant trend). The mean trends (last row in table) only include data from stations where the trends were statistically significant

Station	Period	Ångström's turbidity coefficient	Bright sunshine duration	Global	Diffuse	Direct
Bocholt	1977–2000	−8.42	–	–	–	11.69
Braunschweig	1977–2000	–	8.22	–	–	–
Freiburg	1978–2000	–	5.41	4.50	–	8.45
Hamburg	1964–2000	–	–	–	−5.05	–
Hohenpeissenberg	1953–2000	−5.62	–	−2.22	−4.70	–
Kassel	1979–2000	−12.89	–	–	−2.67	11.48
Mannheim	1979–2000	−15.23	–	3.08	−2.75	9.36
Norderney	1977–2000	−16.56	–	4.46	–	–
Osnabrueck	1979–2000	−14.90	–	–	–	–
Passau	1979–1995	–	–	–	–	–
Stuttgart	1990–2000	–	–	–	–	–
Trier	1979–2000	−11.03	–	3.35	−2.14	11.04
Weihenstephan	1971–1996	–	–	−2.18	–	–
Mean		−12.09	6.81	1.83	−3.46	10.40

industry in Germany since the 1970s (Berentsen et al., 1997; Boesler, 2001; McCormick, 2001; Münch et al., 2001; Power and Goyal, 2003).

The reduction in total column aerosol has been particularly prominent in the last ten years of the time series. For instance, for the period 1991–2000, the percentage of $\hat{\bar{\beta}}_a$ values at these seven stations that fall below the long-term averaged $\hat{\bar{\beta}}_a$ range between 60% and 80%. Similarly, at all seven stations where $\hat{\bar{\beta}}_a$ has declined, $\hat{\bar{\beta}}_a$ values averaged over the period 1991–2000 are all less than $\hat{\bar{\beta}}_a$ averaged over the full time series (Figs. 2 and 3; c.f. columns 2 and 7 in Table 2). At seven stations (Bocholt, Braunschweig,

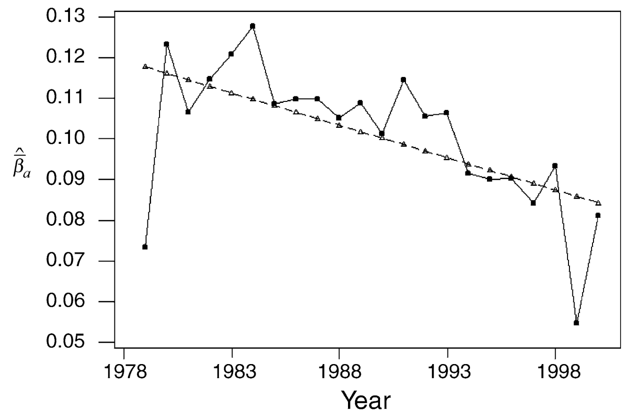

Fig. 2. Linear trend model fit to annual averages of monthly estimates of Ångström's turbidity coefficient ($\hat{\hat{\beta}}_a$) for Kassel, Germany, 1979–2000. Statistically significant decrease in $\hat{\hat{\beta}}_a$ were also observed at Bocholt, Hohenpeissenberg, Mannheim, Norderney, Osnabrueck (see Fig. 3) and Trier (Table 2)

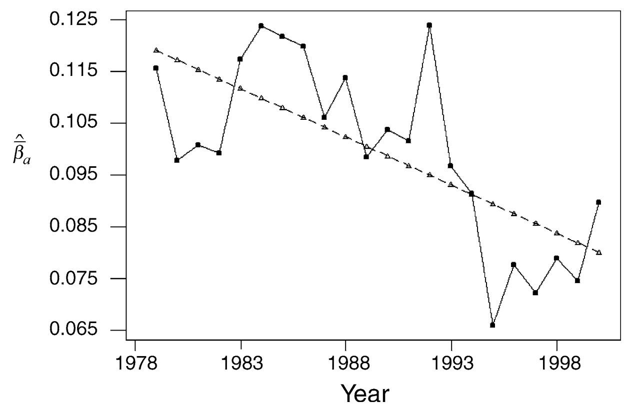

Fig. 3. Linear trend model fit to annual averages of monthly estimates of Ångström's turbidity coefficient ($\hat{\hat{\beta}}_a$) at Osnabrueck, Germany, 1979–2000

Freiburg, Hamburg, Kassel, Stuttgart, and Trier), there was a statistically significant decreasing trend in $\hat{\hat{\beta}}_a$ over the period 1991–2000.

Although $\hat{\hat{\beta}}_a$ has decreased at 11 stations, and seven of those stations have statistically significant decreases, the absence of a consistent, significant decline in $\hat{\hat{\beta}}_a$ across *all* stations in Germany suggests that local or small-scale regional changes in atmospheric dynamics and/or aerosol emissions are responsible for the trends observed at each station.

5.2 Bright sunshine duration

Table 3 summarizes the statistics and trend analyses for daily bright sunshine duration at each of the 13 stations in Germany. Long-term averages of daily sunshine duration range between 4.02 h, at Kassel, and 4.95 h, at Hohenpeissenberg. Interannual variability is greatest at Braunschweig, where the standard deviation in annually-averaged daily sunshine duration is 0.48 h, and smallest at Passau and Weihenstephan, where the standard deviation is 0.30 h.

Bright sunshine duration has increased at nine stations and decreased at four stations, but statistically significant trends are evident at only two stations. At Braunschweig, sunshine duration has increased by 8.22% per decade, and at Freiburg it has increased by 5.41% per decade (Table 3, Figs. 4 and 5). In comparison, Liepert et al. (1994) evaluated bright sunshine duration data for nine stations in Germany–six of which were common to the stations in the present study–for different periods, with most records ending in

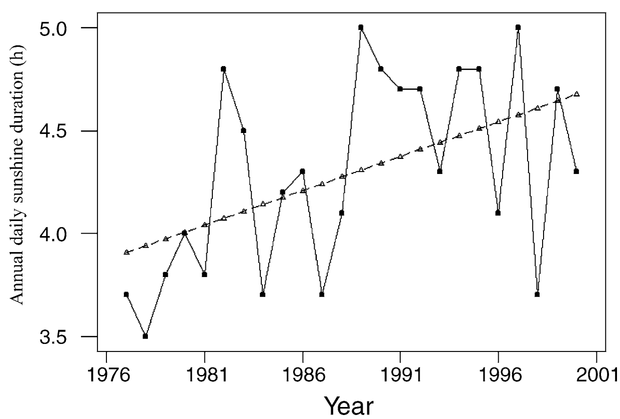

Fig. 4. Linear trend model fit to annually-averaged daily bright sunshine duration at Braunschweig, Germany, 1977–2000

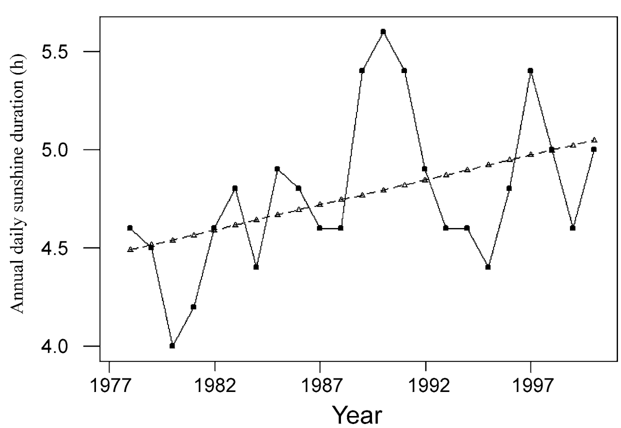

Fig. 5. Linear trend model fit to annually-averaged daily bright sunshine duration at Freiburg, Germany, 1978–2000

1989. Only one station, Würzburg, which was not evaluated in this study, showed a significant trend in sunshine duration with a reduction of 5.6% per decade. Braunschweig showed no significant trend and Freiburg was not included in their analyses.

More recently, Liepert and Kukla (1997) evaluated sunshine data recorded at eight stations in Germany (including Braunschweig, but not Freiburg) over the period 1964–1990 and found no significant changes in sunshine duration except at Hamburg where it had declined. Column 7 in Table 3 shows annual sunshine duration averaged over the period 1991–2000. During this period, seven stations (including Braunschweig and Freiburg) had long-term means higher than sunshine duration averaged over the full time series, four stations had lower means, and two stations (including Hamburg) show no difference in the means (c.f. columns 2 and 7 in Table 3). There were no statistically significant trends in annual sunshine duration during the period 1991–2000.

Based on physical principles, an increase (decrease) in sunshine duration implies less (more) cloud cover, which would result in increases (decreases) in global and direct irradiation and decreases (increases) in diffuse irradiance. The extent to which the observed trends in bright sunshine duration may have contributed to trends in radiation is explored below.

5.3 Radiation

5.3.1 Global

Statistical summaries and linear trend analyses for the annually-averaged global irradiances at each station are provided in Table 4. The long-term averages of the annual global irradiances range between 107.16 Wm^{-2}, in Hamburg, which has the second highest latitude, and 137.19 Wm^{-2}, in Hohenpeissenberg, which has the lowest latitude and the highest elevation (Table 1). Hohenpeissenberg also has the greatest interannual variability, with a standard deviation in the annual mean of 7.88 Wm^{-2}, while Stuttgart has the smallest standard deviation of 4.33 Wm^{-2}. Hohenpeissenberg has the longest period of record (48 years) while Stuttgart has the shortest (11 years) and this may, in part, contribute to the maximum and minimum variability

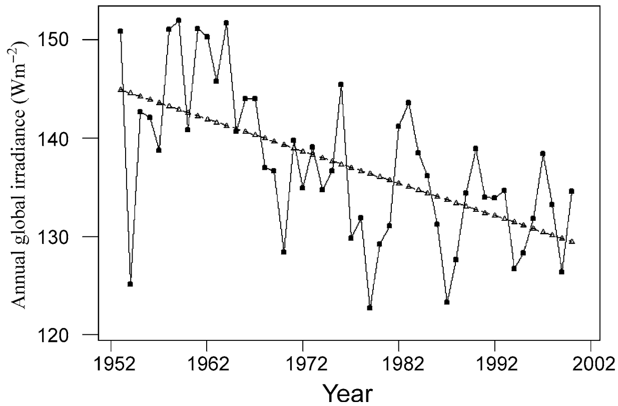

Fig. 6. Linear trend model fit to annually-averaged global irradiance at Hohenpeissenberg, Germany, 1953–2000. A statistically significant decrease in global irradiance was also evident at Weihenstephan (Table 4)

in annual global at these two stations, respectively.

Global irradiance has decreased at Hamburg, Hohenpeissenberg, and Weihenstephan and increased at the remaining 10 stations. Statistically significant trends are evident at six stations, where the mean trend is an increase of 1.94 Wm^{-2} or 1.83% per decade. At Hohenpeissenberg and Weihenstephan global radiation decreased 2.22% (3.22 Wm^{-2}) per decade and 2.18% (2.92 Wm^{-2}) per decade, respectively (Fig. 6). These two stations are both located in rural areas in the southeast of Germany with the highest elevations of all the stations in Germany: 990 m and 469 m, respectively. In contrast to the negative trend at these two stations, Freiburg, Mannheim, Norderney, and Trier show significant increases in global radiation ranging from 3.08% per decade to 4.50% per decade (Figs. 7 and 8). Freiburg, Mannheim, and Trier are all located in the southwest of Germany (Fig. 1), indicating some spatial homogeneity to this trend of increasing global radiation. However, Norderney is remote from these three stations; it is located on an island of the same name 450 km north of Trier in the North Sea.

The decrease in global irradiance at Hohenpeissenberg and Weihenstephan is, not surprisingly, consistent with trends reported by other investigators for these two stations. Liepert et al. (1994), for example, reported statistically significant decreases of 2.8% per decade and 2.5% per decade over the periods 1953–1989 and 1961–1989 at Hohenpeissenberg and

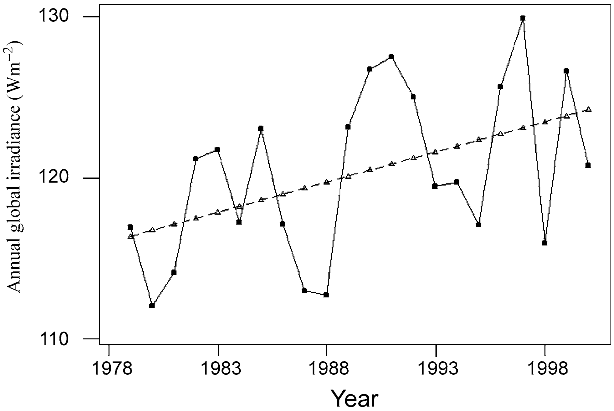

Fig. 7. Linear trend model fit to annually-averaged global irradiance at Mannheim, Germany, 1979–2000. Statistically significant increases in global irradiance were also evident at Norderney (see Fig. 8), Freiburg, and Trier (Table 4)

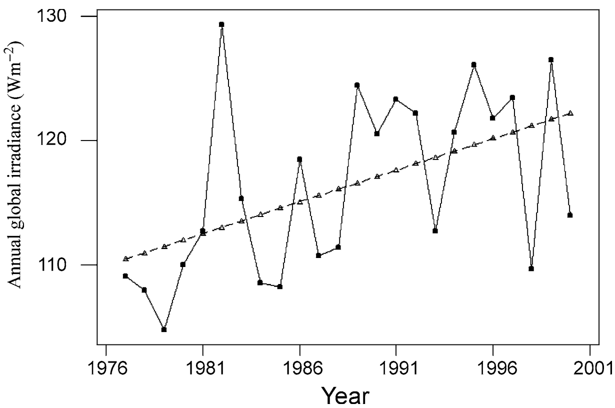

Fig. 8. Linear trend model fit to annually-averaged global irradiance at Norderney, Germany, 1977–2000

Weihenstephan, respectively. Similarly, Stanhill and Moreshet (1992, 1994), Liepert (1997), and Liepert and Kukla (1997) reported declines in global at one or both of these stations.

Of more importance, perhaps, is the fact that the present analysis shows an increase in global at Freiburg, Mannheim, Norderney, and Trier, yet Liepert et al. (1994) and Liepert and Kukla (1997) reported decreases in global at Norderney and no significant trends for Freiburg or Trier. This difference in trends is because the periods of record between the present study and those of Liepert et al. (1994) and Liepert and Kukla (1997) are different. For Norderney, for example, Liepert et al. (1994) evaluated data for the period 1967–1989 whereas in the present analysis data for the period 1977–2000 were examined. As discussed above, analysis in the present study is restricted to periods for which *all* data–radiation, sunshine duration, and model input data–were available.

In addition, most of the time series in this study end in 2000 whereas the time series in the earlier studies ended in 1990 or earlier. Since that time, global irradiance at Freiburg, Mannheim, Norderney, and Trier has been relatively high (Figs. 7 and 8). During the period 1991–2000, for example, 80%, 60%, 70%, and 60% of the annual global irradiances at these four stations, respectively, have been above the long-term means. Similarly, global irradiances averaged for the period 1991–2000 at each of these stations are consistently higher than the global irradiances averaged over the full time series at each station (c.f. columns 2 and 7 in Table 4). This has undoubtedly contributed to the positive trends identified at those stations. Interestingly, at the two stations that showed decreases in global irradiation (Hohenpeissenberg and Weihenstephan), the mean global irradiances over the period 1991–2000 were lower than the irradiances averaged over the full time series for each station (Table 4). Averaged across all stations, the mean global irradiance during 1991–2000 is 0.81 Wm^{-2} (0.67%) more than the mean global irradiance averaged across all years. There were no statistically significant trends in global irradiance during the period 1991–2000.

With regard to the role of aerosols and sunshine duration in explaining the trends in global radiation, at Freiburg, Mannheim, Norderney, and Trier, the increases in global are concomitant with decreases in $\hat{\hat{\beta}}_a$ (6.45%, 15.23%, 16.56%, and 11.03% per decade, respectively) although the trend in $\hat{\hat{\beta}}_a$ at Freiburg is not statistically significant (Tables 2 and 7). At Freiburg, however, there was a concomitant increase in sunshine duration of 5.41% per decade. It appears, therefore, that the increases in global observed at Mannheim, Norderney, and Trier may be due to the decreases in aerosols, while the increase in global at Freiburg is more likely due to the increase in sunshine duration. Furthermore, the relatively low $\hat{\hat{\beta}}_a$ experienced over the period 1991–2000 at Mannheim, Norderney, and Trier (see Section 5.1) likely contributed to the relatively high global irradiances observed at these stations during that period. The decreases in global at Hohenpeissenberg and Weihenstephan, however, cannot be explained by trends in aerosols or sunshine duration; at Hohenpeissenberg aerosols have decreased, at Weihenstephan there is no significant trend in $\hat{\hat{\beta}}_a$, and there are no significant trends in sunshine duration at either station.

5.3.2 Diffuse

Table 5 summarizes the diffuse irradiances and trend analyses for each of the 13 stations. As with global irradiance, Hamburg also has the lowest long-term average of annual diffuse irradiance, at 62.21 Wm^{-2}, although Weihenstephan, rather than Hohenpeissenberg, has the highest with 69.99 Wm^{-2}. The stations that have the greatest and smallest interannual variability in diffuse are the same as those for global irradiance, namely, Hohenpeissenberg, with a standard deviation of 7.91 Wm^{-2} in the annual mean, and Stuttgart, with a standard deviation of only 1.77 Wm^{-2}.

A standard deviation of 7.91 Wm^{-2} at Hohenpeissenberg is particularly high (the mean standard deviation across all stations is only 2.94 Wm^{-2}) and this is likely due to the relatively high annual diffuse irradiances experienced at that site in 1963 and 1964; these were 90.50 and 90.47 Wm^{-2}, respectively (Fig. 9). These values are approximately 32% higher than the long-term annual average of diffuse at Hohenpeissenberg, which is 68.42 Wm^{-2}. Mount Agung, in Indonesia, erupted in March, 1963 and injected between 16 and 30 million tons of material into the stratosphere (Deirmendjian, 1973; Cadle et al., 1976, 1977). This event may have contributed to the anomalously high diffuse irradiances witnessed at Hohenpeissenberg during 1963 and 1964. The radiative impact of Mount Agung is not visible at the other stations because the time series begin after the eruption.

Besides Mount Agung, in the last four decades there have been two other volcanic eruptions of relatively large magnitude. In April, 1982, Mexico's El Chichón injected between 10 and 20 million tons of material into the stratosphere (Hofmann and Rosen, 1983; McCormick and Swissler, 1983; Mroz et al., 1983). Mount Pinatubo, in the Philippines, contributed an estimated 30–40 million tons of material in June, 1991 (McCormick and Vega, 1992). The impact of these eruptions on the diffuse irradiance is evident at many of the stations to varying degrees. At Freiburg, for instance, the annual diffuse irradiance increased 11% from 1982 to 1983 and 8% from 1991 to 1992 (Fig. 10).

Despite the increase in aerosols–and therefore diffuse irradiance–associated with these volcanic eruptions, all stations except Norderney show a decline in annual diffuse irradiance over the respective time series, although the trends are only statistically significant at five stations: Hamburg, Hohenpeissenberg, Kassel, Mannheim,

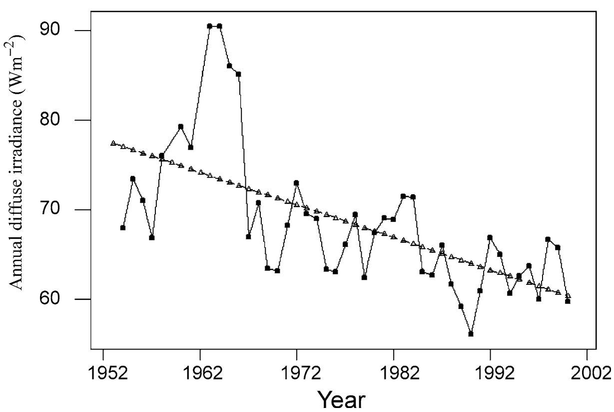

Fig. 9. Linear trend model fit to annually-averaged diffuse irradiance at Hohenpeissenberg, Germany, 1953–2000. The relatively high irradiances observed in 1963 and 1964 are likely due to the eruption of Mount Agung in Indonesia in March, 1963. Statistically significant decreases in diffuse irradiance were also evident at Hamburg (see Fig. 11), Kassel, Mannheim, and Trier (Table 5)

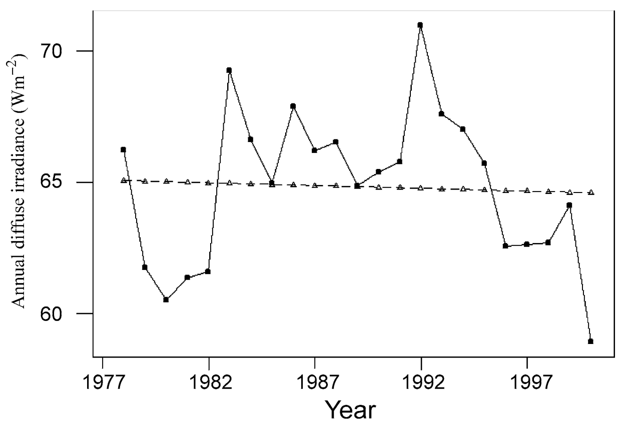

Fig. 10. Linear trend model fit to annually-averaged diffuse irradiance at Freiburg, Germany, 1978–2000. An increase in diffuse irradiance following the eruptions of El Chichón (Mexico; April, 1982) and Mount Pinatubo (Philippines; June, 1991) is evident in the time series

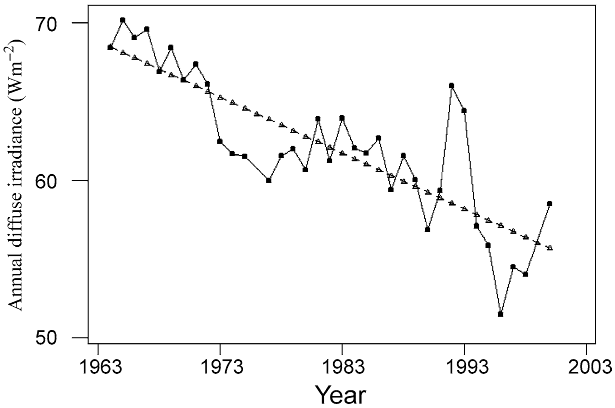

Fig. 11. Linear trend model fit to annually-averaged diffuse irradiance at Hamburg, Germany, 1964–2000

and Trier (Figs. 9 and 11; Table 5). The decreases range from 2.14% per decade, at Trier, to 5.05% per decade, at Hamburg, and the mean decrease is 2.44 Wm^{-2} or 3.46% per decade. Given the geographic distribution of these stations (Fig. 1), there does not appear to be any spatial pattern to these declines in diffuse. The decreases in diffuse are consistent with trends reported by other investigators for earlier time periods; Grabbe and Grassl (1994), Liepert and Kukla (1994), and Liepert (1997) reported decreases in diffuse irradiance at Hamburg and Hohenpeissenberg for periods between 1953 and 1990.

Since 1990, diffuse irradiance has been relatively low. Over the period 1991–2000, for example, nine of the thirteen stations evaluated in this study had long-term means of annual diffuse irradiance that were lower than diffuse irradiance averaged over the full time series (c.f. columns 2 and 7 in Table 5). Averaged across all stations, the mean diffuse irradiance over 1991–2000 is 0.98 Wm^{-2} (1.48%) less than the mean global irradiance averaged across all years. These nine stations include Hamburg, Hohenpeissenberg, Kassel, Mannheim, and Trier i.e. those stations that had significant declines in diffuse over the full time series. Four stations (Braunschweig, Freiburg, Mannheim, and Norderney) have statistically significant decreases in diffuse over the period 1991–2000. Two of these stations (Braunschweig and Freiburg) showed concomitant decreases in turbidity over the same period (Section 5.1).

Of the five stations with significantly decreasing diffuse over the full time series, Hamburg and Kassel have no corresponding trend in global, Hohenpeissenberg shows a simultaneous decline in global irradiance, while Mannheim and Trier have a concomitant increase in annual global irradiance (see the side-by-side comparison of trends in diffuse and global in Table 7). This seeming inconsistency–decreasing diffuse simultaneous with increasing global–at Mannheim and Trier can be explained by the fact that these two stations had fairly large increases in annual horizontal direct irradiance (discussed below). It may also be explained by decreases in turbidity; Mannheim and Trier, as well as Hohenpeissenberg and Kassel, have significant decreases in $\hat{\hat{\beta}}_a$ (Tables 2 and 7). It appears that a decrease in aerosols may therefore be responsible for the decline in diffuse at these four stations. At Hamburg, the decrease in diffuse was also coincident with a decrease in $\hat{\hat{\beta}}_a$ of 4.92% per decade but the trend was not statistically significant. There were no significant trends in sunshine duration at stations with trends in diffuse (Table 7).

5.3.3 Direct

The long-term averages of annual mean direct irradiance vary between 44.34 Wm^{-2}, at Hamburg, and 67.82 Wm^{-2}, at Hohenpeissenberg (Table 6). This range of 23.48 Wm^{-2} is relatively large and constitutes 43.53% of the long-term mean annual irradiances averaged over all 13 stations. By comparison, the ranges in global and diffuse irradiance are only 24.96% and 11.75% of the station-averaged long-term mean annual irradiances, respectively. This indicates that there is greater spatial variability in direct irradiance across Germany than in global and diffuse. Intrastation variability in direct irradiance is relatively small, however, with the standard deviation in the long-term annual averages ranging between 4.99 Wm^{-2}, at Passau, to 6.80 Wm^{-2}, at Norderney.

Direct irradiance has increased at all stations in Germany, although the trend is statistically significant at five stations: Bocholt, Freiburg, Kassel, Mannheim, and Trier (Table 6, Figs. 12 and 13). The significant increases range between 8.45% per decade, at Freiburg, and 11.69% per decade, at Bocholt. The average increase in direct irradiance at these five stations is

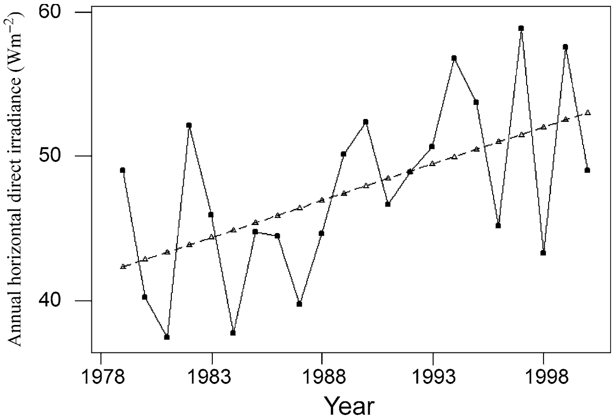

Fig. 12. Linear trend model fit to annually-averaged horizontal direct irradiance at Kassel, Germany, 1979–2000. Statistically significant increases in direct irradiance were also evident at Bocholt, Freiburg, Mannheim, and Trier (see Fig. 13, Table 6)

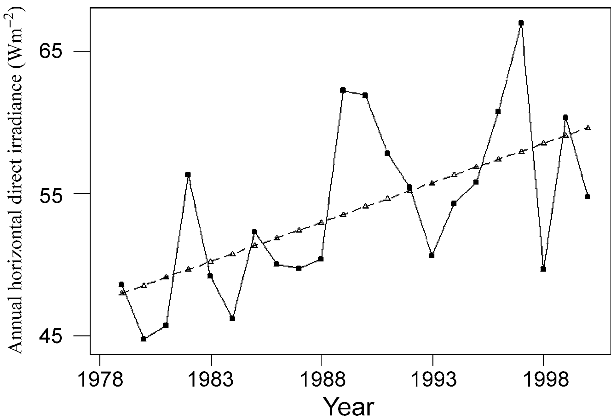

Fig. 13. Linear trend model fit to annually-averaged horizontal direct irradiance at Trier, Germany, 1979–2000

4.86 Wm^{-2} or 10.40% per decade. These decadal percentage increases are substantially larger than the percentage increases and decreases observed in trends in global and diffuse (Table 7). There is also more spatial homogeneity in the direct irradiance trends; four of the five stations that have statistically significant increases are in the southwest quadrant of Germany (Fig. 1).

There were no significant trends in direct irradiance at Hohenpeissenberg and Weihenstephan. This is consistent with assessments conducted by Grabbe and Grassl (1994), Liepert and Kukla (1994), and Liepert (1997) for direct irradiance at these two stations for periods between 1953 and 1990. Since 1990, however, direct irradiance has been relatively high; 11 of the 13 stations in this study had long-term averages of direct irradiance for the period 1991–2000 that were above the long-term averages for the full time series (c.f. columns 2 and 7 in Table 6). Five of those eleven stations were those that had statistically significant increases in direct over the full time series i.e., Bocholt, Freiburg, Kassel, Mannheim, and Trier. This notwithstanding, there were no significant increases in direct irradiance over the period 1991–2000. Averaged across all stations, the mean direct irradiance over 1991–2000 is 1.84 Wm^{-2} (3.41%) more than the mean global irradiance averaged across all years.

At Bocholt, Kassel, Mannheim, and Trier, the increases in direct irradiance are concomitant with decreases in $\hat{\bar{\beta}}_a$ (Table 7). Turbidity also decreased at Freiburg but the trend was not statistically significant. Of these five stations, only Freiburg has a statistically significant increase in sunshine duration (Table 7). Since the decrease in $\hat{\bar{\beta}}_a$ at this station was not statistically significant it appears more likely that the increase in direct is due to the increase in sunshine duration; at the other four stations, the decreasing turbidity may have contributed to the observed increase in direct irradiance. Note that, although the modeled estimates of $\bar{\beta}_a$ are, indirectly, an inverse function of direct horizontal irradiation–and one might therefore consistently expect a strong negative correlation between these two variables–$\hat{\bar{\beta}}_a$ is also dependent on, *inter alia*, precipitable water, total column ozone, atmospheric pressure, total column nitrogen dioxide, bright sunshine duration, and daylength. It is therefore theoretically possible to have simultaneous increases (or decreases) in direct irradiance and $\hat{\bar{\beta}}_a$. Such was the case at Braunschweig, for example, although the increases in direct irradiance and $\hat{\bar{\beta}}_a$ were not statistically significant at that station.

Consistent across the Bocholt, Freiburg, Kassel, Mannheim and Trier stations are concurrent increases in direct, increases in global, and decreases in diffuse irradiances, although not all of the increases and decreases in global and diffuse are statistically significant (Table 7). A plausible physical explanation for these concomitant trends is the decrease in aerosols seen at these stations; fewer aerosols would simultaneously increase the amount of direct and global, and decrease the amount of diffuse. This assumes, of course, that the aerosols are predominantly scattering in nature.

6. Summary and conclusions

Temporal and spatial variability in annually-averaged global, diffuse, and horizontal direct irradiance has been evaluated at 13 stations in Germany, where the time series range between 11 and 48 years. Using a least-squares estimation method and a significance level of 95%, global irradiance has decreased significantly at two stations located in the southeast, and increased at four stations, three of which are in the southwest. The mean trend across these six stations is an increase in global irradiance of 1.94 Wm^{-2} or 1.83% per decade. The positive trends in global irradiance differ from trends reported by previous investigators for Germany and are likely due to the relatively high irradiances experienced during the 1990s. Averaged over the period 1991–2000, nine stations had mean global irradiances that were higher than the global irradiance averaged over the full time series.

Significant reductions in diffuse irradiance are evident at five stations, where the mean decrease is 2.44 Wm^{-2} or 3.46% per decade. Diffuse irradiance has been relatively low in the 1990s, and statistically significant decreases in diffuse were observed at four stations during the period 1991–2000. To varying degrees, the radiative impacts of the Mount Agung, El Chichón, and Pinatubo eruptions are evident in the diffuse record. There is an absence of spatial patterns in the trends in diffuse.

Horizontal direct irradiance has increased at five stations, four of which are located in the southwest quadrant of Germany, and the average increase is 4.86 Wm^{-2} or 10.40% per decade. The largest long-term changes in radiation are in the direct component and there is also greater spatial variability in direct irradiance across Germany than in global and diffuse. Direct irradiance was relatively high in the 1990s, with 11 stations showing mean direct irradiances during 1991–2000 that were higher than the direct irradiance averaged over the full time series.

Stanhill and Cohen (2001) speculated that the two most probable causes of long-term trends in radiation are changes in aerosol loading and cloud cover. Trend analyses of modeled estimates of Ångström's turbidity coefficient indicate that total column aerosol has decreased at seven stations in Germany. These aerosol trend analyses, coupled with an absence of significant trends in sunshine duration at all stations except Braunschweig and Freiburg, suggest that long-term decreases in aerosols are the most likely cause of the observed increases in global at Mannheim, Norderney, and Trier; the decline in diffuse at Hohenpeissenberg, Kassel, Mannheim and Trier; and the increase in direct irradiance at Bocholt, Kassel, Mannheim, and Trier. The increase in sunshine duration at Freiburg likely contributed to the increase in global and direct radiation at that station.

Statistically significant trends in radiation that cannot be explained by changes in aerosols or sunshine duration include decreases in global at Hohenpeissenberg and Weihenstephan, and a decrease in diffuse at Hamburg. Sunshine duration did indeed decrease at Hohenpeissenberg and Weihenstephan, which would contribute to a decrease in global, and aerosols decreased at Hamburg, which would contribute to a decline in diffuse. However, the decreases in sunshine duration and aerosols at these three stations were not statistically significant.

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Author's address: Dr. Helen C. Power (e-mail: power@sc.edu), Department of Geography, University of South Carolina, Columbia SC 29208, U.S.A.