NOTES AND CORRESPONDENCE

Decline in Global Solar Radiation with Increased Horizontal Visibility in Germany between 1964 and 1990

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ABSTRACT

A statistically significant decrease in mean annual global solar radiation between 1964 and 1990 under completely overcast skies was found at five out of eight studied locations in Germany. A decrease of global solar radiation is also evident in partly cloudy conditions. The mean annual cloud cover fraction and sunshine duration did not significantly change, while the visually assessed mean annual horizontal visibility increased at six of the eight stations. The authors' findings point to a decrease of the cloud transmissivity, which in turn could be explained by an increased frequency of multilevel cloudiness, changing cloud types, or by indirect aerosol effects on clouds. The decreasing trend of global solar radiation in clear skies was most expressed at high and intermediate solar zenith angles, whereas a slight increase of global radiation was found at low sun zenith angles. A decline of the diffuse component of the global radiation over time was also detected. It is shown that the observed changes in clear-sky radiation were probably related to the recovery from the effects of major volcanic eruptions in the mid-1960s and 1980s. Increase of submicron aerosol particles with simultaneous reduction of aerosol mass concentrations reported by others and increasing absorption by urban aerosol may also contribute to the observed changes. The results are based on statistical analyses of hourly data of solar radiation, sunshine duration, cloud cover, and horizontal visibility stratified by solar zenith angle.

1. Introduction

Recent interest in climatic impact of aerosols calls for the inspection of actinometric records of radiation reaching ground. It is expected that in the presence of aerosols this entity would decrease. The impact is either direct, due to scattering and absorption by aerosol particles or indirect due to the role of aerosols in the formation of cloud condensation nuclei.

Reliable long-term solar radiation measurements are rare. Stanhill and Moreshet (1992) after analyzing data of 45 actinometric stations for the years 1958, 1965, 1975, and 1985 indeed found a statistically significant recent worldwide decrease of global solar radiation averaging 5.3%. The decline was largest between 45° and 30°N. Regional declines were reported for the western as well as eastern sections of the former Soviet Union (Russak 1990; Abakumova et al. 1996) and from Germany (Liepert et al. 1994; Liepert 1996). Local decrease of incoming radiation was also observed at Hong Kong by Stanhill and Kalma (1995). Model calculations (Hansen et al. 1995) show that the recently observed changes of minimum and maximum temperatures can be explained only if the aerosol increase is taken in account. Empirical observations of possible cooling impact of aerosols on surface air temperature were reported by Karl et al. (1995), Stanhill and Kalma (1995), and Abakumova et al. (1996).

To gain a better understanding of the nature of the observed trends, we analyzed hourly observations of radiation income in Germany stratified by cloud cover types and solar zenith angle. We selected for this study the longest records of the radiation network of the German Weather Service (DWD). They cover more than 25 years and the history of instrument calibration is known and could be assessed for reliability checks (Kasten 1988).

2. Data

The radiation data averaged over hourly intervals were obtained by Moll-Gorczynski pyranometers of Kipp&Zonen with a spectral range between 0.3 and 2.7 μm. The instruments were calibrated every second year. The long-term drift of the instruments was found to be less than 1% yr^{-1} (Kasten 1988). The pyranometers have a zenith angle–dependent bias at high angles. This is shown by Maxwell et al. (1995) for Eppley pyranometers and is also true for Kipp&Zonen pyranometers

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TABLE 1. German solar radiation stations.

	Norderney	Hamburg	Braunlage	Braunschweig	Trier	Wurzburg	Weihen-stephan	Hohenpeissen-berg
Location (°)								
Latitude N	53.72	53.63	51.72	52.30	49.75	49.80	48.40	47.78
Longitude E	7.15	10.00	10.53	10.45	6.67	9.90	11.73	11.02
Time period:								
Cloud cover	1964–90	1964–90	1964–90	1964–90	1964–90	1964–90	1964–90	1964–90
Sunshine duration	1964–90	1964–90	1964–90	1964–90	1964–90	1964–90	1964–90	1964–90
Visibility	1967–87	1964–90	1964–90	1964–90	1964–87	1964–82	1968–90	1960–90
Global radiation	1967–90	1964–90	1964–90	1964–90	1964–90	1964–90	1964–88	1953–90
Diffuse radiation	1977–90	1964–90	—	1977–90	1979–90	1978–90	1971–90	1953–90
Frequency of cloud cover category (%):								
Clear	11.2	8.9	9.4	8.6	9.3	11.0	11.8	15.5
Overcast	25	25.8	26.6	27.0	25.6	26.1	25.0	17.3
Cloudy	88.8	91.1	90.6	91.4	90.7	89.0	88.2	84.5
All sky	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

(Dehne 1996, personal communication). However, results of our work are not likely to be affected because we studied changes of solar radiation income over time within specific unchanging zenith angle categories. The raw data are archived at the Meteorological Observatory in Hamburg (MOH). The homogeneity of the records, due to frequent calibrations and careful maintenance of the instruments, is among the best in the world.

The horizontal visibility and cloud cover data are visually observed and recorded at 1- or 3-h intervals.

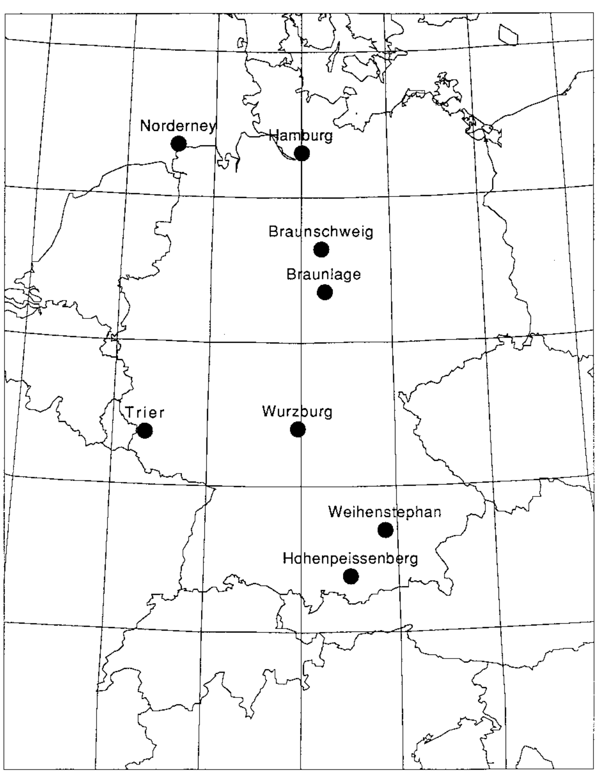

FIG. 1. Location of the used radiation stations.

Homogeneity testing was performed by the MOH on the cloud data and by Liepert (1996) on the visibility data. At four of the stations the visibility records are shorter than the studied interval because of inhomogeneities (Table 1). Only at Wurzburg is the record shorter than 20 years (1964–82). The sunshine duration was measured by the Campbell–Stokes paper track recorders.

The data analyzed in our study come from eight stations with high quality measurements. The position of the station is shown in Fig. 1 and their geographic coordinates are given in Table 1.

1) Norderney is located on East-Friesland Island in a typical maritime environment and is for the most part unaffected by urbanization or industrialization.
2) Hamburg is an urban site near the coast and is therefore partly under maritime influence.
3) Braunlage is a hilltop station in the close vicinity of coal mines and power plants.
4) Braunschweig is located within a heavily industrialized region with several coal firing power stations.
5–7) Trier, Wurzburg, and Weihenstephan are rural stations in moderately hilly areas.
8) Hohenpeissenberg is a high-level rural observatory in the foothills of the Alps.

3. Method

The data on cloud cover, visibility, and sunshine duration were conventionally classified as follows: the cloud cover (N) is given in eighths of the sky hemisphere, the sunshine duration (S) is in tenths of an hour, horizontal visibility (V) was regrouped into classes from 1 to 5 km, 6 to 10, and so on up to 56 to 60 km and above 60 km. The frequency of these groups has been calculated for each year and has been characterized by the median, mean, standard deviation, and skewness. Linear regression of the time series for median, mean, and skewness were used to detect trends. The signifi-

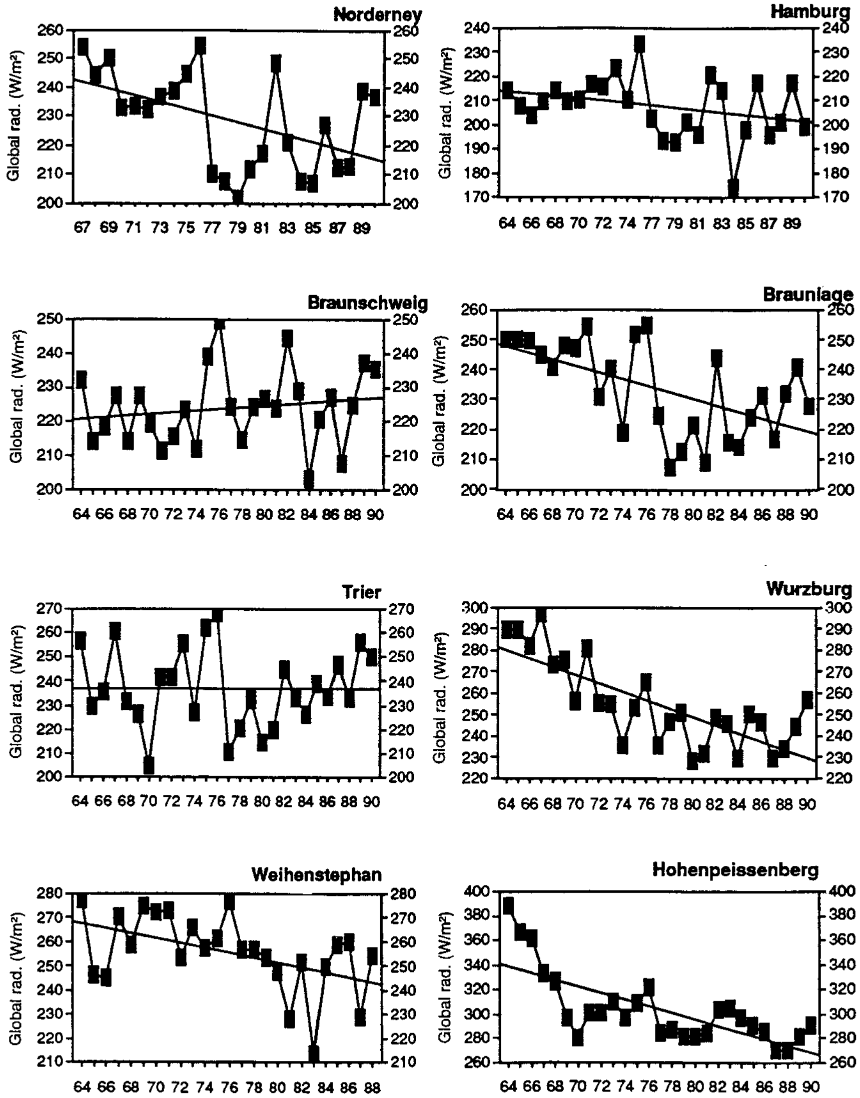

FIG. 2. Time series and trends of the annual global solar radiation at surface at eight German stations from 1964 to 1990 (after Liepert 1996).

cance of the trends is evaluated by Student's t-test of the slope of the regression line.

Hourly totals of global solar radiation (G) were stratified by solar zenith angle (Z). Seven overlapping intervals were used: 90°–75°, 85°–70°, 80°–65°, 75°–60°, 70°–55°, 65°–50°, and finally 60°–30°. The overlap of the groups assures that each measured hourly value is taken into account. Subsequently, a new time series of radiation data stratified by zenith angle, and therefore independent of the diurnal and seasonal cycle, has been constructed.

The radiation data were internally cross-checked with the cloud cover and sunshine duration. In our work, three cloud cover classes were defined by N and S as follows:

- clear: $N \leq 1$; $S = 10$ (little or no cloud in the sky at the end of the hour and continuous sunshine record throughout the hour);
- fractional cloud cover: $N \geq 2$; $S \leq 9$ (between two-eighths and eight-eighths of cloud cover at the end of the hour and sunshine for up to nine-tenths of the observed interval);
- overcast: $N = 8$; $S = 0$ (completely overcast, no sunshine record).

For almost each hourly radiation measurement, information on cloud cover and sunshine duration are available making it possible to analyze solar radiation for each cloud cover class separately.

4. Results

a. All-sky conditions

At all stations throughout parts of the diurnal insolation cycle the annual totals of global shortwave ra-

TABLE 2. Trend analysis of the global solar radiation records from 1964 to 1990 for four cloud cover categories separated by solar zenith angles. Mean in W m^{-2} and Trend in W m^{-2} decade^{-1}. Significance level Sig in %.

		Norderney			Hamburg		
	Zenith angle	Mean	Trend	Sig	Mean	Trend	Sig
All sky	mean	228 ± 15	−11 ± 4	98	199 ± 41	—	—
	90–75	40 ± 4	−3 ± 1	98	38 ± 7	—	—
	85–70	96 ± 8	—	—	91 ± 6	−4 ± 2	99
	80–65	140 ± 10	—	—	152 ± 10	—	—
	75–60	201 ± 15	—	—	187 ± 12	− 8 ± 3	99
	70–55	268 ± 16	−7 ± 5	87	246 ± 14	−7 ± 4	95
	65–50	325 ± 24	−19 ± 7	98	295 ± 18	−12 ± 5	99
	60–30	475 ± 32	−21 ± 10	96	424 ± 26	—	—
Clear	mean	476 ± 48	—	—	424 ± 24	—	—
	90–75	126 ± 23	—	—	135 ± 12	−10 ± 3	99
	85–70	187 ± 17	—	—	184 ± 9	−7 ± 2	99
	80–65	260 ± 14	—	—	252 ± 12	—	—
	75–60	343 ± 19	−9 ± 5	91	331 ± 18	—	—
	70–55	427 ± 29	—	—	415 ± 16	−9 ± 4	96
	65-50	501 ± 20	−17 ± 6	99	483 ± 16	—	—
	60–30	688 ± 25	−16 ± 8	95	655 ± 25	9 ± 6	87
Overcast	mean	77 ± 11	—	—	61 ± 3	−5 ± 1	99
Cloudy	mean	161 ± 24	—	—	152 ± 31	—	—
	90–75	38 ± 4	−4 ± 1	99	30 ± 5	—	—
	85–70	82 ± 5	−5 ± 2	99	73 ± 3	−5 ± 1	99
	80–65	114 ± 7	−5 ± 2	98	103 ± 6	−6 ± 2	99
	75–60	159 ± 20	−7 ± 3	97	145 ± 7	−6 ± 2	99
	70–55	206 ± 15	−10 ± 4	97	192 ± 7	—	—
	65–50	244 ± 19	−12 ± 6	96	234 ± 9	—	—
	60–30	345 ± 25	−15 ± 7	95	340 ± 16	—	—

		Braunlage			Braunschweig		
	Zenith angle	Mean	Trend	Sig	Mean	Trend	Sig
All sky	mean	233 ± 12	−11 ± 3	99	223 ± 11	—	—
	90–75	42 ± 3	−5 ± 1	99	39 ± 2	—	—
	85–70	96 ± 9	—	—	92 ± 5	4 ± 1	99
	80–65	140 ± 10	—	—	132 ± 7	6 ± 2	99
	75–60	194 ± 16	—	—	188 ± 10	6 ± 3	98
	70–55	253 ± 22	—	—	249 ± 13	7 ± 3	95
	65–50	298 ± 19	−11 ± 5	97	299 ± 16	—	—
	60–30	407 ± 26	—	—	429 ± 23	10 ± 6	91
Clear	mean	441 ± 27	—	—	444 ± 23	—	—
	90–75	145 ± 13	−6 ± 3	90	151 ± 15	—	—
	85–70	203 ± 14	−9 ± 4	98	185 ± 13	—	—
	80–65	279 ± 15	—	—	251 ± 15	8 ± 4	95
	75–60	350 ± 18	—	—	321 ± 16	—	—
	70–55	437 ± 19	—	—	407 ± 20	—	—
	65–50	502 ± 20	—	—	470 ± 17	11 ± 4	98
	60–30	661 ± 24	13 ± 6	95	640 ± 18	24 ± 5	99
Overcast	mean	73 ± 6	−3 ± 2	89	72 ± 6	—	—
Cloudy	mean	177 ± 9	−6 ± 2	99	164 ± 6	—	—
	90–75	35 ± 2	−4 ± 1	99	34 ± 2	—	—
	85–70	76 ± 5	−3 ± 1	97	76 ± 4	2 ± 1	97
	80–65	106 ± 7	−4 ± 2	96	106 ± 6	3 ± 2	94
	75–60	144 ± 10	—	—	146 ± 8	3 ± 2	86
	70–55	187 ± 15	—	—	192 ± 11	—	—
	65–50	225 ± 15	—	—	231 ± 11	—	—
	60–30	322 ± 19	—	—	332 ± 16	—	—

		Trier			Wurzburg		
	Zenith angle	Mean	Trend	Sig	Mean	Trend	Sig
All sky	mean	237 ± 16	—	—	255 ± 13	−19 ± 3	99
	90–75	29 ± 3	−2 ± 1	99	37 ± 3	−5 ± 1	99
	85–70	72 ± 5	−2 ± 1	90	102 ± 7	−5 ± 2	99
	80–65	108 ± 8	—	—	146 ± 9	−4 ± 2	92
	75–60	148 ± 11	—	—	194 ± 13	−5 ± 3	87
	70–55	191 ± 15	—	—	265 ± 20	−8 ± 5	90
	65–50	261 ± 21	—	—	322 ± 19	−9 ± 5	92
	60–30	398 ± 27	—	—	451 ± 20	—	—

TABLE 2. (*Continued*)

	Zenith angle	Trier Mean	Trier Trend	Trier Sig	Wurzburg Mean	Wurzburg Trend	Wurzburg Sig
Clear	mean	479 ± 20	—	—	484 ± 21	—	—
	90–75	123 ± 13	—	—	136 ± 11	−6 ± 3	94
	85–70	153 ± 9	−5 ± 2	95	195 ± 15	−8 ± 4	96
	80–65	227 ± 17	—	—	269 ± 14	−6 ± 4	90
	75–60	295 ± 14	−7 ± 4	93	336 ± 17	−7 ± 4	88
	70–55	368 ± 15	—	—	426 ± 20	−12 ± 5	97
	65–50	447 ± 14	−10 ± 4	99	493 ± 21	−9 ± 5	89
	60–30	615 ± 23	—	—	652 ± 21	12 ± 5	97
Overcast	mean	72 ± 5	−5 ± 1	99	85 ± 7	−6 ± 2	99
Cloudy	mean	173 ± 9	−4 ± 2	93	195 ± 9	−12 ± 2	99
	90–75	25 ± 2	−2 ± 1	99	33 ± 2	−5 ± 1	99
	85–70	60 ± 3	−2 ± 1	94	86 ± 6	−5 ± 2	99
	80–65	86 ± 5	−2 ± 1	87	120 ± 8	−4 ± 2	94
	75–60	116 ± 7	−3 ± 2	93	155 ± 9	−5 ± 2	94
	70–55	146 ± 8	−3 ± 2	88	207 ± 15	—	—
	65–50	198 ± 13	−5 ± 3	88	252 ± 16	—	—
	60–30	302 ± 15	−10 ± 4	98	358 ± 14	—	—

	Zenith angle	Weihenstephan Mean	Weihenstephan Trend	Weihenstephan Sig	Hohenpeissenberg Mean	Hohenpeissenberg Trend	Hohenpeissenberg Sig
All sky	mean	255 ± 13	−10 ± 4	99	304 ± 20	−27 ± 5	99
	90–75	37 ± 2	−3 ± 1	99	49 ± 6	−9 ± 2	99
	85–70	112 ± 6	−8 ± 2	99	143 ± 11	−12 ± 3	99
	80–65	162 ± 8	−9 ± 2	99	209 ± 13	−13 ± 3	99
	75–60	207 ± 13	−10 ± 5	99	256 ± 15	−13 ± 4	99
	70–55	274 ± 19	−13 ± 5	98	327 ± 18	−16 ± 5	99
	65–50	330 ± 19	−10 ± 5	92	381 ± 25	−19 ± 6	99
	60–30	454 ± 23	—	—	495 ± 21	−17 ± 5	99
Clear	mean	489 ± 31	−15 ± 9	89	489 ± 31	−15 ± 8	93
	90–75	129 ± 12	−13 ± 3	99	140 ± 16	−15 ± 4	99
	85–70	197 ± 14	−17 ± 4	99	228 ± 14	−22 ± 4	99
	80–65	279 ± 9	−15 ± 3	99	311 ± 13	−15 ± 3	99
	75–60	347 ± 14	−8 ± 4	94	377 ± 17	−11 ± 4	98
	70–55	438 ± 19	−13 ± 5	98	470 ± 19	−17 ± 5	99
	65–50	504 ± 22	—	—	541 ± 20	−14 ± 5	99
	60–30	658 ± 25	12 ± 7	90	694 ± 24	—	—
Overcast	mean	90 ± 5	−8 ± 1	99	101 ± 15	−15 ± 4	99
Cloudy	mean	188 ± 8	−12 ± 2	99	215 ± 17	−23 ± 4	99
	90–75	33 ± 1	−3 ± 0	99	40 ± 5	−6 ± 1	99
	85–70	93 ± 5	−9 ± 1	99	108 ± 7	−10 ± 2	99
	80–65	129 ± 7	−11 ± 2	99	155 ± 9	−12 ± 2	99
	75–60	160 ± 10	−15 ± 3	99	186 ± 11	−15 ± 3	99
	70–55	208 ± 17	−16 ± 5	99	234 ± 13	−16 ± 4	99
	65–50	252 ± 13	−15 ± 4	99	274 ± 21	−17 ± 5	99
	60–30	351 ± 17	−14 ± 5	99	365 ± 17	−22 ± 4	99

diation received at the surface is decreasing, except Braunschweig, where the global solar radiation is increasing at mean and low zenith angles. The decrease varies with zenith angle for each station. At Hohenpeissenberg it does decrease at all zenith angle intervals. The average decline of the daily means is 10 W m^{-2} (=4%) per decade and is statistically significant for five out of the eight stations (Fig. 2). The means and trends with a significance level higher than 85% and the corresponding standard deviations are listed in Table 2.

b. Cloudy conditions

The mean annual cloud cover fraction did not change significantly between 1964 and 1990 (Table 3a). The average of annual means for all stations is 5/8, whereas the average median is 6/8 pointing to an asymmetric frequency distribution with negative skewness, where higher cloud cover fractions are observed more often than the lower ones. The median cloud cover fraction is significantly decreasing at Hamburg and Weihenstephan but increasing at Braunlage, where a parallel shift in the skewness to higher values is also shown.

The average annual sunshine duration for all stations is 4/10 and the median is 2/10 (Table 3b). The mean annual sunshine duration did not notably change between 1964 and 1990, except at Hamburg. This is in accordance with Weber (1990), who analyzed annual sunshine duration in Germany between 1951 and 1987 and also found only a few stations with decreases. At

TABLE 3a. Long-term means, trends, and significance levels of annual means, medians, and skewnesses of cloud cover fraction between 1964 and 1990. Mean in eighths of sky hemisphere. Trend in eighths of sky hemisphere of the whole time period. Significance level Sig in %.

	Mean			Median			Skewness		
Station	Mean	Trend	Sig	Mean	Trend	Sig	Mean	Trend	Sig
Norderney	5.3	—	—	6.1	—	—	−0.7	—	—
Hamburg	5.5	−0.2	86	6.5	−0.4	98	−0.9	—	—
Braunschweig	5.6	—	—	6.6	—	—	−0.9	—	—
Braunlage	5.7	0.3	89	6.7	0.2	95	−1.0	−0.3	93
Trier	5.6	—	—	6.7	—	—	−1.0	—	—
Wurzburg	5.3	—	—	6.2	—	—	−0.7	—	—
Weihenstephan	5.3	—	—	6.5	−0.4	99	−0.7	—	—
Hohenpeissenberg	5.0	—	—	5.0	—	—	−0.5	—	—

Hamburg a parallel decline in cloud cover and in sunshine duration is shown, which may be explained by changing cloud types indicating possible changing circulation patterns over central Europe. Henderson-Sellers (1986) analyzed the difference of cloudiness in western Europe between a colder (1901–20) as opposed to a warmer (1934–53) period. She found that cloud cover is greater in the latter interval with the exception over Germany, France, and parts of Spain.

In the fractional cloud cover category, which includes completely overcast conditions and occurs approximately 90% of the time (Table 1), the radiation received at the ground was on the average 38% of that received in cloudless skies. At all stations, global radiation is decreasing within most of the zenith angle intervals, except at Braunschweig, where increases in intermediate zenith angle groups occur. At five out of eight stations a significant decline in annual means occurred. The average decline for all eight stations is 7 W m^{-2} (=4%) per decade (cloudy of Table 2). The global radiation is decreasing for most of the zenith angle intervals at Norderney, Wurzburg, Weihenstephan, and Hohenpeissenberg. Parallel changes in cloud cover or sunshine duration at these stations are not indicated.

Fully overcast skies occur about 25% of the time (Table 1). Compared to the radiation income under clear skies only 17% of the solar radiation reaches the ground. Over the 1964 to 1990 interval, the global solar radiation under overcast conditions decreased at six out of the eight stations. The average for the eight stations is a drop of 5 W m^{-2} (=6%) per decade (Table 2). This finding points to a decrease of cloud transmissivity, which in turn could be related to an increasing frequency of multilevel cloudiness (including cirrus), to changing cloud types, or to an indirect aerosol effect on clouds. Increasing concentration of tropospheric aerosols (see Kogan et al. 1996; Chuang et al. 1996) lead to a potential increase of both scattering (due to cloud condensation nuclei) and absorption of solar radiation (due to soot particles).

The indirect impact of aerosols on clouds is most effective in maritime stratiform clouds (Hobbs 1993). We therefore analyzed data from Hamburg, a near-coast urban station, where detailed cloud type records are kept. The decline of global radiation is strongest with stratocumulus and stratus overcast (Fig. 3). The decrease per decade is 10 W m^{-2} (=14%) for stratocumulus and 6 W m^{-2} (=12%) for stratus. The influence of any possible changes in higher level clouds (for example, altostratus or nimbostratus) is unknown due to the masking by low-level clouds. Increase of cloud transmissivity or multilevel cloudiness are therefore suggested as possible reasons for the decline of global radiation in these conditions.

c. Clear skies

Horizontal visibility shows a marked improvement over the studied interval (Fig. 4) with distant objects observed more often at six out of the eight analyzed

TABLE 3b. Long-term means, trends, and significance levels of annual means, medians, and skewnesses of sunshine duration between 1964 and 1990. Mean in tenths of an hour. Trend in tenths of an hour of the whole time period. Significance level Sig in %.

	Mean			Median			Skewness		
Station	Mean	Trend	Sig	Mean	Trend	Sig	Mean	Trend	Sig
Norderney	4.0	—	—	2.0	—	—	0.4	—	—
Hamburg	3.6	−0.7	99	1.3	−0.9	93	0.6	0.4	99
Braunschweig	3.7	—	—	1.6	—	—	0.5	—	—
Braunlage	3.6	—	—	1.4	—	—	0.6	—	—
Trier	3.7	—	—	1.6	—	—	0.5	—	—
Wurzburg	3.8	—	—	1.8	—	—	0.5	—	—
Weihenstephan	4.1	—	—	2.3	—	—	0.4	—	—
Hohenpeissenberg	4.4	—	—	3.0	—	—	0.2	—	—

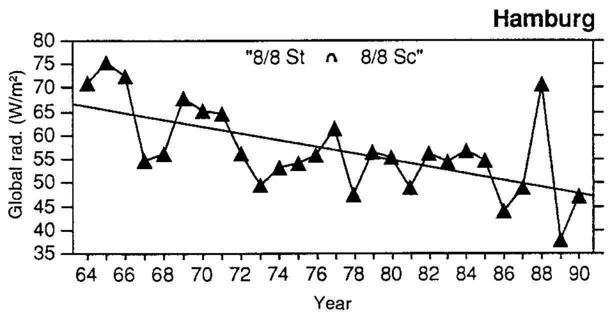

FIG. 3. Annual means of global solar radiation for overcast with stratus and/or stratocumulus in Hamburg from 1964 to 1990 (after Liepert 1996).

TABLE 4. Long-term means and trends (for the whole period of the record) of annual means, medians, and annual mean standard deviation (std dev) of the horizontal visibility in km for the given time intervals.

Station	Time period	Mean		Median		Std dev
		Mean	Trend	Mean	Trend	
Norderney	1967–87	11	−1	9	−2	8
Hamburg	1955–90	12	3	10	4	9
Braunschweig	1964–90	12	5	9	3	11
Braunlage	1964–90	28	9	19	8	25
Trier	1964–87	13	4	11	4	9
Wurzburg	1964–82	14	−2	13	−2	10
Weihenstephan	1968–88	12	3	9	1	10
Hohenpeissenberg	1960–90	61	8	71	—	21

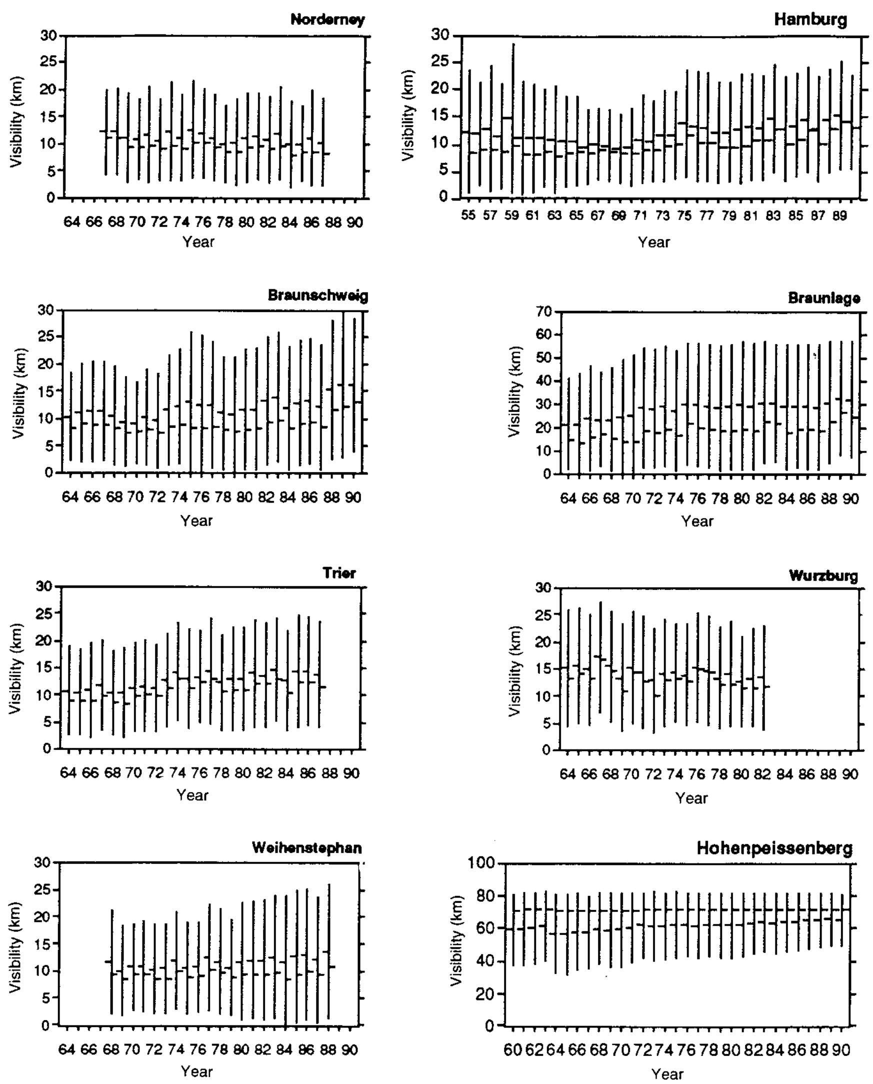

FIG. 4. Annual mean horizontal visibility at eight German stations. The vertical bar is the standard deviation; the right dash shows the median and the left dash the mean (after Liepert 1996).

sites. From 1968 to 1987 the mean horizontal visibility averaged for all the stations increased by approximately 3 km or by 15% (Table 4). Only at Norderney did the visibility slightly decrease. The determination of visibility trends has a subjective component and a high degree of uncertainty. The enormous interannual variation is reflected by the annual standard deviations shown in Fig. 4 and listed in Table 4. However, the horizontal visibility is the only available long-term dataset reflecting the variation of atmospheric turbidity at ground level. Only a few direct measurements of the concentration of aerosol particles are available since the mid-1970s. Arends et al. (1994) summarized the summertime sulfate mass concentrations between 1975 and 1992 at 29 European filter-based aerosol sampling sites. A decline averaging about 3% yr^{-1} was detected in most sites of Central Europe. At Hamburg, the total mass concentration of aerosol particles and the number density of aitken (radius < 0.1 μm) and of optical particles (0.1 μm $<$ radius $<$ 1.0 μm) are measured since 1976. A decline in the total aerosol mass concentration, an increase in the number density of optical particles by 25%, and a small decline in the number density of aitken particles between 1976 and 1993 were reported by Kaminski and Winkler (1988, 1994).

In the context of the decreasing ground-level aerosol mass concentrations and increasing horizontal visibility, one might conclude that the atmospheric turbidity in Germany decreased. However, the incoming radiation in the clear-sky conditions reflects the properties of the entire sky hemisphere and of the total atmospheric vertical column and shows more complex changes.

Clear-sky conditions occur approximately 10% of time. An insignificant decline of daily mean global radiation is detected at Weihenstephan and Hohenpeissenberg (Table 2). A striking difference is observed in the trends of low as opposed to the high and intermediate solar zenith angles. While in the higher solar zenith angles the trends are mostly negative, they are positive or near zero at low angles. This holds for all the stations except Norderney and Braunschweig. Norderney is an island whose maritime air is relatively unaffected by man. It is the most rural site of all the stations. The record shows significant negative trends at low angles. Braunschweig, where a considerable increase of received radiation is documented, is within a heavily industrialized coal mining and burning area. In this region a considerable reduction of gaseous industrial emissions recently took place. This happened as a result of clean-air act regulations.

For most of the stations, the diffuse solar radiation (D) is measured since the late 1970s at least (Table 1 and Fig. 5). We calculated the G/D ratio at clear-sky conditions to study the long-term variations of solar extinction [$G/D = (D + B)/D = 1 + (B/D)$, with $B =$ direct solar radiation]. Higher G/D ratio in clear skies could be due to less scattering, mainly Mie scattering by aerosol particles. Higher G/D ratio could also indicate more absorption at constant or even decreasing optical thickness. This follows from the calculations of broadband solar radiation income after the model of Bird and Hulstrom (Maxwell et al. 1995) for a spring day in Hohenpeissenberg (Fig. 6). The dashed lines show the global, diffuse, and direct radiation calculated for less absorption (single-scattering albedo 0.9) and less horizontal visibility (20 km), and the solid lines are calculated for higher absorption (single scattering albedo 0.7) and a higher horizontal visibility (25 km).

The results of the observed G/D ratios are shown in Fig. 5. The G/D ratio is relatively high in the 1970s and 1990s. Minima are in the years 1983 or 1984 probably affected by the eruption of El Chichón in April 1982. Abakumova et al. (1996) reports similar findings for regions of the former Soviet Union. In the last decade a general increase of G/D at clear skies is indicated. Although we did not analyze the data separately by season, we assume that this change occurred mainly in summer, which dominates the annual mean.

For Hohenpeissenberg the diffuse radiation is recorded since 1954. The horizontal visibility there is extreme because the station is on top of an isolated hill. To minimize the influence of tropospheric aerosols and maximize the effect of a high-level volcanic layer we selected the hourly diffuse solar radiation observations in clear skies at conditions of horizontal visibility above 60 km. Figure 7 shows the anomalies of diffuse radiation at solar zenith angle 80°. These include all hourly means during which a zenith angle of 80° has been reached. The diffuse radiation between 1955 and 1963 is close to the long-term mean and increases by about 40 W m^{-2} after the 1963 Agung eruption followed by a gradual recovery reached in the early 1970s. A smaller but noticeable increase between 1982 and 1984 parallels the El Chichón eruption in April 1982. These two eruptions induced approximately 160–300 $\times$ 10^5 t and 100–200 $\times$ 10^5 t mass loads, respectively, into the stratosphere (McCormick et al. 1993; Cadle et al. 1976, 1977). A general decline of the diffuse radiation component under extreme visibility conditions is observed in Hohenpeissenberg between 1964 to 1990 with the minima reached in 1986 and 1990. While the impact of volcanic aerosol loading is most prominent at high solar zenith angles, it has to affect the radiation income at any solar elevation.

At Hamburg and Hohenpeissenberg, the direct solar radiation (B) is calculated from $G - D$ from 1964 to 1990. At both stations the direct radiation shows opposing trends for low and high zenith angles (Table 5). At urban Hamburg the increase at small zenith angles is larger than at rural Hohenpeissenberg, but the relative declines at large zenith angles are more expressed in Hohenpeissenberg. The daily means show no trends. The diffuse solar radiation is decreasing at all zenith angles and the decrease is stronger in rural Hohenpeissenberg than in urban Hamburg. The measurements with shadow band may introduce a bias into zenith angle

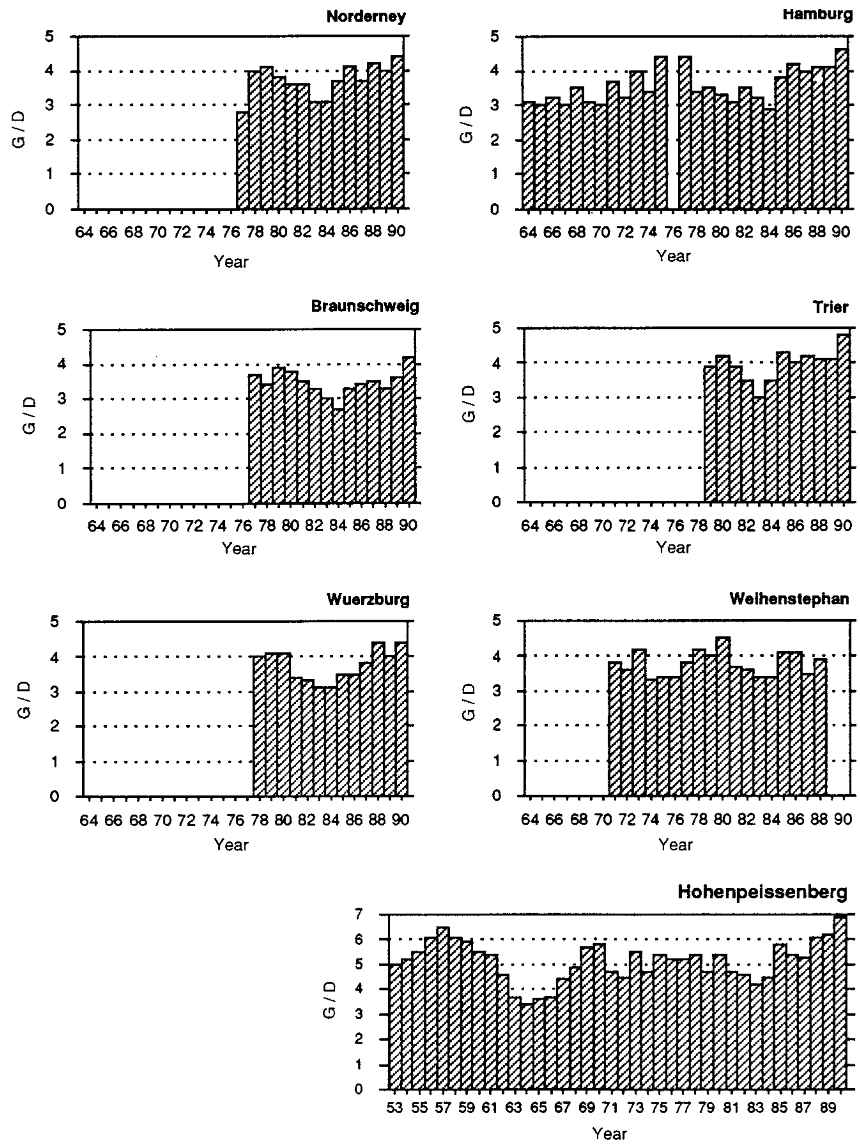

FIG. 5. Annual means of the global to diffuse *G*/*D* ratio of solar radiation at seven German stations for clear skies (after Liepert 1996).

dependence of diffuse solar radiation. Most of the radiation scattered by aerosols is in the forward direction and therefore is likely to be counted as direct radiation. The portion of the component is counted as a direct radiation is higher at small zenith angles than at the large ones. So, at the small zenith angles, the declines in the measured diffuse radiation due to less atmospheric scattering can be underestimated and the increase in direct radiation overestimated, whereas at large zenith angles this bias is relatively small.

Summarizing the various results for the clear-sky category can be interpreted as follows:

1) Increasing horizontal visibility from the mid-1960s at most stations (except the most rural Norderney) and declines in the summertime sulfate mass concentrations in Central Europe indicate decreasing optical thickness of the boundary layer.
2) The relative *G*/*D* minima after El Chichón and Mount Agung eruption are both followed by decreasing scattering of insolation during the recovery from the effects of volcanic dust veil. The increase in the *G*/*D* ratio at all stations since the mid-1970s points to an atmosphere that scatters less and absorbs more. In Hamburg and Hohenpeissenberg the increase of direct solar radiation and decline of diffuse solar radiation at small zenith angles also point to the same direction, although the effect is probably overestimated by the measurement procedure. Declines in the diffuse as well as in the direct solar radiation at large solar zenith angles can also be

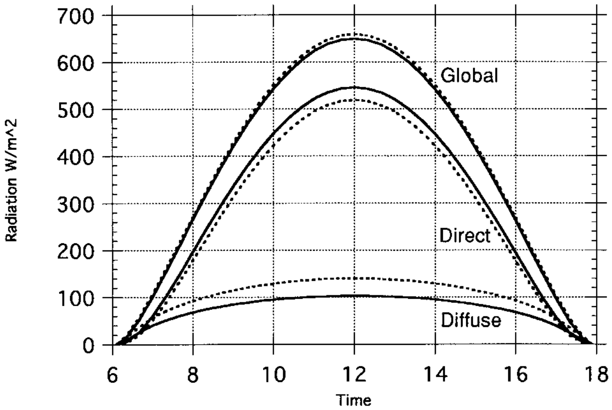

FIG. 6. Diurnal cycle of the global, diffuse, and direct solar radiation calculated after Bird and Hulstrom (Maxwell et al. 1995) for single-scattering albedo 0.9 and horizontal visibility 20 km (solid lines) single-scattering albedo 0.7 and horizontal visibility 25 km (dashed lines) for 20 March and the meteorological conditions of Hohenpeissenberg.

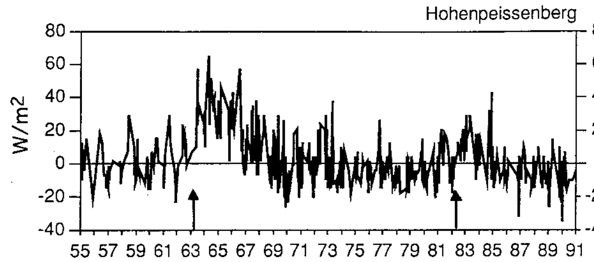

FIG. 7. Departures in W m^{-2} from the average of the diffuse solar radiation observed at clear skies with horizontal visibility over 60 km at 80° solar zenith angle. The years are ticked at 1 January. The data indicate the impact of major volcanic eruptions (Agung in March 1963 and El Chichón in April 1982) on diffuse solar radiation at Hohenpeissenberg.

explained by the atmosphere that scatters less and also absorbs more, because at the large zenith angles the diffuse radiation dominates and the absorption plays a more important role than at small zenith angles.

5. Conclusions

Global solar radiation at all sky conditions throughout much of the diurnal insolation cycle declined between 1964 and 1990 at all stations except Braunschweig. Statistically significant declines are found for cloudy and overcast conditions. They are not paralleled by changes in cloud cover fraction or sunshine duration. At Hamburg, a decline in global radiation in overcast stratus and stratocumulus was detected, suggesting a decrease in cloud transmissivity or increasing frequency of multilevel cloudiness.

The mean daily global radiation in clear skies did not change significantly, but increased at the low and decreased at the high solar zenith angles. This discrepancy may be due to the recovery from the effects of major volcanic eruptions and to changed size distribution of urban aerosols. Both lead to an atmosphere that scatters less and absorbs more incoming solar radiation. This assessment is in line with the observed increasing horizontal visibility, increase of the *G*/*D* ratio and decrease of sulfate aerosol concentrations in summer (Arends et al. 1994).

Our empirical analysis of global radiation stratified by solar zenith angles and cloudiness was made for a few selected stations with the highest quality of measurements available. Suggested explanation of the observed changes is not yet supported by physical models. Corresponding calculations are currently under way but not yet completed. Although the present study is limited to only a few German stations each affected by local

TABLE 5. Long-term means and trends of direct and diffuse solar radiation for clear-sky conditions between 1964 and 1990 separated by solar zenith angles. Mean in W m^{-2}; trend in W m^{-2} decade^{-1}. Significance level Sig in %.

		Hamburg			Hohenpeissenberg		
	Z angle	Mean	Trend	Sig	Mean	Trend	Sig
Direct	mean	296 ± 26	—	—	381 ± 22	—	—
	90–75	81 ± 7	−5 ± 2	99	100 ± 12	−8 ± 3	98
	85–70	114 ± 9	—	—	170 ± 14	−12 ± 4	98
	80–65	164 ± 13	—	—	240 ± 13	—	—
	75–60	223 ± 24	—	—	293 ± 17	—	—
	70–55	288 ± 24	—	—	373 ± 20	—	—
	65–50	338 ± 22	—	—	427 ± 20	—	—
	60–30	476 ± 39	26 ± 10	99	551 ± 32	22 ± 6	99
Diffuse	mean	127 ± 13	−13 ± 3	99	107 ± 18	−17 ± 5	99
	90–75	53 ± 8	−5 ± 2	98	40 ± 12	−8 ± 2	99
	85–70	69 ± 7	−6 ± 2	99	58 ± 11	−10 ± 3	99
	80–65	88 ± 8	−7 ± 2	99	71 ± 12	−11 ± 3	99
	75–60	107 ± 8	−10 ± 2	99	83 ± 15	−13 ± 4	99
	70–55	126 ± 13	−7 ± 3	97	97 ± 18	−15 ± 5	99
	65–50	144 ± 11	−7 ± 0	98	114 ± 21	−14 ± 5	99
	60–30	178 ± 20	−17 ± 5	99	141 ± 21	−19 ± 5	99

conditions, we believe that the results are reasonably representative of rural, industrial, as well as urban environments of Western and Central Europe. When taken into account in physical models of the atmosphere, this data can considerably increase our understanding of ongoing climate change.

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