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Review

Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences

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Abstract

A number of studies show that significant reductions in solar radiation reaching the Earth's surface have occurred during the past 50 years. This review analyzes the most accurate measurements, those made with thermopile pyranometers, and concludes that the reduction has globally averaged $0.51 \pm 0.05\,\mathrm{W\,m^{-2}}$ per year, equivalent to a reduction of 2.7% per decade, and now totals $20\,\mathrm{W\,m^{-2}}$, seven times the errors of measurement. Possible causes of the reductions are considered. Based on current knowledge, the most probable is that increases in man made aerosols and other air pollutants have changed the optical properties of the atmosphere, in particular those of clouds. The effects of the observed solar radiation reductions on plant processes and agricultural productivity are reviewed. While model studies indicate that reductions in productivity and transpiration will be proportional to those in radiation this conclusion is not supported by some of the experimental evidence. This suggests a lesser sensitivity, especially in high-radiation, arid climates, due to the shade tolerance of many crops and anticipated reductions in water stress. Finally the steps needed to strengthen the evidence for global dimming, elucidate its causes and determine its agricultural consequences are outlined.

Keywords: Global dimming; Solar radiation; Agricultural productivity; Arid climates; Shade tolerance

1. Introduction

Global radiation, the total short-wave irradiation from sun and sky, $E_{g\downarrow}$, provides the energy for both the carbon assimilation of plant canopies and their water loss to the atmosphere. To a major extent it also determines the heat balance of agricultural surfaces and thus the temperatures of crop canopies, livestock surfaces, soil and air, the major environmental factor controlling the development of crops, pastures, forest and livestock.

Any significant and widespread change in $E_{g\downarrow}$ is therefore likely to be of major importance for agricultural production as well as for climate change and the direct exploitation of solar energy.

The purpose of this review is to present the evidence that global dimming has occurred, and briefly to

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consider what are its probable causes and its possible agricultural consequences.

2. Evidence from global radiation measurements

Although instruments capable of accurately and continuously measuring and recording $E_{g\downarrow}$ have been available for nearly a century (Chaldecott, 1954) only two published analyses of an early and complete measurement series made with a thermoelectric pyranometer have been found which enabled the size of inter-annual variability to be established and their long-term changes, trends and periodicities to be studied (De Bruin et al., 1995; Kane, 1997).

2.1. The global network

The first global network of $E_{g\downarrow}$ measurements using standard instruments and calibration, operating and recording procedures, was established as part of the meteorological program of the International Geophysical Year 1957/1958. Instructions for the instruments to be used and the procedures to be followed were published (CSAGI, 1957); the measurements obtained were published (WMO, 1960) and later reviewed (Robinson, 1964).

A total of 275 complete years of $E_{g\downarrow}$ measurements are available from the 30 month period of the IGY, the majority were obtained with bimetallic actinographs, the least accurate type of pyranometer recommended for use in the IGY. The review of the measurements made at 16 stations, none of which had more than 5 years of record, indicated a mean inter-annual deviation in annual totals of 5%, with values for individual sites ranging between 1 and 13% (Robinson, 1964).

Since 1964, measurements of $E_{g\downarrow}$ and of some of the other components of the surface radiation balance, have been published by the World Radiation Center in St. Petersburg in a bulletin sponsored by the World Meteorological Organization (WMO, 1964). The data published is that supplied by national meteorological services whose network pyranometers are in nearly all cases regularly calibrated against secondary standard instruments. In turn these instruments are calibrated by reference to national standards whose sensitivities are derived from radiometers representing the world radiometric reference scale (WRRS) (WMO, 1997).

2.1.1. The global network: methods of analysis and results

In this study the global network results analyzed are confined to complete years of thermopile pyranometer measurements, the most accurate radiometer available for routine use, during the years 1958, 1965, 1975, 1985 and 1992. The data was taken from the appropriate WMO bulletins except for 1992 when it was obtained directly from the publications of, or by correspondence with, the various national meteorological services. Values measured before 1981 were transformed to the current WRRS, i.e. increased by 2.2% (WMO, 1997).

Four methods were adopted to circumvent the considerable spatial and temporal non-homogeneity in the data set of 1114 annual values of $E_{g\downarrow}$ as shown in Table 1.

The first method eliminated temporal non-homogeneity by restricting analysis to 675 pairs of data, each measured at the same site. The mean changes in $E_{g\downarrow}$, shown in Table 2, were negative for all 10 combinations of differences possible between the 5 years examined. The decreases were highly significant with a probability $p < 0.005$ in six cases, significant ($p < 0.025$) in three cases, and non-significant ($p > 0.05$) in one case, the difference between 1965 and 1975. Over the entire 34 year period, 1958–1992, for which data was available the mean annual reduction in $E_{g\downarrow}$ averaged $0.34 \pm 0.07\,\mathrm{W\,m^{-2}}$, equivalent to a global dimming of 0.23% per year if the data set was unbiased.

In the second method the annual values from all 854 sites were pooled and the time trend separated from the spatial effects of latitude and altitude by the use of a simple physical model of atmospheric transmittance.

Yearly means of $E_{g\downarrow}$ were converted to atmospheric transmittance, τ_m, by dividing by integrated yearly extra-terrestrial solar irradiance on a horizontal surface computed for the latitude of each pyranometer station. Transmittance was assumed to be an exponential function of the optical thickness of the atmosphere k, and the vertical air mass, m, such that

$$\tau_m = \exp(-km) \quad \text{or} \quad k = -\left(\frac{\ln(\tau_m)}{m}\right) \tag{1}$$

Table 1
Number and global distribution of pyranometer measurements in the data set analyzed; the values inside the parenthesis refer to the total numbers

	Land area (M km^{-2})	1958 (145)	1965 (194)	1975 (229)	1985 (243)	1992 (303)
Latitudinal distribution						
90–75°N	1.50	2	4	4	2	2
75–60°N	15.66	20	20	26	25	15
60–45°N	23.15	40	77	81	110	133
45–30°N	23.59	37	50	45	44	84
30–15°N	21.27	9	10	11	16	22
15–0°N	15.15	9	7	9	6	19
0–15°S	14.82	4	6	5	2	3
15–30°S	14.31	11	10	22	14	11
30–45°S	4.73	5	5	19	18	8
45–60°S	0.59	2	1	3	2	3
60–75°S	5.93	3	3	4	3	2
75–90°S	8.24	3	1	1	1	1
Continental distribution						
Africa	29.8	22	21	27	22	4
Asia	44.3	38	45	51	49	83
South America	17.8	1	0	0	1	2
North and Central America	24.1	33	65	57	35	11
Australia and South Pacific	8.9	4	7	26	25	35
Europe	9.9	41	52	64	107	164
Antarctica	14.1	6	4	4	4	4

For a unit air mass ($m = 1$) Eq. (1) yields

$$\tau_1 = \exp(-k) = \exp\left(\frac{\ln(\tau_m)}{m}\right) \tag{2}$$

Values of τ_1 which expresses the yearly average transmittance of a unit atmosphere at the site, were computed for each yearly mean of $E_{g\downarrow}$, where m was computed from site altitude based on a simple altimetric relationship (Haltiner and Martin, 1957).

The values of τ_1, averaged for each year of measurement and for the northern and southern hemispheres, given in Fig. 1, show an accelerating decrease in the northern hemisphere; the significantly higher values of transmittance in the southern hemisphere only declined between the last 2 years of measurement.

The physical model was validated using an independent data set consisting of 193 globally distributed annual means of $E_{g\downarrow}$ measured in 1979. Estimates for

Table 2
Mean annual changes in global irradiance from paired comparisons, W m^{-2} per year

Time interval	Change	Standard error	Significance, p	No. of pairs
1958–1992	−0.336	0.068	<0.005	24
1958–1985	−0.241	0.052	<0.005	43
1958–1975	−0.220	0.108	<0.025	68
1958–1965	−0.420	0.199	<0.025	80
1965–1975	−0.081	0.174	Not significant	99
1965–1985	−0.214	0.064	<0.005	75
1965–1992	−0.193	0.086	<0.025	32
1975–1992	−0.513	0.107	<0.005	66
1975–1985	−0.392	0.128	<0.005	131
1985–1992	−0.475	0.175	<0.005	84

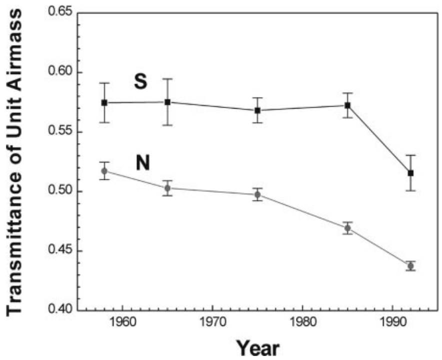

Fig. 1. Changes in atmospheric transmittance per unit air mass in the northern (N) and southern (S) hemispheres, 1958–1992. Vertical bars indicate ±1 standard error.

this year using Eq. (2), with values of transmission for 1979 interpolated for the northern and southern hemispheres from Fig. 1, had a R^2 value of 0.70 and a mean square residual of 13.38 W m^{-2}, 9.5% of the mean measured value.

A third method, an empirical multi-linear model derived from a stepwise regression analysis of the complete data set, was used to quantify the effects of five site factors and the year of measurement on annual values of $E_{g\downarrow}$. Eq. (3) accounted for more than three quarters of the total variance in the data set ($R^2 = 0.78$) and the contribution of each factor was highly significant ($p < 0.0001$).

$$E_{g\downarrow} = 154.4 + 147.3\cos^3\Psi + 0.0091A - 0.0720L - 18.39H - 0.00619\,\mathrm{FF} - 0.514\,\mathrm{Yr} \quad (3)$$

where $E_{g\downarrow}$ is the mean annual irradiance in W m^{-2}, Ψ the latitude in degrees (northern hemisphere positive and southern hemisphere negative), A the altitude in meters, L the longitude in degrees (east of the 0° meridian positive and west negative), H the hemisphere (northern = 1, southern = 0), FF the fossil fuel emissions in g C m^{-2} per year, and Yr the year of measurement after 1900. The data on anthropogenic fossil fuel carbon emissions for the 1° grid cell of each pyranometer site were taken from the data bases published by Andres et al. (1996, 1999), and Brenkert (1998).

Almost 90% of the total variance explained by Eq. (3) is accounted for by the relationship between global irradiance and the cubed cosine of latitude, selected because of its close fit to the latitudinal distribution of extra-terrestrial irradiance.

Of the remaining variance 41% is explained by the time trend, a mean annual decrease of 0.514 ± 0.055 W m^{-2} (standard error), more than the contributions of altitude: 27%, hemisphere:17%, or fossil fuel emissions: 7%. The slope of the fossil fuel term, -0.0062 W m^{-2} g C^{-1} m^{-2}, had a standard error of 0.0012. There was no significant interaction between year of measurement and fossil fuel emissions, nor was there any significant relationship between irradiance and population density in the 1° cells. However, significant linear interactions were found between year of measurement and site variables, i.e. latitude and longitude. Therefore, the influence of time in Eq. (3) should not be taken as conclusive as it may be confounded by the uneven and changing distribution of sites at different parts of the globe documented in Table 1.

The multi-linear model was validated by a comparison of estimated values for 1979 with those of the independent measured data set for that year. The two sets of values were highly significantly correlated ($R^2 = 0.72$, $p < 0.0001$), with a mean square residual of 18.45 W m^{-2}, 13.1% of the mean measured annual irradiance.

A fourth, graphic method was used to examine the time changes in the data set by calculating spline regressions of $E_{g\downarrow}$ on latitude for each of the 5 years of measurements. This yielded information on the zonal as well as hemispherical and global time trends although the large number of degrees of freedom used in the spline fitting program did not allow the statistical significance of the latitudinal differences to be established (Anonymous, 1995a).

Integrated values of $E_{g\downarrow}$ (Fig. 2A) show a globally averaged annual decrease of 0.60 W m^{-2} between 1958 and 1992, identical in the northern and southern hemispheres. In the northern hemisphere the rate of decrease accelerated since 1958, in the southern hemisphere a decline was only evident after 1985; a similar pattern of time trends to that in atmospheric transmittance calculated by the physical model and presented in Fig. 1.

In the agriculturally relevant portion of the Earth's surface between 60°N and 45°S the mean annual reduction in $E_{g\downarrow}$ was 0.66 W m^{-2}, and was similar in the northern (-0.65 W m^{-2}) and southern hemispheres (-0.66 W m^{-2}). For the temperate, extra-tropical

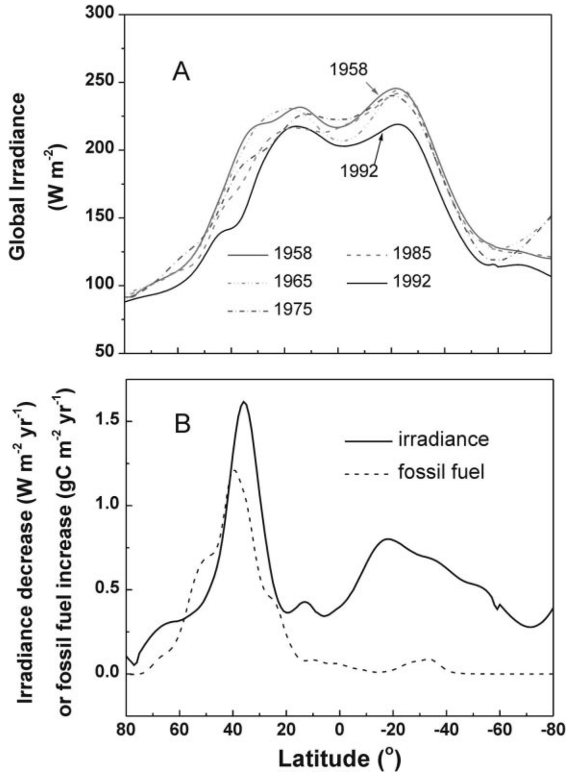

Fig. 2. Latitudinal distributions of global irradiance and anthropogenic carbon emissions. Spline fitted decreases in annual means of $E_{g\downarrow}$ from 1958 to 1992, $\mathrm{W\,m^{-2}}$ per year (solid line), and for increases in fossil fuel emissions from 1960 to 1990, $\mathrm{g\,C\,m^{-2}}$ per year (broken line). Integrated values of curves in A are given in Table 4.

zones the average annual reduction was $-0.88\,\mathrm{W\,m^{-2}}$ in the northern zone (60–23.5°N) and $-0.59\,\mathrm{W\,m^{-2}}$ in the southern zone (45–23.5°S). Within the tropics the average annual reductions were $-0.38\,\mathrm{W\,m^{-2}}$ north of, and $-0.65\,\mathrm{W\,m^{-2}}$ south of the equator.

The maximum rate of decrease, $-1.7\,\mathrm{W\,m^{-2}}$ per year, or -1.2% per year (Fig. 2B) was centered around 35°N, close to the latitudinal zone with maximum insolation, fossil fuel energy consumption, industrial activity and population.

2.2. Regional analyses: methods and results

Regional trends in annual values of $E_{g\downarrow}$ held in the Global Energy Balance Archive (GEBA) have been analyzed on a $2.5° \times 2.5°$ grid scale (Gilgen et al., 1998). The mapped results show that a significant decline has occurred over large regions of Africa, Asia, Europe and North America where the relative decrease averaged 2% of the mean over 10 years. Significant positive trends were only observed in four very small regions. In the sample of seven European non-mountainous and non-coastal regions $2.5° \times 2.5°$ grid cells which were studied in detail the mean relative annual decrease found was 0.53% per decade, with reductions ranging from 0.23 to 2.2% in four of the cells; in the remaining three cells the irradiances increased from 0.4 to 1.2%.

A small number of regional studies of measured changes in global irradiance have been published which were based on data from pyranometer networks of very different sizes and densities. The results obtained are briefly summarized below.

The study of long-term changes in $E_{g\downarrow}$ over the territory of the former Soviet Union (FSU), published by Zhitorchuk et al. (1994) [and in an English version by Abakumova et al. (1996)] was based on an analysis of measurements over the period 1960–1987 from the national radiation network which consisted of 160 frequently calibrated thermopile pyranometers. Reductions in $E_{g\downarrow}$ were found in 94% of the time series analyzed, 60% of these were statistically significant.

Three large areas where the reductions averaged more than 2% per decade were identified (Fig. 3): the European part of the FSU, where the decreases reached 6–7% per decade at some of the sites, West Siberia and the Far East. The smallest reductions were found in stations on the Central Siberian Plateau, where decreases were less than 1% per decade. Reductions in $E_{g\downarrow}$ were also measured at five high altitude stations with elevations ranging between 1918 and 4169 m. The only sites in the FSU where *increases* in $E_{g\downarrow}$ were found were two pyranometer stations on the extreme North-East coast of Siberia where the average increases exceeded 2% per decade. Over the major agricultural areas of the FSU the reduction in $E_{g\downarrow}$ averaged 2.4% per decade.

A study of $E_{g\downarrow}$ changes in Ireland (Stanhill, 1998a) showed results comparable with those from the FSU study despite the great contrast in area, density of pyranometer network and climates of the two regions. Reductions in $E_{g\downarrow}$ were found in seven out of eight measurement series available. Decreases in southern and central Ireland exceeded 4% per decade and were

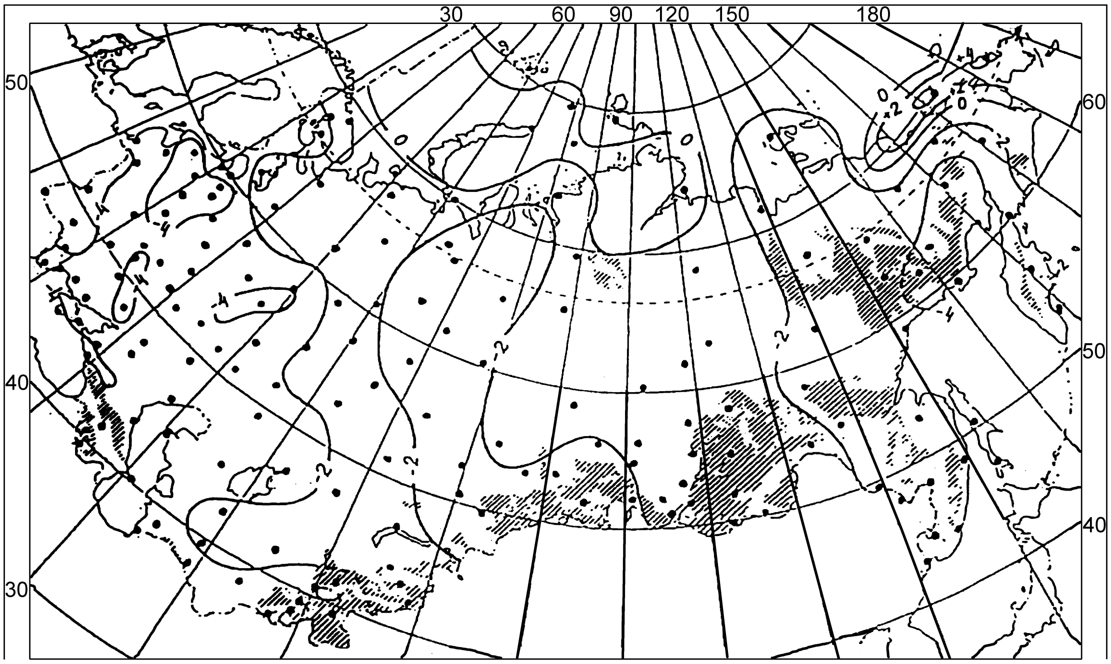

Fig. 3. Changes in annual mean global irradiance over the territory of the FSU, 1960–1987 in % per decade. From Abakumova et al. (1996).

highly ($p < 0.01$) or very highly ($p < 0.001$) significant; in the north of Ireland non-significant reductions of 1% per decade were found. A significant ($p < 0.05$) increase of 5% per decade was found in the measurement series from Dublin Airport near the central east coast.

As the Irish data set was not fully homogeneous in that the length of the eight measurement series varied between 14 and 41 years, all years of measurement were pooled to derive a very highly significant ($p < 0.001$) negative linear relationship between $E_{g\downarrow}$ and year of measurement. The weighted mean annual reduction for Ireland as a whole averaged $16.39 \pm 1.73\,\mathrm{MJ\,m^{-2}}$, or 2.7% per decade.

Studies of changes in $E_{g\downarrow}$ within the northern and southern Polar Circles have been published based on thermopile pyranometer measurements made within the Arctic Circle (Stanhill, 1995) and on the mainland of Antarctica (Stanhill and Cohen, 1997). In both these studies the individual measurement series were of different lengths, started in different years and were made independently by a number of national meteorological services and research institutions. Because of these non-homogenieties in the data bases the weighted average changes for both polar regions were derived from the pooled data as these were considered to provide the most reliable results.

The Arctic data base totaled 389 complete years of measurements made over the 1950–1994 period by seven different national authorities at 22 sites between 65° and 81°N. A linear regression of the pooled data against year of measurement (Fig. 4) indicates a very highly significant ($p < 0.0001$) weighted average annual reduction of $0.36 \pm 0.05\,\mathrm{W\,m^{-2}}$ or 3.7% per decade. Seven of the individual time series showed significant changes in the annual sums of $E_{g\downarrow}$, all but one indicating reductions. Within the Arctic Circle region the reductions were confined to the North American, Scandinavian and Eastern Siberian sectors with the few increases confined to Western Siberia (Fig. 5).

The Antarctic data base consisted of 203 complete years of measurement made over the period 1956–1994 by eight different national authorities at 12 sites between 65° and 90°S, all but two of the pyranometer sites were situated on the coast between 66°W and 167°E. The two inland sites were at the South Pole

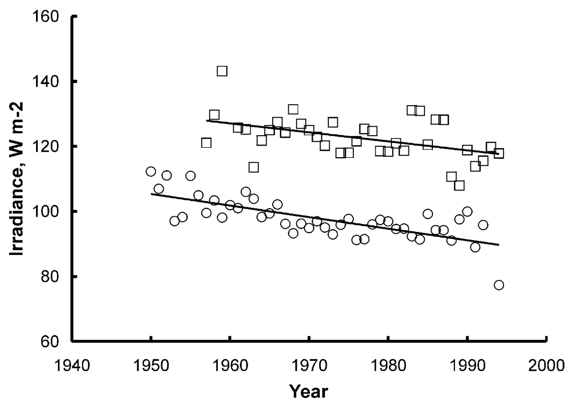

Fig. 4. Changes in annual mean global irradiance measured within the Polar Circles: Upper line — the Antarctic (1957–1994); source Stanhill and Cohen (1997). Lower line — the Arctic (1950–1994); source Stanhill (1995). Slopes for Arctic and Antarctic were -0.36 and $-0.28\,\mathrm{W\,m^{-2}}$ per year, respectively.

(2800 m) and at Vostok (3488 m) near the Pole of Inaccessability. The linear regression of the pooled data against year of measurement (Fig. 4) showed a highly significant ($p < 0.01$), weighted average annual reduction for Antarctica of $0.28 \pm 0.09\,\mathrm{W\,m^{-2}}$ or 2.3% per decade. Only two of the individual time series, both measured at coastal sites, showed significant changes in the annual sums of $E_{g\downarrow}$, both indicated reductions of more than 3% per decade.

An analysis of changes in measurements of $E_{g\downarrow}$ in Australia (Stanhill and Kalma, 1994) was based on a comparison of the data available from the seven station national network measured over two periods. In the first, 1953–1968, calibrated bimetallic actinographs were used; in the second period, 1968–1986, calibrated thermopile pyranometers were used. No significant changes were found between the two periods; mean differences in annual values were less than 1% per decade at any of the sites.

The Israel data base analyzed for time changes in $E_{g\downarrow}$ (Stanhill and Ianitz, 1997) was also non-homogeneous. Analysis of the pooled measurements indicated a highly significant ($p < 0.001$) annual decrease averaging $1.02\,\mathrm{W\,m^{-2}}$, equivalent to 4.7% per decade over the period 1954–1994. Analysis of the two long-term series available from the central coastal plain and central mountain range showed similar,

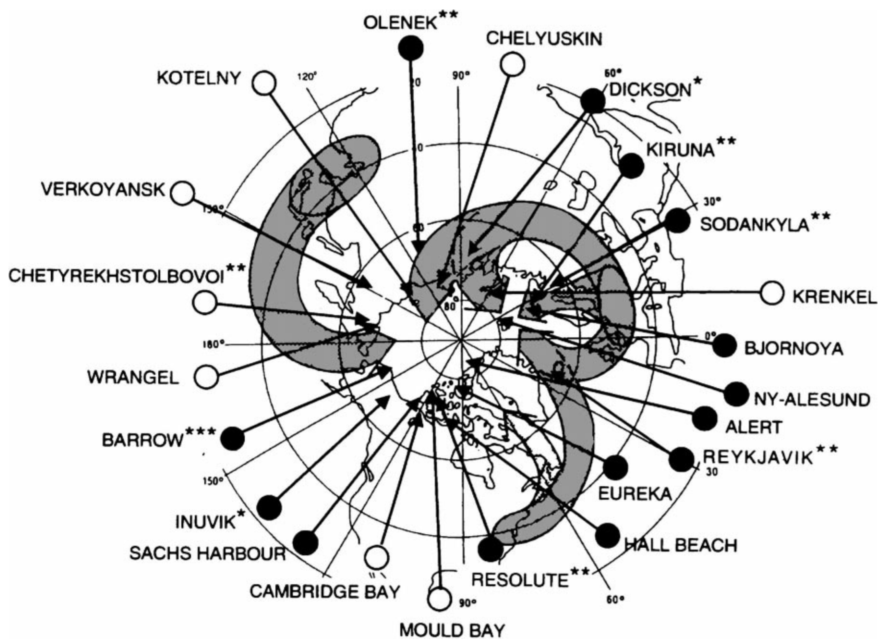

Fig. 5. Mean annual changes in global irradiances within the Arctic Circle with locations of pyranometer stations; closed circles indicate a decrease in irradiance, open circles an increase. The probability level of the fitted linear regression on year of measurement is indicated by one star for $p < 0.05$, two for $p < 0.01$, and three for $p < 0.001$. Major sources and pathways for pollutants reaching the Arctic from mid-latitudes after Jaworowski (1989). From Stanhill (1995).

Table 3
Linear trends in global irradiance from continuous measurement series (all values significant at $p < 0.05$)

Measurement sites		Period examined	Mean $E_{g\downarrow}$ ($W\,m^{-2}$ per year)	Linear trend		Reference
				($W\,m^{-2}$ per year)	(% per year)	
Individual sites						
Arctic						
Resolute	75°N 95°W	1964–1993	99.9	−0.52*	−0.53	Stanhill (1995)
Barrow	71°N 157°W	1951–1992	100.9	−0.23**	−0.23	Stanhill (1995)
Inuvik	68°N 134°W	1950–1993	107.2	−0.06*	−0.06	Stanhill (1995)
Verkhoyansk	68°N 133°E	1960–1985	109.2	−0.20	−0.18	Abakumova et al. (1996)
Kiruna	68°N 20°E	1952–1991	97.7	−0.06**	−0.06	Stanhill (1995)
Sodankyla	67°N 27°E	1953–1993	92.7	−0.11*	−0.12	Stanhill (1995)
Reykyavik	64°N 22°W	1958–1991	91.9	−0.17*	−0.18	Stanhill (1995)
Former Soviet Union						
Toravere	58°N 26°E	1955–1993		−0.23		Russak (1990)
Toropots	56°N 32°E	1960–1985	107.5	−0.46	−0.42	Abakumova et al. (1996)
Kaunus	55°N 24°E	1960–1985	113.0	−0.34	−0.30	Abakumova et al. (1996)
Odessa	46°N 31°E	1960–1985	140.8	−0.37	−0.26	Abakumova et al. (1996)
Tibilisi	42°N 45°E	1960–1985	150.2	−0.47	−0.31	Abakumova et al. (1996)
Ireland						
Dublin	53°N 6°W	1975–1995	107.9	+0.56	+0.52	Stanhill (1998a)
Birr	53°N 8°W	1971–1995	108.0	−0.51*	−0.47	Stanhill (1998a)
Kilkenny	53°N 7°W	1969–1995	114.7	−0.55*	−0.48	Stanhill (1998a)
Valentia	52°N 10°W	1954–1995	116.6	−0.49**	−0.42	Stanhill (1998a)
UK						
Aberporth	52°N 5°W	1959–1990	120.4	−0.38*	−0.32	Stanhill (1998a)
Baltic						
Helsinki	60°N 25°E	1964–1986	107.3	−0.56*	−0.52	Russak (1990)
Stockholm	59°N 18°E	1965–1986	105.7	−0.58*	−0.55	Russak (1990)
Germany						
Hohenpeissenberg	48°N 11°E	1953–1990	272	−1.0*	−0.37	Liepert (1997)
Israel						
Bet Dagan	32°N 35°E	1963–1994	219.1	−0.91**	−0.41	Stanhill and Ianitz (1997)
Jerusalem	32°N 35°E	1954–1994	244.2	−0.90**	−0.37	Stanhill and Ianitz (1997)
China						
Chengdu	29°N 103°E	1957–1992	116.9	−0.90	−0.76	Li et al. (1995)
Chongying	29°N 107°E	1956–1992	105.3	−1.01	−0.96	Li et al. (1995)
Hong Kong						
Kowloon	22°N 114°E	1958–1992	170.0	−1.80**	−1.05	Stanhill and Kalma (1995)
Japan						
Chichijima	27°N 142°E	1971–1991	184.0	−0.29*	−0.16	Stanhill and Moreshet (1994)
Minamotorishima	24°N 154°E	1970–1991	218.6	−1.24*	−0.57	Stanhill and Moreshet (1994)
Australia						
Griffith	34°S 146°E	1968–1992	203.9	+0.76*	+0.37	Stanhill and Kalma (1994)
Antarctica						
Scott	78°S 167°E	1957–1994	109.5	−0.50**	−0.46	Stanhill and Cohen (1997)
Mirny	66°S 93°E	1956–1987	137.4	−0.46**	−0.33	Stanhill and Cohen (1997)
Pooled regional groups of sites						
Arctic	Above 66°N, 22 sites	1950–1992		−0.36**		Stanhill (1995)
Ireland	8 sites	1954–1995		−0.52**		Stanhill (1998a)
Israel	17 sites	1956–1994		−1.02**		Stanhill and Ianitz (1997)
Antarctic	Below 65°S, 12 sites	1957–1994		−0.28*		Stanhill and Cohen (1997)

* $p < 0.01$.
** $p < 0.001$.

highly significant reductions averaging $0.91\,\mathrm{W\,m^{-2}}$ per year, more than 4% per decade.

2.3. Individual sites: methods and results

Results are available from published analyses of $E_{g\downarrow}$ measurement series at 39 individual sites, in all cases calibrated thermopile pyranometers were used for the measurements; only those extending over a period of at least 20 complete years have been included. Significant changes were found at 30 sites, and details of these are summarized in Table 3. The nine sites at which no significant changes were found are listed in Appendix A.

For the 28 sites at which significant decreases in annual sums of $E_{g\downarrow}$ were found the mean decrease was $0.55\pm0.39\,\mathrm{W\,m^{-2}}$ per annum or, expressed relatively, $4.0 \pm 2.4\%$ per decade.

2.4. Accuracy of measurements

A common response encountered to the evidence presented above is the suggestion that the reductions found may be due to errors of measurement. However, in order to explain changes of the magnitude found the errors would have to be larger, more widespread and systematically biased than is indicated by the literature.

A recent assessment of the size of the various uncertainties to be expected with the instruments used to obtain the data analyzed here, i.e. thermopile pyranometers of the type used for routine network operation, shows all the sources of error to be random and has estimated the total achievable uncertainty of daily totals of $E_{g\downarrow}$ at 5% with a confidence level of 95% (WMO, 1997). On the basis of the inverse square root law the uncertainty to be expected for the mean *annual* values analyzed in this study would be one-nineteenth of that of daily values; however the uncertainty of annual values is greater than this because the accuracy of long-term averages or totals is limited by the stability (annual change) in the sensitivities of pyranometers and the accuracy of their calibration; both of these were assessed at 1.5%.

As during the period analyzed there has been no major change in the radiometers used in measurement networks or in their maintenance procedures it is not surprising that similar uncertainties, i.e. 5% for daily totals, were specified for, and achieved in, the 1958 IGY program (CSAGI, 1957; Robinson, 1964).

Table 4
Annual means of spline fitted $E_{g\downarrow}$, $\mathrm{W\,m^{-2}}$ (see Fig. 2A)

Year	Northern hemisphere (0–90°)	Southern hemisphere (0–90°)	Globe (90°N–90°S)
1958	187.3	196.2	191.8
1965	185.4	194.3	189.8
1975	181.7	193.7	187.7
1985	175.8	193.8	184.8
1992	167.1	176.0	171.6

An earlier error analysis for the UK solar radiation network (BMO, 1982) gave a similar total error term although it was pointed out that when earlier models of non-temperature corrected thermopile pyranometers are used this source of error is not strictly random and is complimentary to non-linearity so that lower values of $E_{g\downarrow}$ will be associated with smaller error terms.

The above considerations indicate that the error of measurement to be expected for the annual mean values of $E_{g\downarrow}$ analyzed in this study is 1.5%; relative to the mean global annual average irradiance of $186.3\,\mathrm{W\,m^{-2}}$ over the same period (Table 4) the mean error to be expected is $2.8\,\mathrm{W\,m^{-2}}$. This error can be compared with the $20\,\mathrm{W\,m^{-2}}$ measured decrease in global irradiance over the same period (see Table 4).

Theoretically a substantial, undetected time drift in the WRRS, the source from which sensitivities of the network pyranometers are ultimately derived, could cause an apparent systematic change in the values of $E_{g\downarrow}$ reported. In 1965 the absolute accuracy of the WRRS was stated to be ‘almost certainly 1% and probably 0.5%’ (WMO, 1964), the 1981 edition of the same instruction manual gave the uncertainty in the WRRS as less than 0.3% root mean square error with a precision over a year of 0.1%; the same accuracy is given in the latest edition of the manual (WMO, 1997).

No evidence for any systematic change in the WRRS has been reported since the 2.2% increase adopted in 1981 which has been corrected for in this study. It can be concluded that the increased absolute accuracy of calibration is very unlikely to have introduced a trend or bias in network measurements because of the regular calibration of the field pyranometers in use and their occasional replacement by new and newly calibrated instruments.

The relative random error of yearly mean values of $E_{g\downarrow}$ was assessed at 1.9% on the basis of an analysis of measurements made at five pairs of pyranometer stations sited a few kilometers apart although not operating over the same time periods (Gilgen et al., 1998); thus the time trends — decreases in four of the pairs and no change in the fifth pair — were included in this assessment of error.

The above study concluded that the total random error in yearly means was approximately 2% after allowing for possible differences in the width of the solar waveband to which pyranometers were exposed during calibration and during routine measurements due to changing atmospheric conditions.

2.5. Evidence for changes in the diffuse component of global irradiance

In a very few cases measurements of direct sun beam and/or diffuse sky and cloud irradiance have accompanied those of global irradiance enabling the changing component of $E_{g\downarrow}$ to be distinguished. This distinction is of importance both as an indication of the cause of global dimming (see Section 3.7), and of its agricultural consequences (see Section 4.1).

Analyses of these measurements show all possible combinations of results. Two long-term measurement series in Germany showed that decreases in the diffuse rather than the direct component were the cause of reductions in $E_{g\downarrow}$ (Liepert, 1997). A similar conclusion was drawn from an analysis of radiation measurements and cloud observations in Israel (Stanhill and Ianitz, 1997). The opposite conclusion emerged from the long-term measurement series from Toravere in Estonia (Russak, 1990) as well as from a number of stations in Russia (Abakumova, 2000; Abakumova et al., 1996). In contrast, in Ireland the reduction was similar for the diffuse and direct components (Stanhill, 1998a).

2.6. Conclusions: evidence from pyranometer measurements

The evidence from thermopile pyranometer measurements of global irradiance obtained from the global network presented above, together with previously published regional and individual site studies, indicate that a worldwide but spatially variable reduction in $E_{g\downarrow}$ has taken place during the last four decades.

The four methods of analyzing the global network data set, which contains more than 1100 complete years of data, indicated statistically significant annual reductions averaging between 0.34 and 0.60 W m^{-2} or, relatively, between 0.23 and 0.32% per year. These are equivalent to total reductions for the period analyzed here, 1958–1992, between 11.4 and 20.4 W m^{-2}.

Consideration of the four methods provides an overview of the data set and of the evidence it provides for global dimming. The paired analysis is the most solid statistically, since the set is balanced in time, but it contains a relatively small number of measurement sites. The physical model accounts for differences in latitude and altitude, yielding mean atmospheric transmittance values with small standard errors, thus yielding statistically significant reductions in mean transmittance with time. In contrast, the multiple (stepwise) regression, which statistically is flawed because of the significant interactions between site location variables and time, gives a quantitative picture of the relative importance and magnitude of the influences of the various site variables, including fossil fuel emissions. Finally, the spline analysis goes one step further, by allowing observation of the non-linear distribution of radiation reduction with latitude, and the correspondence with changes in fossil fuel emissions. This information should be helpful in future investigations of the global dimming phenomenon.

Seven regional analyses yielded widely varying results, ranging from no significant change in Australia to a highly significant decrease of -1.0 W m^{-2} per year in Israel. Normalized to mean annual values of $E_{g\downarrow}$, the regional reductions varied between 0 and -0.47% per year, averaging -0.28 ± 0.16% per year.

Thirty out of the 39 time series from individual sites where changes have been analyzed and the results published showed significant time trends, all but two of which were negative. The average annual decrease was 0.55 ± 0.14 W m^{-2}, with a maximum reduction of 1.8 W m^{-2} at Hong Kong.

3. Possible and probable causes of global dimming

In the absence of a theoretically based hypothesis capable of quantitatively explaining the widespread and substantial reductions in $E_{g\downarrow}$ documented in the previous section; the aim of this section is restricted to discussing which of the many possible causes is the most probable.

Possible causes have been identified in accordance with the following simplified model, after Darnell et al. (1992):

$$E_{g\downarrow} = E_0 \exp(-\tau_r + \tau_g + \tau_w + \tau_a + \tau_c) \quad (4)$$

where global irradiance at the earth's surface, $E_{g\downarrow}$, is estimated as the product of extra-terrestrial irradiance at the top of the atmosphere, E_0, modified by a chain of five transmissivities τ which quantify the solar scattering and absorbing properties of the different components of the atmosphere. These include τ_r, representing Rayleigh scattering and τ_g, permanent gas absorption, τ_w, absorption by water vapor and τ_a and τ_c, the absorption and scattering by aerosols and cloud components, respectively.

3.1. Extra-terrestrial radiation

The changes in $E_{g\downarrow}$ reported herein are much greater and are of different sign than those reported for extra-terrestrial irradiance. Over the last 300 years the maximum *change* in E_0 has been estimated, on the basis of proxy measurements related to historical sunspot observations, at $5.4\,W\,m^{-2}$ (Hoyt and Schatten, 1993). Over the last 150 years, an irregular *increase* in E_0 of $0.3\,W\,m^{-2}$ with an uncertainty of $0.2\,W\,m^{-2}$ was estimated (Houghton et al., 1996). The short-term variations in E_0 measured from satellites indicate an *amplitude* of $1.36\,W\,m^{-2}$, or 0.1% over the 11 year solar cycle (Lean, 1997).

3.2. Rayleigh scattering and gas absorption

The increase in Rayleigh scattering and permanent gas absorption required to substantially reduce $E_{g\downarrow}$ implies a much greater change in the known gaseous composition of the atmosphere than has been reported. Of course the effects of increases in concentrations of new, unidentified and therefore unmonitored gases of anthropogenic origin, which are extremely radiatively active in the solar spectrum, remains a remote possibility.

3.3. Water vapor

The influence of atmospheric water vapor content, measured as column water vapor, CWV, on atmospheric absorption has been quantified by models and regression studies (Ramanathan and Vogelmann, 1997; Arking, 1996). These two approaches give, for a global average of CWV of approximately 25 mm (Garrat et al., 1998), a 1% increase in short-wave absorption for CWV increases of 3 and 6 mm, respectively. Changes in the water vapor content of the atmosphere reported from the global radiosonde network have been reviewed (Houghton et al., 1996). Most of the studies indicate that a small and variable increase has occurred during the last 20 years when comparable and reliable data became available. However, the magnitudes of the increases reported are insufficient to significantly affect τ_w (Ramanathan and Vogelmann, 1997; Wilson and Mitchell, 1987).

3.4. Aerosols and clouds

The effects of changes in the remaining two atmospheric transmissivities, aerosols τ_a, and cloud τ_c, are very difficult to quantify not only because of the difficulty in their measurement but also because of the large variations in their optical properties and distributions both in time and space, and their important interactions. The latter are due to the major role of many anthropogenic aerosols as cloud condensation nuclei which strongly influence the size, longevity and radiative properties of clouds.

3.5. Aerosols

Despite these difficulties recently there have been many attempts to model the direct and even the indirect effects of the increasing concentrations of anthropogenic aerosols on the radiation balance of the atmosphere and it is generally accepted that the negative short-wave forcing of aerosols has to some extent compensated for the positive long-wave radiative forcing caused by the increased concentrations of CO_2 and the other well mixed 'greenhouse' gases which have occurred since the start of the industrial era. This long-wave forcing has been currently assessed at $2.45\,W\,m^{-2}$ (Houghton et al., 1996).

The extent of this compensation is subject to much uncertainty. The IPCC report ‘Climate Change 1995’ estimated the direct cooling effect of anthropogenic sulfate aerosols since the start of the industrial era to be $0.40\,\mathrm{W\,m^{-2}}$ with a twofold uncertainty. The indirect, cloud interaction effect was estimated at between 0 and $-1.5\,\mathrm{W\,m^{-2}}$ (Houghton et al., 1996).

A more recent listing of the many estimates of the size of the direct negative short-wave radiative forcing by anthropogenic sulfate aerosols yields a mean value of $0.44\,\mathrm{W\,m^{-2}}$ with a standard error of $\pm 0.13\,\mathrm{W\,m^{-2}}$ for the nine estimates published during the last decade and a mean value of $1.28 \pm 1.12\,\mathrm{W\,m^{-2}}$ for the 14 estimates of indirect forcing that have been published (Harvey, 2000). As all these estimates represent the total effect of 140 years of emissions the calculated effects of anthropogenic sulfate aerosols account, on a mean annual basis, for less than one-fiftieth of the mean annual reduction in $E_{g\downarrow}$ measured during the last 40 years. An even larger discrepancy is found between Mitchell and Johns’s (1997) estimate of the short-wave cooling effect of increases in anthropogenic sulfate aerosols during the same 1960–1990 period, which they calculated to average $0.0066\,\mathrm{W\,m^{-2}}$ per year, one-hundredth of the measured global decrease in $E_{g\downarrow}$ during the same period (Fig. 2).

On the other hand, Arking (1996) found that model calculations based on daily climate observations underestimate solar energy absorbed by the atmosphere by $25–30\,\mathrm{W\,m^{-2}}$ (10–12%). Based on multiple regression analysis, he attributed this to inadequate modeling of the influence of water vapor on atmospheric absorption. In an alternative attempt to explain this error, Garrat et al. (1998) showed that clear sky models with and without aerosol loading resulted in estimates of direct negative short-wave forcing of $15–20\,\mathrm{W\,m^{-2}}$ (6–8%) over continents and $5–10\,\mathrm{W\,m^{-2}}$ (2–4%) over oceans.

These values are closer to the observed widespread reports of solar dimming. Further research on the history of atmospheric aerosol content, and the dynamics of their loading, transport, and unloading are necessary to determine if this phenomenon can explain the observed decreases in $E_{g\downarrow}$, and to what extent aerosols can be expected to cause additional decreases in surface solar radiation in the future.

Although the current estimates of the effect of increases in aerosol concentrations are not able to fully account for the reductions measured in $E_{g\downarrow}$, the spatial distribution of the reductions is similar, on both a hemispherical and latitudinal scale (Figs. 1 and 2), to that of the industrial activity leading to anthropogenic aerosol production. Also, on a regional scale, the spatial distribution of measured reductions of $E_{g\downarrow}$ in the FSU (Fig. 3) resembles that of industrial activity while in the Arctic Circle (Fig. 5) it follows that of the pollution paths (Stanhill, 1995).

3.6. Cloud transmissivity

The reductions in $E_{g\downarrow}$ reported in the former section are also greater than those attributable to the increases in cloud cover c, that have been observed. Over the last 50–80 years c has increased by approximately 1% per decade over four continental areas whose observational records have been analyzed (Houghton et al., 1990); in contrast a 1–3% per decade decrease in total cloud cover has been reported over much of China (Kaiser, 2000). The uncertainties associated with these cloud cover observations are very large.

The sensitivity of changes in $E_{g\downarrow}$ normalized to E_0, to changes in c, as established from their seasonal correlations at 10 sites (Linacre, 1992; Stanhill and Moreshet, 1992, 1994; Stanhill, 1998b) averages 0.49 ± 0.13, indicating that the reduction in $E_{g\downarrow}$ to be expected over the last 40 years due to a 4% increase in c is only 2%.

A more direct assessment of the sensitivity of long-term changes in $E_{g\downarrow}$ to changes in c is possible for the Arctic. The long-term mean annual increase in mean total cloud cover observed at 20 Arctic sites between 1960 and 1990 was 0.007 tenths, equivalent to a small but statistically significant ($p < 0.05$) annual increase of 0.01% (Przybylak, 1999); using radiation data measured at essentially the same sites the measured annual decrease in $E_{g\downarrow}$ was $0.36\,\mathrm{W\,m^{-2}}$, a very highly significant ($p < 0.0001$) annual decrease of 0.37% per year (Stanhill, 1995). The high solar transmission of Arctic clouds (Gavrilova, 1966) indicates that the observed increase in c cited above was less than one-fiftieth of that required to completely explain the measured reduction in $E_{g\downarrow}$.

It may also be noted that a number of analyses of series of long-term observations of both $E_{g\downarrow}$ and c have shown significant decreases in the former without any significant changes in the latter (Abakumova et al., 1996; Stanhill and Moreshet, 1994; Stanhill and Cohen, 1997; Stanhill and Ianitz, 1997; Stanhill, 1998a).

Significant interactions between inter-annual changes in daytime cloud cover and in $E_{g\downarrow}$ has been reported at three sites. At Bet Dagan, Israel and at Resolute, in the Canadian Arctic, the interactions were positive, reductions in $E_{g\downarrow}$ being above average in years of greater than average cloudiness (Stanhill and Ianitz, 1997; Stanhill and Moreshet, 1994) while at Valentia, Ireland the interaction was negative (Stanhill, 1998b). An explanation could be that changes in the radiative characteristics of the clouds, associated with cloud type (Haurwitz, 1946) and/or aerosol contamination (Hobbs, 1993), accompanied changes in the amount of cloud cover.

The observed total degree of sky cover by cloud is of course a very inadequate as well as very inaccurate measure of the radiative effects of clouds and the possibility cannot be excluded that unanalyzed changes in cloud type and their radiative properties have occurred and that these are responsible for significant changes in $E_{g\downarrow}$.

It has been noted (Changnon, 1981; Stief, 1992; Mims and Travis, 1997) that the marked expansion of air traffic has increased sky cover by high level cirrus clouds evolving from aircraft contrails and this may have led to a reduction in $E_{g\downarrow}$. It has been calculated that such an increase in cirrus cloud cover could have been responsible for an additional cloud radiative forcing of $0.7\,\mathrm{W\,m^{-2}}$ between 1982 and 1991 (Boucher, 1999). If substantiated, this additional, indirect aerosol effect needs to be taken into consideration.

3.7. Conclusions concerning possible causes of global dimming

The above discussion suggests that changes in aerosol loading and cloud cover and their interactions are not only the most probable causes of the contemporary global dimming phenomenon but will also be the most complex and difficult to quantify.

The results of Meyers and Dale's (1983) error analysis confirms this. Even when the aerosol and cloud transmissivities were derived empirically and successively as the remaining terms in Eq. (4) using local radiation and climatological measurements, the uncertainties in estimates of daily values of $E_{g\downarrow}$ in North America averaged 5% under clear sky conditions and double this amount for days with cloud cover (Meyers and Dale, 1983).

This conclusion is also supported by a recent review of atmospheric absorption of solar radiation (Ramanathan and Vogelmann, 1997), in which the combined results of aircraft, satellite and surface measurements were analyzed to show that currently, on a global annual scale, the measured solar absorption by the average cloudy sky exceeds the theoretically calculated value by 8%. The measured annual average value of $E_{g\downarrow}$ at the bottom of the atmosphere is $27\,\mathrm{W\,m^{-2}}$ less than the estimated pre-1990s value. Ramanathan and Vogelmann explain the excess solar scattering and absorption by aerosols and clouds as due to a combination of some five factors neglected in the radiation models used currently in climate studies.

Perhaps coincidentally the reduction of $E_{g\downarrow}$ at the Earth's surface they report is very close to the one presented here on the basis of measurements from the global radiation network.

4. Possible agricultural consequences of global dimming

The definition of agriculture 'as the art of converting solar energy into fuel for consumption by the human machine' (Smith, 1972) recognizes the central role of $E_{g\downarrow}$ in many of the processes of major significance to food and fiber production.

No attempt will be made here to review all of the many solar radiation affected processes listed in the review cited above. Rather the discussion will be confined to a review of the direct solar effects on dry matter production and to a lesser degree, transpiration.

These relationships have been studied in two ways: experimentally with a range of radiation-modifying treatments and statistically from an analysis of data gathered under naturally varying radiation regimes. A very widely used method of integrating and applying this experimental and statistical information is by the use of process-based simulation models.

4.1. Solar radiation and plant processes

The key to plant productivity is photosynthesis, the process by which solar energy is fixed in carbohydrates and their secondary products. Under current conditions, it is generally accepted that the main limitation to leaf photosynthesis at high photon flux density is the concentration of CO_2, but when photon flux densities decreases to approximately 30% of that at full sunlight then photosynthesis becomes light limited (Taiz and Zeiger, 1991). This might suggest that plants would be insensitive to changes in solar radiation at high light, but since plant canopies usually consist of several leaf layers, in which radiation decreases exponentially from layer to layer, low light levels at which photosynthesis is light limited are common in crop canopies. Thus, any decreases in solar radiation might be expected to decrease productivity.

However, the very fact that at different positions and times leaves are subject to high and low light levels has given plants considerable genetic plasticity and a considerable ability to adapt to different light regimes through changes in leaf internal and external properties, as well as canopy structure (for reviews see Bjorkman and Denmig-Adams, 1994; Boardman, 1977). Furthermore, in many places and times plant activity is limited by soil water availability and/or by the plant's ability to transport water to active leaves. Thus when some plants are exposed to high light conditions (i.e. high radiative heat load), leaf conductance to gas exchange decreases. Reductions in radiative heat load can induce increases in leaf conductance and photosynthesis. In general, theoretical and experimental studies indicate that in many climates small decreases in direct radiation, if accompanied by increases in the fraction of diffuse radiation, will cause significant increases in photosynthesis (Healey et al., 1998). These concepts should be kept in mind when considering the studies reviewed in the following sections.

4.2. Simulation modeling

The wide use of process-based models to simulate crop yield and water loss in which $E_{g\downarrow}$ serves as the primary input might suggest that the calculation of the effects of global dimming on agricultural production and water requirements would be a trivial pursuit. For reasons already discussed and those given below this is not so, justifying the use of the precautionary word 'possible' in the title of this section, this caveat also applies to the experimental and statistical approaches to estimating the agricultural consequences of reduced insolation.

The inevitably simplified flow sheet of the processes of yield formation, and of the characteristics influencing them, adopted for crop model simulation, for example by the Wageningen group (van Keulen and Wolf, 1986), of necessity ignores many of the radiation influences listed in Smith (1972). The difficulty of incorporating the complexity of yield formation into a usable model which allows for feedback and interactive effects no doubt explains why, to date, simulation models have demonstrated a very limited ability to account for actual measured inter-annual variations in yield on the basis of measured inter-annual variations in climate. In the absence of a verifiable hypothesis to explain past changes in $E_{g\downarrow}$, as discussed in the previous section, yield simulation models can hardly be expected to provide a reliable basis to estimate the agricultural consequences of future changes in global irradiation.

Field evidence of the limitations of climate-based yield simulation models has been documented by Landau et al. (1998) in their comparison of winter wheat yields measured and simulated at 341 field trial sites in the UK between 1975 and 1993. Their data base of almost 2000 yield measurements and estimates showed neither significant correlation for any of the three widely used and in one case locally developed winter wheat models tested (CERES-WHEAT, AFRCWHEAT2 and SIRIUS), nor did the predictions of yields, other growth variables and yield-limitations due to unfavorable water conditions, simulated by the three models, agree.

The marked divergence in the output from different models given common initialization parameters and climatic conditions was previously demonstrated in a computer experiment with 10 wheat models. Simulated yields varied from 2.5 to 8.0 t ha^{-1} and even the use of a common time course of leaf area development for all models did not resolve these differences (Anonymous, 1995b).

There are other reasons for rejecting the simplistic, positive role allocated to $E_{g\downarrow}$ in crop yield simulation models. One is that non-modeled, indirect effects of $E_{g\downarrow}$ on pest–crop competition and on other climate factors important for crop growth and development may well be as important as the direct effects; another is the general observation that crop yields in glass, plastic or screen-clad houses, or in tree-shaded conditions, all of which substantially *reduce* irradiance, are usually greater than those obtained under fully exposed conditions. This paradox highlights the complexity of $E_{g\downarrow}$–crop relationships as documented in the review of experimental evidence (see Section 4.3).

Limitations in simulation models specifically dealing with the agricultural consequences of global dimming can be seen in a recent study in which the reduction of $E_{g\downarrow}$ caused by air pollution-induced regional haze in China was modeled and served as the input to a linked model which simulated the effect of the estimated reductions in $E_{g\downarrow}$ on yields of the Chinese rice and wheat crops (Chameides et al., 1999).

In the first stage of this study the regional distribution of anthropogenic sulfate aerosols over South East Asia was modeled and the inferred optical depths of the atmosphere were compared with values estimated from 12 years of direct solar beam irradiance measurements from 35 sites in China. The model estimates, significantly smaller than the observed values, were used to calculate the pollution-induced reductions in $E_{g\downarrow}$; these ranged regionally between 5 and 30%. No measured data was presented to validate the modeled reductions in $E_{g\downarrow}$ although an extensive pyranometer network exists in China (Gao and Lu, 1981).

The effect of the simulated reductions in $E_{g\downarrow}$ on yields of rice and winter wheat in China was estimated using the CERES 3.1 Rice and Wheat crop simulation models to derive yield sensitivity to $E_{g\downarrow}$ under the climate conditions measured at Nanjing in the 1970s. Modeled yield sensitivities were calculated to be slightly greater than 1.0 for wheat and approximately 0.7 for rice, resulting in estimates of yield reductions from pollution-induced global dimming which ranged regionally from 5 to 30% for wheat and from 3 to 21% for rice. No attempt to validate these estimates was presented.

Whatever be the accuracy of these simulated yield *reductions* due to regional haze, they are much less than the measured national average yield *increases* reported in the FAO Production Yearbooks. Data reported there shows that over the last 35 years the national wheat yield in China increased linearly ($r = 0.98$, $p < 0.01$) by an annual average of 96 kg ha^{-1}, equivalent to an annual increase of 3.6%. Over the same period the national rice yield increased linearly ($r = 0.97$, $p < 0.01$), by an average of 113 kg ha^{-1} per year, equivalent to an average annual increase of 2.3%. Thus the model-predicted reductions in the Chinese wheat and rice yields due to reductions in global irradiance were of the opposite sign as well as an order of magnitude less than the measured time-trend increases.

This inability of crop simulation models to account for the time-trend yield increases which are common to all but the most primitive agricultural systems, is also evident in the test of UK winter wheat models previously discussed (Landau et al., 1998). The average annual yields from the extensive field trials, tabulated in a subsequent paper (Landau et al., 2000), showed a linear ($r = 0.71$, $p < 0.01$), annual yield increase averaging 98 kg ha^{-1} between 1976 and 1993, equivalent to 1.1% per year, this despite the fact that optimum, uniform, cultivation practices were adopted at all of the field trial sites.

Amthor (1998) has calculated that only an insignificantly small part of the worldwide increase in agricultural crop yields, including those reported here for the wheat crop in the UK and the rice crop in China, can be ascribed to the fertilizing effect of rising atmospheric concentrations of CO_2.

Modeling the effect of changes in $E_{g\downarrow}$ on evaporation from agricultural surfaces without significant surface resistances or advective effects, i.e. under non-water limited conditions, is much simpler than predicting their yield response, as models exist which are based on the well understood physics of the evaporation process, such as Penman's combined radiation balance-aerodynamic equation (Penman, 1948). Not surprisingly under such conditions accurate estimates of water loss to the atmosphere have been obtained.

To estimate the effect of reduced irradiance on transpiration from crop surfaces under water-limiting conditions, data on the conductance through the soil–plant–atmosphere continuum is required as these largely biological control mechanisms are of major importance. As yet such conductances cannot be modeled on a non-empirical basis as the physiological processes involved, for example in stomatal control, are not fully or quantitatively understood.

Global irradiance is one important environmental parameter influencing stomatal opening and closing, as is also the changing CO_2 concentration of the atmosphere. Changes in air temperature will also interact with changes in $E_{g\downarrow}$ by altering the relative importance of the radiation balance term in the combination equation; this increases with air temperature (Penman, 1948).

4.3. Statistical analysis

The many studies published which have statistically related variations in crop yields to those in global radiation and other climatic parameters (Evans, 1993) show these relationships to vary widely with crop and climate. For this reason this brief review has been confined to one well studied crop growing in one region, i.e. wheat in the UK.

The first study linking solar radiation with wheat crop yields was published 200 years ago when the frequency of sunspots was related to the price of wheat in England, taken as an inverse index of yield. During the five periods since 1650 when sunspots were absent, the price of wheat was found to exceed that before or after these periods of reduced solar activity (Herschell, 1801). One hundred and seventy five years later a positive correlation between sunspot number and wheat yield was again reported, this time on the basis of statistics of world wheat production over the two solar cycles between 1949 and 1973 (King et al., 1974).

A more direct but still proxy measure of $E_{g\downarrow}$, the duration of bright sunshine, was related to the long-term series of wheat yields measured at the Broadbalk field plot experiment which started at Rothamsted, southern England in 1852; a positive relationship was found (Tippett, 1926).

Six other statistical studies of the relationship between climate and yield based on results from this same long-term field plot experiment were listed in a recent review. Since the advent of the electronic computer, it has been possible to increase the number of climatic parameters and growth periods included as inputs into multiple regression models of growing complexity. However this has not lead to a corresponding increase in the predictive or explanatory ability of the purely statistical models used. At the Rothamsted site only one-quarter to one-third of the yearly variation in wheat yields have been explained by inter-annual variations in climate (Landau et al., 2000). Only a minor fraction of this climate-related variation could be attributed to variations in $E_{g\downarrow}$.

A similar conclusion that random inter-annual variations in $E_{g\downarrow}$ play a minor role emerges from Monteith's analysis of the effect of climatic variations on the growth of crops (Monteith, 1981). His calculations indicate that the inter-annual variations in $E_{g\downarrow}$ found in the English midlands in individual summer months were responsible for 3% variation in carbon assimilation while, for the three summer months, inter-annual variations resulted in a 1.7% change in dry matter production.

Recently a new 'hybrid' type of statistical model of crop–climate relationship has been reported which incorporates some of the features of process-based simulation models (Landau et al., 2000). In this approach a range of climatic parameters, at the phenological stages known from previous studies to be important for growth and yield determination, are correlated with final yield. Those parameters contributing significantly to the determination of yield are then incorporated in a final model which seeks to combine the minimum number of input parameters with maximum predictive power.

Using the same very large data set previously employed for their test of three wheat simulation models Landau et al. (2000) found that with this 'parsimonious' multiple regression model, climate was able to explain over half ($r = 0.77$) of the mean inter-annual variation in winter wheat yield when tested against an independent data set. This can be compared with the third of the variance explained by a simple empirical statistical model and the less than one-twentieth accounted for by the three simulation models tested (Landau et al., 1998).

In the 'maximum' version of the hybrid statistical model $E_{g\downarrow}$ contributed four of the 23 explanatory variables first selected but only two of the 11 variables finally retained in the 'parsimonious' model. Both of these $E_{g\downarrow}$ effects were positive, however the association of irradiance with yield in the second growth stage (early terminal spikelet to start of ear growth) was less than a hundredth of that in the third stage (start of ear growth to start of grain filling).The sensitivity of final yield to total $E_{g\downarrow}$ measured during the second anthesis stage found ($0.002\,\mathrm{t\,ha^{-1}\,MJ^{-1}\,m^{-2}}$) was considerably less than that previously reported in the literature for this growth stage (Evans, 1993).

A widely employed statistical method relating $E_{g\downarrow}$ to crop dry matter production and yield has used canopy radiation absorption as the determinant of growth (Monteith, 1977; Black and Ong, 2000). This 'light efficiency' approach can also be described as a 'hybrid' statistical model in that radiation absorption combines $E_{g\downarrow}$ with canopy size, structure and optical properties, thus including measures of with determinants of growth. This introduces logical difficulties in the interpretation of such relationships, especially when cumulative values are used (Demetriades-Shah et al., 1992). Ignoring these, statistically high correlations between yields and intercepted radiation have been reported for many crops, including wheat (Evans, 1993) over a wide range of time scales including hourly values (Anderson et al., 2000).

Statistical methods of estimating crop water loss to the atmosphere were at one time very widely used but have now to a large extent been replaced by physically based methods. However at least two simplified forms of the combination equation which only include the radiation term are still in use (Makkink, 1957; Priestley and Taylor, 1972), and in greenhouse practice empirical statistical methods based on $E_{g\downarrow}$ measurements have been widely employed to control, often automatically, irrigation systems (Jolliet, 1999).

Details of these relationships have been given for a number of greenhouse vegetable crops, in England (Morris et al., 1957), in the Netherlands (De Graaf and van den Ende, 1981), and in Turkey (Kirda et al., 1994) as well as for a rose crop in Israel (Stanhill and Scholte Albers, 1974). All show high correlations and linear relationships whose parameters differ between crops, growth stages and sites.

The reason why these empirical radiation-based methods are successful in greenhouses practice is presumably because the low vapor pressure deficits and air movement prevailing in protected cultivation reduce the size of the aerodynamic term in the combination equation, as do the high air temperatures, leaving the radiation term as the dominant factor controlling water loss.

4.4. Experimental studies

Understanding the relationships between solar irradiance and the many processes of importance to agriculture (Smith, 1972) has been derived mainly from experimental studies under controlled environmental conditions.

Technological advances have extended the space and time range which can be investigated and the spectral range and intensities of the radiation to which plants can be subjected; on the finer scale processes can now be studied at the sub-cellular and fraction-of-a-second level with wavelengths controlled to a few nanometers. On the larger scale it is now technically possible to grow whole canopies to maturity under controlled conditions with irradiance intensities and spectral distributions similar to that of extra-terrestrial irradiance although the cost of such solar simulators developed for space studies has so far precluded their use in agricultural research.

In accordance with the aims of this review attention will be confined to the most relevant field studies in which $E_{g\downarrow}$ has been experimentally reduced by moderate shading of the crop, in some cases by coating the foliage with reflectants. Studies which simulated the differences between sun and shade leaves by the use of extreme shading have not been included.

The early shading experiments were part of a program of quantitative analysis of plant growth in which a series of spectrally neutral screens of different transmissivities was used to grow a variety of plant spp. under a range of reduced levels of $E_{g\downarrow}$. These studies showed that light levels affected the two major determinants of the rate of dry matter increase in two different ways: the net assimilation rate (the dry matter increase per unit leaf area per unit time) increased proportionally with the logarithm of light intensity while the leaf area ratio (leaf area per unit leaf dry matter) was inversely proportional to light intensity, thus compensating for the reduction in assimilation rate. The extent of this compensation was found to vary with plant type with most of variation caused by the differences occurring in the leaf area ratio (Blackman and Wilson, 1951).

Of the eight crop species studied by Blackman and Wilson in southern England, five gave their maximum rates of dry matter increase when grown at shade levels which ranged from 0.70 of full daylight (Barley) to 0.95 (Buckwheat). The remaining two crop spps. gave maximum rates of dry matter production at full daylight, although extrapolation of the relationships between light intensity, net assimilation rate and leaf area ratio indicated that the growth rate of pea plants would increase with light intensity up to a level 1.29 of that prevailing in the English mid-summer (approximately 20 MJ m^{-2} per day) and 1.78 for Subterranean clover (Blackman and Wilson, 1951).

In the case of the latter pasture spp. this expectation was confirmed by growth analysis of a full year's dry matter production under the high light conditions prevailing in Southern Australia, approximately $30\,\mathrm{MJ\,m^{-2}}$ per day (Black, 1955). The same author reviewed the results of shading experiments with a wide range of pasture spps. and showed that the majority of these were shade intolerant, in particular the pasture legumes (Black, 1957).

The application of the results of growth analysis studies to agriculture crop production established the importance of the size of crop canopies and their interception of radiation as the major determinant of dry matter production and often crop yield (Watson, 1956), laying the foundations for current thinking in environmental crop physiology in general and the 'light efficiency' approach in particular. Shading experiments at various crop growth stages were used to establish their relative importance to the determination of the final yields of a number of cereal crops. Examples of two such field studies with wheat and rice crops are shown in Fig. 6, which is taken from Evans (1993). For both crops the curves indicate no loss of yield until shading exceeded 20%.

Shading experiments have also been used to examine the sensitivity of crop weed spps. to light. In a study in India two ecotypes of four important crop weeds were subject to five levels of shading (Singh and Gopal, 1970). Many of the weed spps. and ecotypes showed maximum dry matter accumulation when grown under light to moderate shade.

With the expansion of protected cropping, the early crop physiology shading experiments were extended to studies of their agronomic effects under commercial cropping conditions. One example is Sagi's (1979) experiments under the high radiation levels prevalent in Israel in which the effects of four degrees of shading on the development and yields of two tomato cultivars were studied during both the summer and winter cropping seasons; in the winter the levels of shade imposed were 0, 12, 34 and 55% and in the summer 0, 24, 45 and 62%. In both summer and winter, the flower and fruit development and growth of both varieties increased with $E_{g\downarrow}$ up to zero shade; however in all cases maximum fruit yields were achieved at the lowest level of shade and not under full daylight, confirming Blackman and Wilson's earlier results with this crop under the very much lower light levels of southern England.

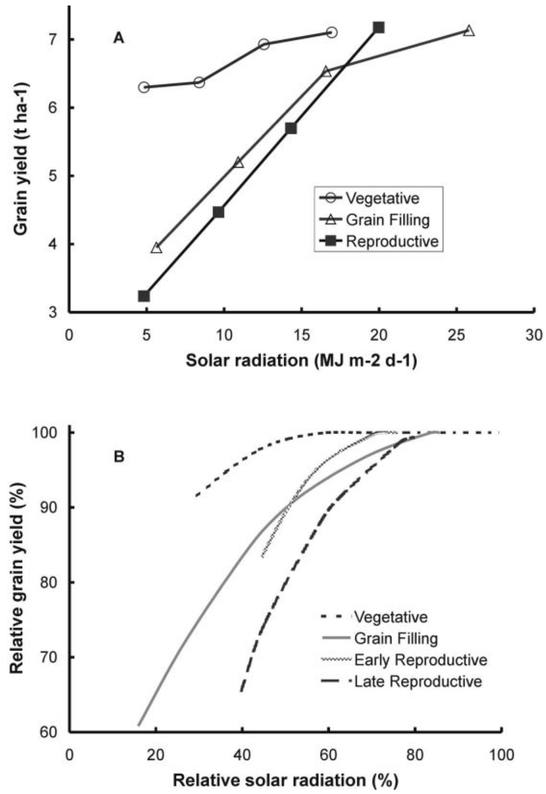

Fig. 6. The effect of solar radiation on grain yields during three successive stages in the development of crops of: (A) rice in the Philippines and (B) wheat in Mexico. From Evans (1993).

The effects of various degrees of shading on three tropical plantation crops were reviewed by Murray and Nichols (1966) who presented experimental evidence that maximum yields for cacao were achieved at shade levels between 50 and 70% full daylight and at 80% for coffee and banana. Similarly, moderate shade was found to have no significant influence on growth of a C_4 grass in the humid tropics (Cruz, 1997), and to increase dry matter yield of two tropical grass species (Healey et al., 1998). Similarly, 20–40% shade, together with the increase in the diffuse component accompanying shading, was found to significantly increase carnation yields in Japan (Yamaguchi et al., 1996).

The effect of natural shading by clouds on the stomatal conductance and CO_2 assimilation rate responses of two tropical fruit trees, Macadamia and Litchi, were studied under the high light climate conditions of tropical northern NSW, Australia. Above a relatively low light threshold both leaf conductance and assimilation were higher under overcast than clear sky conditions (Lloyd et al., 1995).

In a wet, northern climate, the effect of shade on growth of Thuja plicata (red cedar) seedlings was studied along a gradient of shading from a clear cut into a forest (Wang et al., 1994). After quantifying the degree of shading by radiometry, a monotonic decrease in growth was found as the degree of shading increased.

Shading experiments have recently been used to evaluate the relationship between $E_{g\downarrow}$ and tree crop water relations as affected by the expanding practice of protected orchard cropping. Cohen et al. (1997) studied the effects of reflective aluminized nets of two densities suspended for one summer month above a lemon orchard in Israel. They found that during mid-day the radiation balance above the shaded trees was 27, or 53% in the case of the denser shade, below that in the non-shaded treatment, reducing leaf temperatures by 1.6 and 2.7°C, respectively. The shade treatments led to large increases in leaf conductances which almost compensated for the reductions in vapor pressure gradients so that the measured transpiration fluxes in both shade treatments were almost equal to that in the non-shaded trees. Similar results were later reported for shaded grapefruit and murcott tangor trees (Cohen et al., 1999). The above reference also reports increases in rates of photosynthesis measured with these two citrus species in Israel and Florida as a result of shading, suggesting that agronomic benefits could result from the reduction of $E_{g\downarrow}$ under semi-arid conditions.

This possibility was previously explored in a series of field experiments under summer conditions in Israel in which a non-irrigated sorghum row crop was shaded by the direct application of a highly reflecting suspension of kaolin sprayed on the crop canopies. This treatment, applied at the critical pre-panicle emergence stage, significantly increased grain yield by increasing the number of panicles even though the rate of soil water depletion was not affected (Stanhill et al., 1976). Measurements of leaf conductance showed that the reduced radiation absorption did not significantly affect leaf conductance while net photosynthesis was reduced and leaf senescence enhanced (Moreshet et al., 1977). A possible explanation of this result is that earlier senescence may have enhanced translocation of photosynthates to the developing grain so increasing yield despite the reduction in assimilation.

Application of reflectants such as kaolin to the inter-row soil surfaces can also change the radiation regime to which the crop plants are subject. Such a treatment was included in the above experiments where it was found to have little effect on final yield or water loss although it significantly changed the partitioning and balance of solar radiation in the crop canopy (Fuchs et al., 1976).

Other experiments in which increasing inter-row reflectance was found to improve the quantity and especially quality of yield have been reported for glasshouse roses (Stanhill et al., 1975; Stanhill and Moreshet, 1977) and a hedge-row apple orchard (Stanhill et al., 1975).

4.5. Conclusions on possible agricultural consequences of global dimming

The evidence presented in the previous sections indicates that a 10–20% decrease in solar radiation reaching the surface of the earth, if unaccompanied by other climatic changes, would probably have only a minor effect on crop yields and plant productivity.

The experimental studies indicate that where or when crop productivity is limited by water, small decreases in solar radiation, especially if accompanied by increases in the diffuse radiation component, will either have no impact on productivity, or may actually increase it. This moisture limitation will often occur in tropical latitudes and in the arid and semi-arid regions of other latitudes. In wet climates with low radiative heat load on the plants, any decrease in solar radiation is likely to be accompanied by a small decrease in productivity (Wang et al., 1994).

Crop water balance and evapotranspiration, unlike crop productivity, are closely coupled to solar radiation (Monteith, 1965). Therefore, with the exception of situations where decreased solar irradiance increases plant canopy conductance to water vapor, solar radiation decreases are likely to reduce water use and evapotranspiration. It should be noted that a worldwide reduction in open water surface evaporation has been noted in recent years (Peterson et al., 1995).

5. Discussion

Most of the discussion which follows is limited to suggestions as how best to advance the aims of this review, that is promoting awareness of and strengthening the evidence for the contemporary reductions in global irradiance, understanding its causes and, in particular, establishing its agricultural consequences on a sounder and less speculative basis than is presently possible.

5.1. Additional evidence of global dimming

Accurate and continuous thermopile pyranometer measurements began at a number of observatories in Europe, England, Russia and the USA in the first 2 decades of the previous century (Budyko, 1956; Hand, 1937). Analyses of the 1928–1992 measurement series from Wageningen that have been published (De Bruin et al., 1995; Kane, 1997) demonstrate the feasibility of locating and exploiting more of these early, long-term records.

A much larger volume of global radiation data is potentially available from the second half of the century, for example, from the extensive Chinese network (Gao and Lu, 1981). Additionally, the measurements made between 1958 and 1964, i.e. between the end of the IGY and the beginning of data publication in the WMO Bulletin, could be sought and the full 25 years of published data from the Global Radiation Network, not included in this study for reasons of economy, could be analyzed.

The success of attempts to document, critically analyze and make available the much longer and more numerous data sets of average, and more recently, maximum and minimum, surface air temperature and rainfall (Houghton et al., 1996) shows the practical possibility of retrospectively enlarging the $E_{g\downarrow}$ data base given sufficient scientific interest and funding support.

Another major source of information on changes in solar irradiance that could be exploited are the many series of measurements of the duration of bright sunshine made with the Campbell–Stokes sunshine recorder which exist. Introduced in its current form 120 years ago, this obsolescent but still widely used instrument automatically records the duration of direct solar beam irradiance above a threshold of $120\,\mathrm{W\,m^{-2}}$ (WMO, 1997). Sunshine duration measurements made with this instrument are the most highly and linearly correlated with $E_{g\downarrow}$ of the widely available and used proxy measurements (Stanhill, 1965; Barr et al., 1996). However the parameters of this relationship vary according to the site and the time period correlated (Martinez et al., 1984). As is to be expected even higher and less spatially variable correlations have been demonstrated between the number of hours of bright sunshine and direct solar beam irradiance (Stanhill, 1998a).

The dozen century-long series of European sunshine measurements which have been published to date show varying results. Of the three series which have been statistically analyzed, variable but overall significant decreases were reported at both Pheonix Park, Dublin and at the Astronomical Observatory, Cracow (Stanhill, 1998b; Morawska-Horawska, 1985). The long-term series from Kew Observatory, a suburb of London, also shows much variation but no clear long-term trend (Hatch, 1981). In all three cases, urbanization, industrialization and air pollution were suggested as important factors causing decreases in sunshine duration.

To provide better evidence for global changes in $E_{g\downarrow}$ in the future it would be highly desirable to correct the currently very uneven distribution of the World Radiation Network as shown in Table 1. The paucity of thermopile pyranometer data from oceanic areas and from the land surfaces of Africa, Central and Southern America, China and the USA tabulated there is partly due to the difficulty of access to existing but unpublished measurements. This is almost certainly the case with respect to the last two regions; thus in China a national network of 77 solar radiation stations has been mapped (Gao and Lu, 1981), while in the USA the national network currently consists of 14 sites measuring $E_{g\downarrow}$ (Hicks et al., 1996), the same number as 60 years ago (Hand, 1937). The data obtained from these two national networks is not routinely published, neither is that from the four overseas USA national observatories, nor that from the 100 permanent automatic weather stations in the USA and Canada which were reported as routinely measuring solar radiation (Snyder et al., 1996).

The difficulty of access to $E_{g\downarrow}$ measurements is, as with other climatic data, partly due to economic reasons. Increasingly routine publication of validated climatic data in widely available monthly and annual bulletins is being discontinued on grounds of economy and the data is now only available electronically, often at a cost which restricts its use to large and well funded research projects. Another advantage of the classical method of data publication is that information on calibration procedures and results, and instrument and site changes were often routinely included with the data.

5.2. Causes of reductions in global irradiance

Research into the most probable cause of global dimming — indirect aerosol effects — is currently an active topic in climate change research; in part due to the need to explain the overestimation of global warming by the earlier models which did not include negative short-wave radiative forcing by aerosols (Houghton et al., 1996). The current research effort to reconcile the large differences between the measured and modeled radiation balance of the Earth's atmosphere and establish the role of clouds in the Earth's radiation balance is also very relevant to global dimming (Ramanathan and Vogelmann, 1997).

While further expansion of this research may not be necessary its success in quantitatively explaining reductions in $E_{g\downarrow}$ of the magnitude documented in this review would almost certainly lead to the recognition of solar radiation change as a legitimate topic for climate change research and in particular help promote the study of its agricultural consequences.

5.3. Probable agricultural consequences of global dimming

The case for modifying the current emphasis on the use of the simulation and statistical modeling approach and encouraging experimental studies under field conditions, made in the previous section, is not intended to suggest that that there is neither place for model studies nor that the results of earlier shade experiments can be used to reliably predict the effects of global dimming on agricultural production systems under current field conditions.

Such predictions will require a series of experiments under quasi-commercial conditions in which replicate plots are subject to shading by a range of occulting screens of different transmissivities, preferably in combination with treatments involving other climatic variables, in particular water supply. Such studies would be comparable to the FACE (Free-air CO_2 Enrichment) program of elaborate and large scale field experiments in which a number of crop and forest surfaces have been exposed to different levels of carbon dioxide concentrations throughout their growing seasons and their responses studied at both the physiological process and final yield and total water loss level (Dugas and Pinter, 1994).

The results of a comparable research program should allow realistic simulation of the effects of global dimming on agricultural production. In its absence the limited experimental evidence currently available suggests that the direct effect of reduced $E_{g\downarrow}$ on agricultural production may well be less than the proportional reduction suggested by simulation modeling. In seasons and regions of high insolation and restricted precipitation, where the major reductions in $E_{g\downarrow}$ have been found (Fig. 2), the effects of global dimming on crop production could even in some cases be positive due to the reduction of water stress and photo-inhibition of the photosynthetic system.

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Appendix A

Published analyses of thermoelectric pyranometer measurement series of more than 20 years duration showing no significant time trends are given in Refs. De Bruin et al. (1995), von Dirmhirm et al. (1992), Russak (1990), Stanhill and Kalma (1994), Stanhill and Moreshet (1994) and Stanhill (1998b).

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