INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **25**: 295–318 (2005)
Published online 11 February 2005 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.1134

SOLAR RADIATION CLIMATE CHANGE OVER SOUTHERN AFRICA AND AN ASSESSMENT OF THE RADIATIVE IMPACT OF VOLCANIC ERUPTIONS

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Received 17 December 2003
Revised 25 October 2004
Accepted 25 October 2004

ABSTRACT

Spatial and temporal variability in global, diffuse, and horizontal direct irradiance and sunshine duration has been evaluated at eight stations in South Africa and two stations in Namibia where the time series range between 21 and 41 years. Global and direct irradiance and sunshine duration decrease from northwest to southeast; diffuse irradiance increases toward the east. Annually averaged global irradiance G_a decreased between 1.3% (2.8 W m^{-2}) and 1.7% (4.4 W m^{-2}) per decade at Bloemfontein, Cape Town, Durban, Pretoria, and Upington. Annually averaged diffuse irradiance D_a decreased 5.2% (3.0 W m^{-2}) per decade at Grootfontein and 4.2% (3.1 W m^{-2}) per decade at Port Elizabeth. Annual direct irradiance B_a decreased 2.1% (3.5 W m^{-2}) per decade at Cape Town and 2.8% (5.7 W m^{-2}) per decade at Alexander Bay. A simultaneous decrease in annually averaged daily sunshine duration S_a may have contributed to the decrease in B_a at Alexander Bay and the decrease in G_a at Pretoria. Increases in aerosols may have contributed to the observed decrease in G_a at Cape Town and Durban, and the decrease in D_a at Grootfontein may be due to a decrease in aerosols. On average, variability in S_a explains 89.0%, 50.4%, and 89.5% of the variance in G_a, D_a, and B_a respectively. The radiative response to changes in sunshine duration is greater for direct irradiance than for global and diffuse. In the 2 years following the 1963 Mount Agung eruption in Indonesia, changes in global irradiance over southern Africa were small and inconsistent. At eight stations, diffuse irradiance increased 21.9% (13.3 W m^{-2}) on average and direct irradiance decreased 8.7% (15.5 W m^{-2}). After the 1982 El Chichón eruption in Mexico, global irradiance increased at two stations and decreased at seven stations. Eight stations witnessed an increase in diffuse irradiance averaging 7.2% (4.0 W m^{-2}) and a decrease in direct irradiance of 5.0% (9.0 W m^{-2}). The contribution of changes in cloud cover to the observed changes in irradiances appears to be small. Following the 1991 Mount Pinatubo eruption in the Philippines, diffuse irradiance increased an average of 18.8% (10.0 W m^{-2}) at three stations and direct irradiance decreased by 7.2% (13.0 W m^{-2}). Copyright © 2005 Royal Meteorological Society.

KEY WORDS: solar radiation; climate change; volcanic; volcano; southern Africa; South Africa; Namibia

1. INTRODUCTION

Understanding the range of variability of past climates is critical in order to understand the climate system and to reduce our uncertainty regarding future climate change (Moore *et al*., 2001). Evaluating and understanding past climate change is also a primary goal of the United States Climate Change Science Program (Moss *et al*., 2003).

Solar radiation is the principal source of energy for the climate system. Variability in the amount of energy received at the surface of the Earth, therefore, has implications for climate change at global, regional, and local scales, as well as for water resources, agriculture, architectural design, and solar thermal devices.

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Previous analyses of solar radiation trends and variability are not optimally distributed in space, in that most studies have evaluated Northern Hemisphere radiation observations. These include stations in the Arctic (Stanhill and Moreshet, 1994; Stanhill, 1995), China (Stanhill and Cohen, 2001), Egypt (Omran, 2000), Finland (Russak, 1990), Germany (Grabbe and Grassl, 1994; Liepert *et al*., 1994; Stanhill and Moreshet, 1994; Liepert, 1997; Liepert and Kukla, 1997; Power, 2003), Hong Kong (Stanhill and Kalma, 1995), Ireland (Stanhill, 1998), Japan (Stanhill and Moreshet, 1994), Israel (Stanhill and Moreshet, 1992; Stanhill and Ianetz, 1997), Sweden (Russak, 1990), the former Soviet Union (Russak, 1990; Stanhill and Moreshet, 1994; Abakumova *et al*., 1996; Liepert, 2002), the United Kingdom (Stanhill and Moreshet, 1994; Stanhill, 1998), and the United States (Liepert, 2002). In comparison, Southern Hemisphere radiation studies are limited to stations in Antarctica (Dutton *et al*., 1991; Stanhill and Moreshet, 1992, 1994; Stanhill and Cohen, 1997), Australia (Stanhill and Kalma, 1994), Kenya (Stanhill and Moreshet, 1992), Namibia (Stanhill and Moreshet, 1994), New Zealand (Stanhill and Moreshet, 1992), and South Africa (Stanhill and Moreshet, 1992). Moreover, it appears that all of the Southern Hemisphere studies (and the majority of the Northern Hemisphere analyses) have evaluated trends and variability in global radiation only; very few studies have assessed variability in the diffuse and direct (beam) components of solar radiation. The geographic bias, coupled with the global radiation constraint, has led to uncertainties regarding the variability of solar radiation — and, therefore, climate change — over the southern half of the globe.

Besides astronomical considerations, one of the key factors influencing solar radiation fluxes, especially under clear-sky conditions, is the aerosol content of the atmosphere. Aerosols originate from both anthropogenic and natural emissions, both of which vary over space and time. The concentration of aerosols in the stratosphere is dramatically enhanced following major volcanic eruptions. Sulphurous gases emitted by volcanoes convert to sulphate aerosols and these can remain in the stratosphere for several years (e.g. Herber *et al*., 1996; Nagel *et al*, 1998; Niranjan *et al*., 1999; Remer *et al*., 1999; Michalsky *et al*., 2001). Their net effect is to increase the planetary albedo and thereby reduce the amount of solar radiation that reaches the Earth's surface (e.g. Dutton and Christy, 1992; Dutton *et al*., 1994; Alados-Arboledas *et al*., 1997; Olmo *et al*., 1999; Robock, 2000).

Our ability to predict the climatic response to future volcanic eruptions relies on evaluating the radiative response to past eruptions. Notwithstanding, of those studies that evaluated radiation variability in the Southern Hemisphere, it appears that none has investigated the radiative impact of volcanic eruptions. This is in spite of the fact that one of the largest eruptions of the 20th century took place in the Southern Hemisphere, in Indonesia.

In light of the above, the objectives of this research were to evaluate trends and variability in global, diffuse, and direct radiation at Southern Hemisphere locations and to document the impact of major volcanic eruptions on the radiation regime. Accordingly, this paper evaluates radiation data from 10 stations in southern Africa over the period 1957–97. Coincident observations of bright sunshine duration (defined as the number of hours per day that the sunshine intensity exceeds some predetermined threshold of brightness) were also examined to determine the extent to which variability in radiation could be attributed to changes in sunshine duration.

2. DATA

The South African Weather Bureau (SAWB) provided monthly averaged global and diffuse irradiation and bright sunshine duration data for eight stations in South Africa and two stations in Namibia (Table I, Figure 1). Four of the stations are coastal; the remaining six are inland at elevations above 800 m.

South Africa occupies the southernmost region of the African continent, with the Atlantic Ocean to the west and the Indian Ocean to the east. South Africa enjoys fairly mild climates in the coastal lowlands, including humid subtropical, marine west coast, and Mediterranean. In the western interior and in the north of the country the desert and steppe climates are relatively hot and dry.

Namibia, formerly known as South West Africa, is located on the Atlantic Ocean and is bordered by South Africa to the south, Botswana to the east, and Angola to the north. The climate in Namibia is hot and dry. In the coastal region the climate is characterized as desert; inland the climate is steppe.

Table I. Latitude, longitude, elevation, and period and length of record for each of the 10 climate stations in South Africa and Namibia for which trend analyses of radiation and bright sunshine duration were performed

	Lat. (°S)	Lon. (°E)	Elevation (m)	Period	Length (years)
South Africa					
Alexander Bay	28.57	16.53	21	1958–83	26
Bloemfontein	29.10	26.30	1351	1957–91	35
Cape Town	33.97	18.60	44	1958–94	37
Durban	29.96	30.95	8	1957–90	34
Grootfontein	31.48	25.03	1270	1969–89	21
Port Elizabeth	33.98	25.60	60	1958–89	32
Pretoria	25.73	28.18	1330	1957–97	41
Upington	28.40	21.27	836	1965–92	28
Namibia					
Keetmanshoop	26.57	18.12	1066	1957–82	26
Windhoek	22.57	17.10	1725	1957–83	27

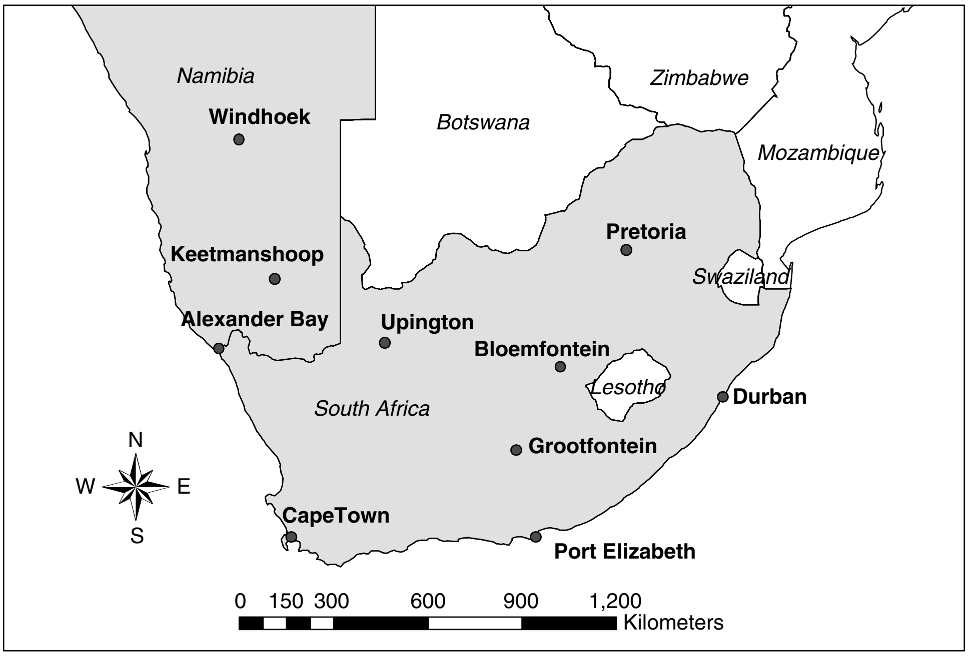

Figure 1. Location of the 10 climate stations in Namibia and South Africa

The appeal of the South African and Namibian network is the relatively high station density, the availability of coincident high-quality measurements of radiation and sunshine duration, the variability in climates, the temporal extent of the records, and the standardized instrumentation and calibration procedures adopted by the SAWB. Although Stanhill and Moreshet (1992, 1994) evaluated radiation observations for these two countries, the earlier study was restricted to global radiation for just five stations in South Africa for four discrete and nonconsecutive years; the later study was restricted to global observations from one station in Namibia, and neither study evaluated volcanic impacts on the radiation climatology.

The SAWB measured global and diffuse irradiance with Kipp and Zonen pyranometers, and Campbell–Stokes sunshine recorders were used to measure bright sunshine duration (the threshold irradiance for the Campbell–Stokes sunshine recorder is 120 W m^{-2}). For all 10 stations, the monthly averaged daily direct irradiance on a horizontal surface B_m was calculated as the difference between monthly averaged daily global irradiance G_m and monthly averaged daily diffuse irradiance D_m. Appropriate shadowband correction factors were applied to the Kipp and Zonen diffuse radiation data and the uncertainty associated with both G_m and D_m is estimated to be less than 2% (Esterhuyse, personal communication, 2000). The Campbell–Stokes sunshine recorders have an expected root-mean-square error of approximately 4.1% of the monthly percentage of possible sunshine (Benson *et al*., 1984).

The periods for which coincident observations of all three variables, i.e. global, diffuse, and sunshine duration, were available range between 21 and 41 years, and the average period of record is 31 years (Table I). Most of the time series begin in the 1950s and end in the late 1980s or early 1990s, when the Kipp and Zonen pyranometers were replaced with Li-Cor pyranometers. The Li-Cor observations were not considered to be of research quality (Esterhuyse, personal communication, 2000) and were, therefore, excluded from the analysis.

3. SPATIAL AND TEMPORAL VARIABILITY IN RADIATION AND SUNSHINE DURATION

In order to examine spatial variability in irradiance and sunshine duration, long-term means were calculated from the respective time series available for each station and for the period for which observations were available at all stations, namely 1969–82. Using the 'common window' sets of data, surfaces of irradiance and sunshine duration were then created using the 10 sample data points and an ordinary kriging procedure. These surfaces were then examined to identify spatial trends across the study region.

A least-squares regression was employed to evaluate long-term trends in radiation and sunshine duration using the full time series at each station. A t-test with a significance level of 95% was used to determine whether the slope of the fit was significantly different from zero. Regression analyses were performed on two sets of data: annual averages of the monthly averaged data, and discrete monthly averages. Annual averages were used to avoid autocorrelation inherent in monthly climate data, and the discrete monthly data were evaluated to determine whether there were significant long-term trends in any particular month or season. Where the trends were statistically significant, decadal trends were calculated in physical units and as a percentage change relative to the first modelled value, i.e.

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

and

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

where n is the number of years in the time series, $y(n)$ is the modelled value (for a given climate variable) for the nth year, and $y(1)$ is the modelled value for the first year in the time series.

3.1. Global irradiance

Statistical summaries and linear trend analyses of annually averaged global irradiance G_a for South Africa and Namibia are provided in Table II. Averaged across all 10 stations for all years, the long-term mean annual global irradiance is 234.5 W m^{-2}. Long-term means of G_a range between 186.9 W m^{-2}, in Durban, and 278.0 W m^{-2}, in Keetmanshoop. Figure 2 illustrates a broad northwest–southeast spatial trend in global irradiance, with the lowest values in the southeast and highest values in the northwest of the region. The likely causal mechanisms behind this spatial trend are discussed further in Section 3.4. The mean standard deviation in G_a across all stations is 9.1 W m^{-2}. Port Elizabeth exhibits the lowest interannual variability, with a standard deviation in G_a of 5.6 W m^{-2}; Grootfontein has the most variability, with a standard deviation of 10.1 W m^{-2}. This is in spite of the fact that Grootfontein has the shortest time series of 21 years.

Annually averaged global irradiance has decreased at eight stations and increased at two stations over the respective time series. Averaged across all stations, the mean trend is a statistically significant decrease

Table II. Summary statistics and trend analyses of annual averages of global irradiance G_a for 10 stations in South Africa and Namibia. Stations with significant trends ($p \leq 0.05$) are shown in bold

Station	Long-term annual mean (W m^{-2})	Standard deviation of annual mean (W m^{-2})	Trend (W m^{-2} per decade)	Trend (% per decade)	Significance level (%)
Alexander Bay	254.6	6.9	-0.6 ± 3.8	−0.2	23.4
Bloemfontein	246.6	9.5	$\mathbf{-4.4 \pm 2.8}$	**−1.7**	**99.7**
Cape Town	221.1	6.4	$\mathbf{-2.8 \pm 1.8}$	**−1.3**	**99.7**
Durban	186.9	7.6	$\mathbf{-2.6 \pm 2.5}$	**−1.4**	**96.0**
Grootfontein	243.2	10.1	0.4 ± 7.3	0.2	8.6
Port Elizabeth	208.2	5.6	-1.5 ± 2.1	−0.7	85.0
Pretoria	229.8	7.4	$\mathbf{-3.3 \pm 1.6}$	−1.4	**100.0**
Upington	259.8	8.0	$\mathbf{-4.0 \pm 3.4}$	−1.5	**97.7**
Keetmanshoop	278.0	8.0	1.7 ± 4.1	0.6	59.9
Windhoek	268.2	8.0	-3.4 ± 3.7	−1.2	92.2
Mean	234.5	9.1	$\mathbf{-5.4 \pm 1.6}$	**−2.2**	**100.0**

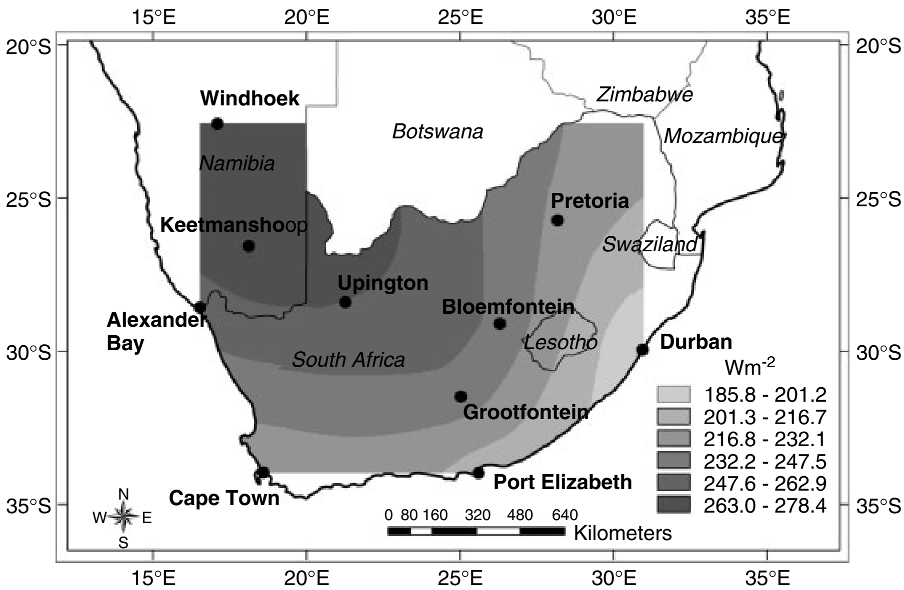

Figure 2. Surface of annually averaged global irradiance for Namibia and South Africa for the period 1969–82 created using ordinary kriging

of 2.2% (5.4 W m^{-2}) per decade. Statistically significant trends are evident at five stations (Table II). At Bloemfontein, Cape Town, Durban, Pretoria, and Upington, G_a has decreased between 1.3% (2.8 W m^{-2}) and 1.7% (4.4 W m^{-2}) per decade. There does not appear to be any spatial homogeneity to the decreasing temporal trends in annually averaged global irradiance. The decreases at Bloemfontein and Cape Town are consistent with trends reported by Stanhill and Moreshet (1992), although, not surprisingly, the magnitudes of the trends differ, since Stanhill and Moreshet reported trends over the years 1958, 1965, 1975, and 1985. In the present study, continuous time series were evaluated and for longer periods (see Table I).

Table III summarizes the long-term statistics and trend analyses for monthly averaged global irradiance at each station. Bloemfontein, Cape Town, Durban, Pretoria, Upington, and Windhoek show statistically significant long-term trends in G_m for at least 1 month of the year. Across these six stations there were 18

Table III. Long-term mean, standard deviation (SD), and trend analyses for monthly averaged daily global irradiance G_m at each of the 10 climate stations in South Africa and Namibia. Statistics and trends calculated for the length of each respective time series (see Table I)

Station[a]	Variable[b]	Jan	Feb	May	Apr	Mar	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AB	Mean	349.7	315.9	270.1	212.1	172.2	148.1	157.2	194.0	243.3	293.2	341.0	351.4
	SD	15.6	13.4	9.9	8.3	9.0	7.0	7.0	7.8	16.3	10.4	10.4	10.7
	Trend	7.0	−3.1	−2.5	0.1	3.3	0.6	1.4	1.5	−5.8	−3.3	−2.6	−0.4
BL	Mean	317.8	287.1	249.2	208.1	176.3	156.2	168.9	206.1	247.4	286.1	321.1	334.7
	SD	27.6	32.5	20.7	13.8	8.5	9.3	9.0	13.5	18.8	22.5	20.8	22.7
	Trend	−3.3	**−13.0**	−5.1	−3.8	−1.5	−1.7	−1.0	**−4.8**	**−6.4**	−6.2	−2.6	−3.0
CT	Mean	335.1	301.7	247.0	173.6	122.5	100.9	111.1	145.1	197.2	262.2	319.0	338.2
	SD	14.0	12.2	11.6	13.7	11.5	10.7	11.3	11.1	14.7	12.3	17.1	19.2
	Trend	−2.4	−1.9	**−4.9**	**−4.6**	−2.6	**−3.6**	**−5.5**	−1.1	**−5.1**	0.6	−2.3	**−5.9**
DN	Mean	238.6	231.9	206.6	170.4	140.3	126.8	133.1	154.7	173.6	201.0	224.4	246.6
	SD	16.7	17.6	17.1	8.9	7.2	8.1	7.3	14.3	16.9	17.8	21.0	19.8
	Trend	−2.9	−3.0	−5.8	0.3	−0.9	**−3.6**	−1.2	−4.5	−2.7	−2.1	3.2	−2.9
GR	Mean	339.2	285.6	245.3	198.7	158.7	143.0	154.5	192.9	238.5	285.5	331.4	349.5
	SD	23.9	28.6	22.7	11.3	13.4	5.3	9.4	14.1	21.7	19.4	22.8	27.0
	Trend	9.4	3.9	7.1	−1.8	7.6	−0.8	1.1	−2.6	−0.3	−3.4	−4.3	4.8
PE	Mean	294.8	265.1	216.9	169.8	131.4	113.7	123.2	154.1	194.4	243.9	283.6	309.4
	SD	14.7	13.2	11.9	9.5	7.6	7.2	6.9	8.2	15.7	17.7	14.5	15.0
	Trend	1.1	−4.3	−0.1	−0.5	0.9	−0.7	−0.5	−1.1	−2.1	−0.1	−4.9	−4.9
PR	Mean	276.1	259.8	233.2	202.4	181.3	165.4	174.6	206.4	240.5	260.2	271.3	285.9
	SD	22.7	24.9	22.7	16.4	9.5	7.1	7.8	11.4	20.6	17.9	19.3	18.5
	Trend	−4.3	**−7.1**	**−6.0**	1.3	−1.6	0.1	−0.7	**−3.7**	−4.4	**−5.8**	−4.2	−2.4
UP	Mean	346.6	309.2	264.8	217.6	180.6	158.8	170.3	208.2	253.7	303.5	345.0	353.7
	SD	24.2	21.8	12.6	12.5	5.8	6.3	7.0	10.0	12.3	15.4	15.0	22.2
	Trend	0.9	−7.6	−1.2	−1.8	−0.4	−2.2	−3.0	−4.3	**−5.5**	−3.2	**−8.1**	−2.3
KM	Mean	357.7	321.9	281.3	245.5	204.2	181.8	192.2	230.6	275.6	322.5	360.9	374.2
	SD	24.6	20.5	14.2	10.5	7.3	6.8	7.1	8.5	9.7	14.9	18.6	15.6
	Trend	2.6	−2.8	2.7	−2.7	−0.9	1.6	1.1	1.8	1.3	2.9	8.2	5.4
WH	Mean	303.9	284.4	261.9	243.9	221.6	203.1	213.7	246.0	281.3	310.7	322.0	329.4
	SD	27.3	25.6	21.2	14.7	8.6	7.6	7.6	9.7	11.9	18.8	24.8	22.4
	Trend	−6.6	−8.8	−0.5	−6.9	**−4.4**	**−5.5**	−2.4	−3.7	−5.2	−3.6	6.2	−7.2

[a] AB = Alexander Bay; BL = Bloemfontein; CT = Cape Town; DN = Durban; GR = Grootfontein; PE = Port Elizabeth; PR = Pretoria; UP = Upington; KM = Keetmanshoop; WH = Windhoek.
[b] Mean and SD units W m^{-2}; trend units are W m^{-2} per decade. Trends shown in bold are significant at $p < 0.05$.

significant long-term trends in G_m, all of which were negative. Decreases in G_m range between 3.6 W m^{-2} per decade (at Durban in June) and 13.0 W m^{-2} per decade (at Bloemfontein in February) and occurred in all months except January at at least one of the six stations. All of the five stations that had significant long-term trends in G_a also had long-term trends in G_m for at least 1 month of the year. Windhoek showed significant decreases in G_m for May and June but did not show significant trends in G_a.

3.2. *Diffuse irradiance*

Long-term averages of annual mean diffuse irradiance D_a range between 50.2 W m^{-2}, in Upington, and 69.9 W m^{-2}, in Durban (Table IV). Thus, Durban had the lowest annually averaged global irradiance but the highest diffuse irradiance. The mean annual diffuse irradiance averaged across all stations is 61.8 W m^{-2}, with a mean standard deviation of 4.9 W m^{-2}. Alexander Bay has the least variability in D_a, with a standard deviation of just 3.1 W m^{-2}, whereas Windhoek has the largest standard deviation in D_a of 7.0 W m^{-2}. The

Table IV. As Table II, but for annual averages of diffuse irradiance D_a

Station	Long-term annual mean (W m^{-2})	Standard deviation of annual mean (W m^{-2})	Trend (W m^{-2} per decade)	Trend (% per decade)	Significance level (%)
Alexander Bay	61.2	3.1	1.8 ± 1.8	3.1	94.3
Bloemfontein	59.6	4.9	-1.5 ± 1.6	−2.4	93.9
Cape Town	61.4	4.2	0.2 ± 1.4	0.4	26.1
Durban	69.9	4.0	0.4 ± 1.5	0.6	39.5
Grootfontein	54.5	3.8	$\mathbf{-3.0 \pm 2.4}$	**−5.2**	**98.3**
Port Elizabeth	68.6	6.4	$\mathbf{-3.1 \pm 2.5}$	**−4.2**	**98.1**
Pretoria	68.1	5.5	-1.1 ± 1.4	−1.6	89.2
Upington	50.2	3.5	-0.8 ± 1.6	−1.6	70.2
Keetmanshoop	50.6	6.5	0.3 ± 3.4	0.5	12.8
Windhoek	61.0	7.0	-0.5 ± 3.4	−0.9	24.3
Mean	61.8	4.9	0.0	0.0	0.9

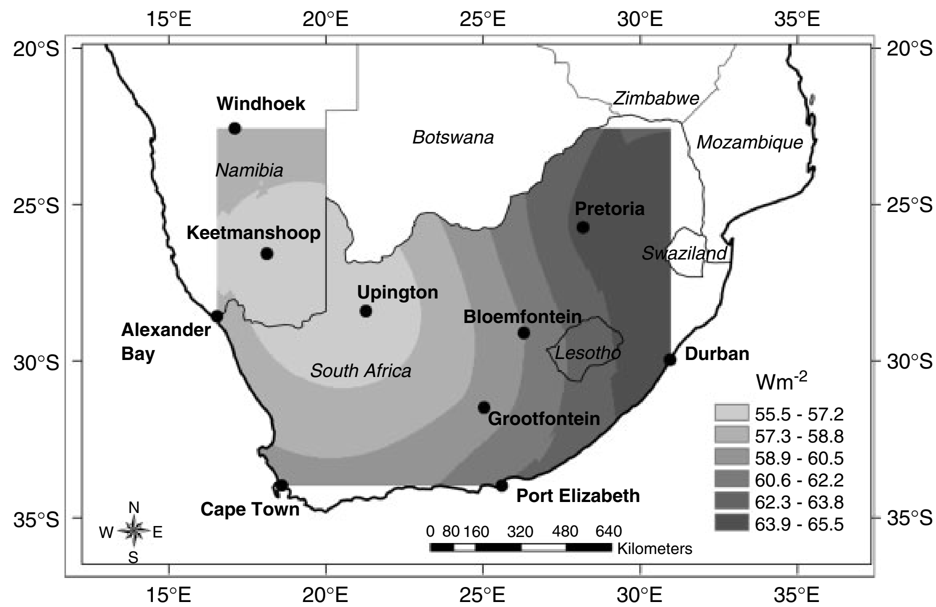

Figure 3. As Figure 2, but for annually averaged diffuse irradiance

highest values of diffuse are at Pretoria and the four coastal locations, and the lowest values are in Namibia and the remaining three inland locations. In general, diffuse irradiance is highest in the eastern part of the study area (Figure 3).

Annually averaged diffuse irradiance decreased at six stations and increased at four stations. Significant trends, however, are evident at just two stations: diffuse irradiance decreased 5.2% (3.0 W m^{-2}) per decade at Grootfontein and decreased 4.2% (3.1 W m^{-2}) per decade at Port Elizabeth. Thus, none of the five stations that had significant trends in annual global irradiance had significant trends in annual diffuse. There is no trend in D_a when the data are pooled from all stations.

Summary statistics and trend analyses for monthly averaged diffuse irradiance are presented in Table V. Six stations had statistically significant trends in D_m for at least 1 month of the year and there were 14 significant trends in D_m across these six stations. Decreases in D_m were evident at Bloemfontein, Grootfontein, Port Elizabeth, Pretoria, and Windhoek, with the trends ranging between 1.8 W m^{-2} per decade (at Port Elizabeth

Table V. As Table III, but for monthly averaged daily diffuse irradiance D_m

Station	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AB	Mean	76.3	71.7	61.7	50.3	42.4	39.3	42.0	52.2	67.1	76.4	77.4	80.9
	SD	8.7	8.4	6.4	5.1	4.9	5.2	4.6	6.3	8.5	8.0	7.9	5.8
	Trend	−1.5	4.4	**4.0**	−0.1	−2.1	0.8	0.6	1.6	**5.8**	1.1	3.7	1.5
BL	Mean	85.0	78.1	67.0	49.9	36.4	31.2	32.7	40.9	59.6	73.8	79.1	81.1
	SD	13.7	12.7	10.7	6.5	5.9	5.7	6.0	7.5	8.1	12.4	11.3	10.9
	Trend	−1.5	1.0	−2.9	−0.6	**−3.0**	**−2.3**	**−2.2**	−1.6	−0.3	−1.2	−0.8	−2.5
CT	Mean	76.7	67.3	57.2	50.0	42.5	36.1	38.3	50.0	67.1	78.4	83.9	83.3
	SD	9.4	8.9	7.0	6.1	5.4	3.9	3.9	5.1	8.0	8.5	9.9	10.7
	Trend	−0.3	−0.8	0.0	−0.3	−0.3	−0.9	0.3	0.2	0.5	−0.9	1.4	2.2
DN	Mean	103.0	90.2	74.5	54.7	41.3	34.5	38.6	50.4	68.5	85.3	98.6	105.1
	SD	8.6	9.2	7.5	5.8	4.3	4.4	4.6	4.7	5.5	6.7	7.6	9.1
	Trend	0.3	3.0	0.7	−0.2	0.6	0.2	0.5	0.8	0.5	−1.5	0.5	3.0
GR	Mean	72.9	72.0	59.3	46.7	35.1	29.8	30.7	39.0	58.9	67.9	73.8	69.4
	SD	12.4	14.5	7.0	6.8	6.1	2.6	3.9	4.0	6.6	9.6	10.4	8.7
	Trend	−6.5	−5.0	−4.0	−3.5	−2.1	−0.9	−1.5	1.2	−1.3	−0.7	0.5	**−7.7**
PE	Mean	98.8	87.5	70.3	52.8	39.6	33.2	35.8	47.8	70.6	87.9	101.9	100.4
	SD	14.1	11.3	9.1	5.9	4.3	4.4	4.9	5.9	8.0	10.5	9.9	8.7
	Trend	−3.7	−1.9	−3.1	**−3.2**	**−1.8**	**−2.0**	−1.6	−1.1	−3.0	**−5.2**	**−4.2**	**−3.8**
PR	Mean	101.8	94.1	78.8	57.3	40.3	35.4	37.4	45.9	60.8	76.5	91.8	98.3
	SD	12.4	13.2	10.2	10.1	6.2	5.3	5.5	6.0	8.2	11.9	11.5	12.3
	Trend	−1.9	−0.5	−1.1	−1.0	−0.3	−1.3	−1.2	−0.3	0.1	0.4	**−3.2**	−2.5
UP	Mean	61.7	63.5	56.2	45.7	33.1	30.8	30.7	40.5	53.1	64.6	62.0	59.4
	SD	13.8	11.7	7.8	6.5	6.5	4.8	4.3	5.8	8.3	7.2	9.9	9.8
	Trend	−5.8	−0.1	−2.9	−0.5	−1.5	−0.6	−0.4	0.2	−1.6	0.8	4.2	−3.0
KM	Mean	66.9	66.8	56.1	40.1	33.8	31.4	32.7	40.5	55.0	61.6	60.2	60.8
	SD	13.7	12.8	8.2	7.1	5.8	6.2	6.4	9.5	12.1	10.0	11.0	10.9
	Trend	−0.6	2.0	0.3	0.6	−0.7	−1.3	−0.4	1.3	3.3	−0.9	−3.4	−2.5
WH	Mean	92.9	86.9	77.1	51.6	32.3	28.9	29.3	40.2	57.3	70.2	78.6	79.6
	SD	12.7	11.5	11.1	9.5	6.0	5.8	7.5	8.4	10.7	12.2	13.4	11.3
	Trend	1.3	0.9	−2.2	−0.9	−2.1	−0.9	−2.2	−2.1	−1.7	−4.3	**−8.3**	−3.9

for the month of May) and 8.3 W m^{-2} per decade (at Windhoek in December). Alexander Bay was the only station that showed a statistically significant increase in D_m, with increases evident in March (4.0 W m^{-2} per decade) and September (5.8 W m^{-2} per decade). Significant trends occurred in all months except January, February, and August at at least one of the six stations. Port Elizabeth had negative trends for all months of the year, although none was significant. Of those stations that showed significant trends in G_m, only Bloemfontein, Pretoria, and Windhoek also showed significant trends in D_m, but none of the trends in global and diffuse irradiance was for the same month. On average, negative percentage decadal trends in D_m are larger than the negative percentage decadal trends in G_m. Grootfontein showed significant decreases in both D_a and D_m (for the month of December).

3.3. Direct irradiance

Statistical summaries and trend parameters for the annually averaged direct irradiance B_a are provided in Table VI. The mean annual diffuse irradiance across the 10 stations is 173.9 W m^{-2}. Durban has the lowest long-term average B_a, with 117.4 W m^{-2}; as with global irradiance, Keetmanshoop has the highest mean B_a at 229.3 W m^{-2}. Thus, of all stations, Durban has the lowest global and direct irradiance but the highest diffuse component. Figure 4 demonstrates a strong northwest–southeast gradient in direct irradiance.

Table VI. As Table II, but for annual averages of direct irradiance B_a

Station	Long-term annual mean (W m^{-2})	Standard deviation of annual mean (W m^{-2})	Trend (W m^{-2} per decade)	Trend (% per decade)	Significance level (%)
Alexander Bay	191.8	7.1	**−5.6 ± 3.6**	**−2.8**	**99.4**
Bloemfontein	187.1	10.6	−2.9 ± 3.4	−1.5	90.4
Cape Town	159.7	8.4	**−3.5 ± 2.5**	**−2.1**	**99.1**
Durban	117.4	6.7	−2.0 ± 2.5	−1.7	89.4
Grootfontein	188.6	11.6	3.4 ± 8.3	1.8	59.1
Port Elizabeth	139.2	8.8	2.5 ± 3.7	1.2	81.1
Pretoria	161.6	9.1	−2.1 ± 2.3	−1.3	93.3
Upington	211.8	18.1	−1.9 ± 8.4	−0.9	35.2
Keetmanshoop	229.3	11.6	3.3 ± 5.9	1.5	74.2
Windhoek	208.6	11.7	−2.4 ± 5.7	−1.1	60.7
Mean	173.9	11.5	**−4.8 ± 2.6**	**−2.6**	**99.9**

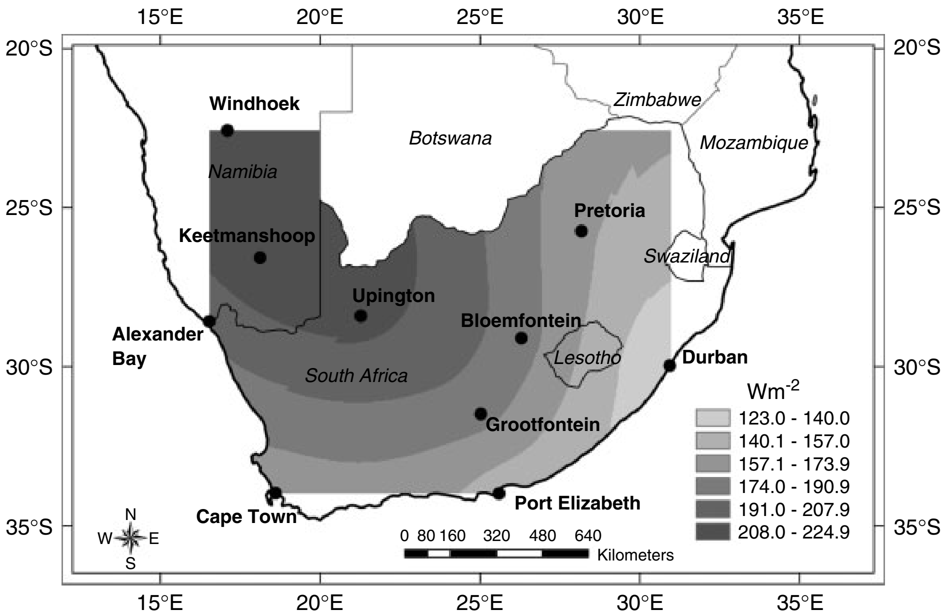

Figure 4. As Figure 2, but for annually averaged direct irradiance

The range in mean annual diffuse irradiance across the 10 stations (111.9 W m^{-2}) is relatively large and constitutes 64.3% of the long-term average annual direct irradiance averaged over all 10 stations. In comparison, the ranges in global and diffuse are only 38.8% and 31.8% of the station-averaged long-term mean annual irradiances respectively. This suggests that the spatial variability in radiation across South Africa and Namibia is greater for the direct component than it is for the global and diffuse components. Among the 10 stations, variability in B_a is smallest at Durban, with a standard deviation of 6.7 W m^{-2}, and greatest at Upington, with a standard deviation of 18.1 W m^{-2}. The mean standard deviation in direct irradiance across all stations is 11.5 W m^{-2}, which is large relative to the mean standard deviation for global (9.1 W m^{-2}) and diffuse (4.9 W m^{-2}). Again, this indicates that there is greater variability in direct than in global and diffuse irradiance.

Annually averaged direct irradiance has increased at Grootfontein, Port Elizabeth, and Keetmanshoop and decreased at the remaining seven stations. Across all 10 stations, B_a has decreased significantly by 2.6% (4.8 W m^{-2}) per decade. Statistically significant trends exist at just two stations, however. B_a decreased 2.8% (5.7 W m^{-2}) per decade at Alexander Bay, and B_a decreased 2.1% (3.5 W m^{-2}) per decade at Cape Town. Thus, of those stations that showed significant decreases in G_a, only Cape Town showed a simultaneous decrease in B_a. No stations showed significant trends in both D_a and B_a.

Five stations had statistically significant trends in monthly averaged direct irradiance B_m for at least 1 month, namely Alexander Bay, Bloemfontein, Cape Town, Durban, and Upington, and there were just nine significant trends at those stations (Table VII). All of those trends were negative and ranged between 4.9 W m^{-2} per decade at Cape Town in March and 13.9 W m^{-2} per decade at Bloemfontein in February. Across all stations, significant trends occurred in February, March, June–September, November, and December. As with diffuse irradiance, Port Elizabeth had decreases in B_m for all months of the year, but none was significant. Stations that showed significant trends in both G_m and B_m include Bloemfontein, Cape Town, Durban, and Upington, and all of these stations have trends in monthly global and direct for at least one common month. Alexander Bay had significant trends in both D_m and B_m for the month of September; Bloemfontein had significant trends in both D_m and B_m although not for the same months. Bloemfontein is the only station with significant trends in G_m, D_m, and B_m. Alexander Bay and Cape Town had significant decreases in both B_a and B_m.

Table VII. As Table III, but for monthly averaged daily direct irradiance B_m

Station	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AB	Mean	271.1	243.7	206.6	161.4	129.8	108.9	114.7	141.3	173.3	216.7	263.4	269.4
	SD	21.0	21.1	12.6	12.1	13.0	10.9	9.9	11.5	19.1	17.6	17.1	14.5
	Trend	4.7	−8.2	−6.9	−0.6	5.7	−0.2	0.2	−0.8	**−12.2**	−5.2	−7.5	−3.8
BL	Mean	232.9	209.0	182.3	158.2	139.9	125.1	136.3	165.3	187.8	212.3	242.1	253.6
	SD	38.3	41.3	28.0	16.9	12.3	12.3	12.2	17.3	23.7	31.6	28.8	28.0
	Trend	−1.8	**−13.9**	−2.2	−3.2	1.5	0.6	1.2	−3.2	−6.1	−5.0	−1.8	−0.6
CT	Mean	258.3	234.4	189.8	123.8	80.0	64.4	72.8	95.3	130.5	184.2	235.6	255.3
	SD	20.1	18.1	15.9	16.3	15.7	12.1	12.4	12.4	20.3	18.2	23.8	27.1
	Trend	−2.1	−1.0	**−4.9**	−4.2	−2.3	−3.3	**−5.8**	−1.1	−5.2	2.1	−4.3	**−8.7**
DN	Mean	135.5	142.4	132.5	115.9	99.0	92.1	94.1	104.2	104.9	115.6	125.6	142.7
	SD	22.1	20.9	20.8	12.3	7.6	10.0	9.5	15.5	16.2	19.8	21.8	19.7
	Trend	−3.2	**−7.5**	−6.2	0.8	−1.5	**−3.7**	−1.3	**−5.3**	−3.1	−0.6	2.4	−3.9
GR	Mean	266.3	213.6	186.0	152.0	123.7	113.2	123.8	153.8	179.7	217.6	257.6	280.1
	SD	33.5	39.9	27.5	16.3	17.1	6.5	11.3	17.1	26.2	24.1	29.5	31.9
	Trend	15.8	8.9	11.1	1.7	9.7	0.1	2.6	−3.8	1.0	−2.6	−4.8	12.5
PE	Mean	195.5	177.8	146.7	117.0	91.8	80.6	87.4	106.2	124.2	156.2	182.3	208.9
	SD	23.7	20.2	16.6	12.8	10.1	10.4	10.5	12.7	20.7	24.4	19.9	18.9
	Trend	−3.7	−1.9	−3.1	−3.2	−1.8	−2.0	−1.6	−1.1	−3.0	−5.2	−4.2	−3.8
PR	Mean	175.3	165.8	154.4	145.0	141.0	130.0	137.2	160.5	179.7	183.7	179.6	187.6
	SD	30.1	34.3	29.1	22.5	14.0	10.4	11.3	14.4	25.8	25.0	25.0	24.9
	Trend	−1.4	−6.6	−5.0	2.3	−1.3	1.3	0.5	−3.5	−4.5	−6.2	−1.0	0.0
UP	Mean	286.2	246.1	209.5	171.3	147.6	126.9	140.1	167.4	201.7	237.5	282.3	293.8
	SD	36.2	31.2	16.6	17.6	11.1	8.9	8.8	14.5	16.4	21.3	22.5	29.1
	Trend	6.4	−5.6	1.6	−1.6	1.0	−0.9	−2.6	−4.4	−3.1	−4.8	**−11.6**	1.1
KM	Mean	291.6	255.1	225.2	206.3	170.4	150.4	159.1	190.3	220.6	260.9	300.8	313.4
	SD	34.8	28.3	19.2	14.0	10.6	11.2	11.0	15.1	18.8	23.1	25.3	21.8
	Trend	4.1	−4.8	2.4	−2.2	−0.2	2.9	0.9	0.4	−2.0	3.8	11.6	7.9
WH	Mean	209.8	197.5	183.1	192.0	189.4	174.8	185.1	206.5	224.6	240.1	243.5	250.8
	SD	37.7	35.0	30.7	22.6	12.6	11.1	11.9	15.7	20.4	27.8	35.2	30.4
	Trend	−10.5	−9.7	−0.1	−7.4	−2.4	−4.0	0.4	−0.9	−3.1	−0.3	13.5	−6.5

3.4. *Sunshine duration*

Global, diffuse, and direct irradiance are known to be correlated with cloud cover and bright sunshine duration (e.g. Löf *et al*., 1966; Rietveld, 1978; Hay, 1979; Iqbal, 1979; Benson *et al*., 1984; Ahmad *et al*., 1991; Hamdan and Al-Sayeh, 1991). Indeed, one of the most probable causes of trends in solar radiation is a change in the amount of cloud cover (Stanhill and Cohen, 2001). A decrease in sunshine duration implies more cloud cover, which would give rise to a decrease in global and direct irradiance and increases in diffuse irradiance. Conversely, an increase in sunshine duration implies less cloud cover, which would give rise to an increase in global and direct irradiance and decreases in diffuse irradiance. In order to determine whether variability in sunshine duration may have contributed to the long-term trends observed in solar irradiance, summary statistics of sunshine duration were calculated and linear trend models were fit to the sunshine duration time series using the procedures and criteria described earlier in Section 3. Spatial variability and long-term trends in sunshine duration were then compared with variability and trends in each irradiance component.

Averaged across all stations for all years, the annually averaged daily sunshine duration S_a in South Africa and Namibia is 8.8 h (Table VIII). Durban has the lowest long-term mean annual daily sunshine duration, with 6.5 h, and Keetmanshoop has the highest, at 10.5 h. The low sunshine duration in Durban likely contributed to the minimum global (Section 3.1, Table II), maximum diffuse (Section 3.2, Table IV), and minimum direct irradiance (Section 3.3, Table VI) at that station, whereas the maximum sunshine duration in Keetmanshoop likely contributed to the maximum global (Section 3.1, Table II), second lowest diffuse irradiance (Table IV), and maximum direct irradiance (Section 3.3, Table VI) at that station. Among the 10 stations, variability in S_a is smallest at Alexander Bay and Cape Town, with a standard deviation of 0.2 h. The mean standard deviation in S_a across all stations is 0.3 h. More broadly, there is a strong northwest–southeast gradient in sunshine duration (Figure 5). This undoubtedly contributes to the spatial trends in global, diffuse, and direct irradiance described earlier, i.e. lower sunshine duration in the southeast implies greater cloudiness, which yields lower global, higher diffuse, and lower direct irradiance, whereas higher sunshine duration (less cloud) in the northwest would give rise to higher global, lower diffuse, and higher direct irradiance.

The spatial trends in irradiance and sunshine duration can be linked to the synoptic climatology of southern Africa and the southwest Indian Ocean. In this region, the westerlies are the prevailing weather feature during all seasons. However, the geographical location of southern Africa places it in a zone of large-scale movement of heat and moisture from the tropics to the mid-latitudes (Washington and Todd, 1999; Tyson and Preston-Whyte, 2000). This process of energy and mass transfer is accomplished by the formation of tropical–temperate troughs, which are long zones of surface convergence linking the tropics to the mid-latitudes. Disturbances in the easterly tropical flow to the north can, when coupled with a westerly wave to the south, create a long, northwest-to-southeast zone of low-level convergence along with upper level (500

Table VIII. As Table II, but for annual averages of daily bright sunshine duration S_a

Station	Long-term annual mean (h)	Standard deviation of annual mean (h)	Trend (h per decade)	Trend (% per decade)	Significance level (%)
Alexander Bay	9.1	0.2	**-0.1 ± 0.1**	**−1.6**	**99.7**
Bloemfontein	9.1	0.3	-0.1 ± 0.1	−0.7	79.3
Cape Town	8.5	0.2	0.0 ± 0.1	0.4	59.9
Durban	6.5	0.3	-0.1 ± 0.1	−1.0	82.2
Grootfontein	9.1	0.3	-0.1 ± 0.2	−0.6	34.2
Port Elizabeth	7.7	0.3	-0.1 ± 0.1	−1.0	88.7
Pretoria	8.8	0.3	**-0.1 ± 0.1**	**−1.1**	**98.8**
Upington	10.2	0.3	-0.1 ± 0.1	−0.6	63.1
Keetmanshoop	10.5	0.2	-0.1 ± 0.1	−0.8	80.8
Windhoek	9.6	0.3	-0.1 ± 0.1	−0.8	70.1
Mean	8.8	0.3	**-0.1 ± 0.1**	**−0.8**	**95.4**

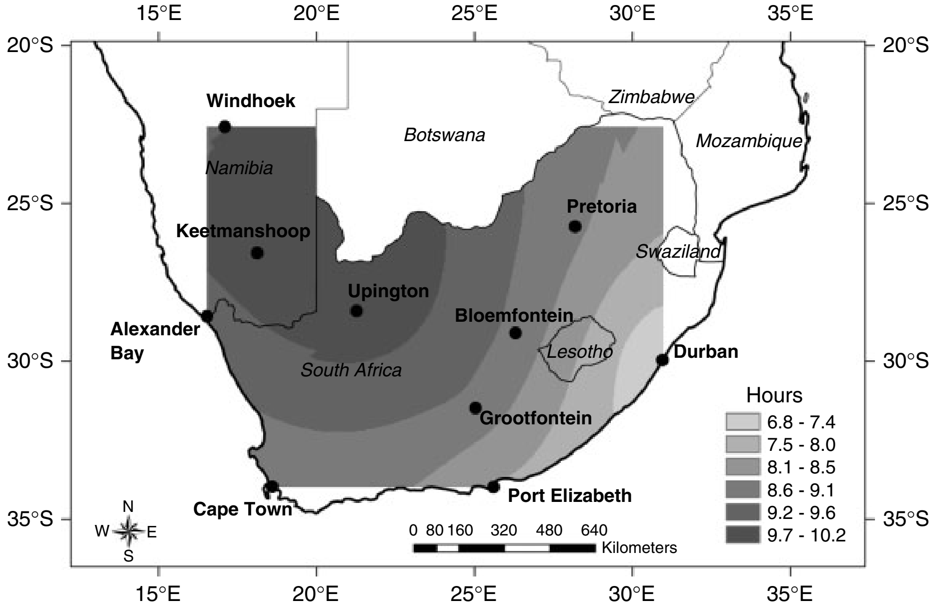

Figure 5. As Figure 2, but for annually averaged sunshine duration

mbar) divergence. These zones produce strong uplift, leading to the creation of bands of clouds. Typically, these clouds range from central southern Africa to the southeast and out over the southwest Indian Ocean. These troughs and their associated cloud bands are most discernible during the Southern Hemisphere summer and are the dominant system in terms of summertime rainfall (Todd and Washington, 1999; Washington and Todd, 1999). These cloud bands likely contribute to the northwest–southeast gradients observed in sunshine duration and global, diffuse, and direct irradiance. On a smaller scale, sea breezes and their associated cloud cover may also contribute to the relatively low global, high diffuse, and low direct irradiance observed at most of the coastal locations.

Annually averaged daily sunshine duration has decreased at all stations except Cape Town. Averaged across all 10 stations, S_a has decreased significantly by 0.8% (0.1 h) per decade (Table VIII). Statistically significant decreases occurred at only two stations: at Alexander Bay, S_a decreased 1.6% (0.2 h) per decade, and at Pretoria the S_a decreased 1.1% (0.1 h) per decade. Alexander Bay, Bloemfontein, Port Elizabeth, Pretoria, Upington, Keetmanshoop, and Windhoek had statistically significant decreases in monthly averaged daily sunshine duration S_m for 1 month of the year, ranging between 0.2 h per decade at Windhoek in June and 0.5 h per decade at Bloemfontein in February (Table IX). Cape Town showed a significant decrease in S_m in July (0.3 h per decade) and an increase in October (0.2 h per decade). The two stations that showed significant decreases in S_a (Alexander Bay and Pretoria) also showed significant decreases in S_m (in June and October respectively).

Since trends in annually averaged sunshine duration were significant at just Alexander Bay and Pretoria, possible causal mechanisms between long-term trends in annual sunshine duration and irradiance can only be evaluated at those two stations. At Alexander Bay, the 1.6% (0.2 h) per decade decrease in annual sunshine duration was coincident with a decrease in annual direct irradiance B_a of 2.8% (5.7 W m^{-2}) per decade. Thus, it appears that the decrease in annual sunshine duration may have contributed to the decrease in annual direct irradiance observed at that station. Similarly, at Pretoria, the 1.1% (0.1 h) per decade decrease in S_a was coincident with a decrease in annual global irradiance of 1.4% (3.3 W m^{-2}). Thus, annual sunshine variation may have contributed to the observed trend in global irradiance. There were no significant trends in annually averaged diffuse or direct irradiance at Pretoria. None of the long-term trends in G_a, D_a, or B_a observed at other stations can be attributed to long-term trends in S_a.

With regard to long-term trends in monthly irradiance, at Bloemfontein the monthly averaged daily sunshine duration S_m decreased significantly for the month of February (Table IX). This trend was coincident with

Table IX. As Table III, but for monthly averaged daily bright sunshine duration S_m

Station	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AB	Mean	10.6	9.8	9.1	8.5	8.2	7.7	8.0	8.4	8.6	9.3	10.4	10.3
	SD	0.7	0.8	0.5	0.6	0.6	0.7	0.5	0.5	0.8	0.7	0.6	0.6
	Trend	0.2	−0.4	−0.2	−0.1	0.2	**−0.4**	−0.1	−0.1	−0.3	−0.2	−0.2	−0.2
BL	Mean	9.6	9.0	8.4	8.4	8.6	8.4	8.8	9.4	9.3	9.3	9.9	10.2
	SD	1.3	1.5	1.0	0.8	0.7	0.6	0.6	0.8	0.9	1.0	0.8	0.9
	Trend	0.1	**−0.5**	−0.1	−0.1	0.2	0.0	0.1	−0.1	−0.3	−0.2	0.1	0.0
CT	Mean	11.0	10.6	9.4	7.7	6.4	5.8	6.3	6.9	7.5	9.0	10.4	10.8
	SD	0.6	0.6	0.5	0.7	1.0	0.8	0.8	0.7	0.8	0.7	0.8	0.8
	Trend	0.0	0.1	0.0	−0.1	0.1	0.0	**−0.3**	0.1	−0.1	**0.2**	0.1	−0.1
DN	Mean	6.0	6.4	6.5	6.9	7.2	7.6	7.4	7.0	5.8	5.5	5.5	6.2
	SD	0.8	1.0	0.9	0.6	0.6	0.5	0.7	0.9	0.9	0.8	0.9	0.7
	Trend	−0.1	−0.2	−0.2	0.0	0.1	0.0	−0.1	−0.3	−0.2	−0.1	0.2	−0.1
GR	Mean	10.6	9.1	8.5	8.3	8.2	8.0	8.4	8.9	8.8	9.5	10.4	11.0
	SD	1.0	1.2	1.0	0.7	0.8	0.4	0.6	0.8	0.9	0.9	0.9	1.0
	Trend	0.0	−0.2	0.2	0.1	0.5	0.1	0.2	−0.1	−0.3	−0.5	−0.5	−0.2
PE	Mean	8.5	8.1	7.5	7.3	7.1	7.0	7.3	7.6	7.1	7.6	8.4	9.1
	SD	0.9	0.8	0.8	0.6	0.6	0.6	0.6	0.7	1.0	0.9	0.8	0.7
	Trend	0.0	**−0.3**	0.0	0.1	0.1	−0.1	−0.1	−0.1	−0.3	0.0	−0.2	−0.2
PR	Mean	8.3	8.4	8.2	8.4	9.1	9.0	9.3	9.6	9.3	8.9	8.5	8.7
	SD	1.0	1.2	1.1	0.9	0.6	0.5	0.5	0.6	1.0	0.8	0.8	0.8
	Trend	−0.2	−0.3	−0.2	0.1	0.0	0.1	0.0	−0.1	−0.2	**−0.2**	−0.1	−0.1
UP	Mean	11.4	10.7	9.6	9.4	9.4	9.0	9.3	9.9	9.9	10.6	11.5	11.7
	SD	1.1	0.9	0.7	0.7	0.5	0.5	0.4	0.6	0.6	0.8	0.6	0.7
	Trend	0.2	−0.2	0.1	0.0	0.2	0.0	−0.1	−0.1	−0.2	−0.1	**−0.4**	−0.2
KM	Mean	11.3	10.5	9.8	10.2	9.8	9.5	9.8	10.3	10.4	10.9	11.7	12.0
	SD	1.2	0.9	0.7	0.6	0.4	0.4	0.4	0.3	0.5	0.6	0.7	0.6
	Trend	−0.1	**−0.5**	−0.1	−0.2	0.0	0.0	0.0	−0.1	−0.1	−0.1	0.1	0.0
WH	Mean	8.7	8.5	8.1	9.4	10.0	9.9	10.2	10.4	10.3	10.2	9.8	10.0
	SD	1.3	1.2	1.2	0.8	0.4	0.4	0.3	0.3	0.4	0.8	1.1	1.0
	Trend	−0.2	−0.3	−0.1	−0.1	0.0	**−0.2**	0.0	−0.1	−0.1	−0.1	0.4	−0.1

significant decreases in monthly averaged global irradiance G_m (Table III) and direct irradiance B_m (Table VII) during the same month. Similarly, at Cape Town, a decrease in S_m in July was coincident with decreases in G_m and B_m; at Pretoria, a decrease in S_m in October coincided with a decrease in G_m; at Upington, a decrease in S_m in November coincided with decreases in both G_m and B_m; and at Windhoek, there was a simultaneous decrease in S_m and G_m in June. Thus, at these five stations, it appears that the decreases in S_m may have contributed to the observed decreases in G_m and/or B_m for the respective months. None of the trends in S_m was coincident with trends in D_m.

Besides changes in cloud cover (and, therefore, sunshine duration), Stanhill and Cohen (2001) speculated that changes in the amount of insolation are likely due to changes in the amount of aerosol in the atmosphere. Typically, an increase in aerosols will decrease global and direct irradiance and increase diffuse irradiance (Iqbal, 1983). Power and Goyal (2003) used a parameterized model to estimate monthly averages of Ångström's turbidity coefficient β over South Africa and reported increases in annually averaged β of approximately 40% per decade at Cape Town and Durban, and decreases of 16.8% and 23.1% per decade at Port Elizabeth and Grootfontein respectively. Thus, it appears that the observed decreases in G_a at Cape Town and Durban and the decrease in B_a at Cape Town may be due to an increase in aerosols. Similarly, the decrease in D_a observed at Grootfontein may be due to the decrease in β at that station.

3.5. Interannual variability in irradiance and sunshine duration

The above analysis suggests that long-term trends in sunshine duration can, to some extent, explain some of the long-term trends in both annual and discrete monthly irradiance over Namibia and South Africa. However, interannual variability in sunshine duration may also contribute to interannual variability in irradiance for the same reasons articulated in Section 3.4. In order to explore this possibility further, annually averaged global, diffuse, and direct irradiance were regressed against annually averaged sunshine duration using a linear least-squares regression.

For global irradiance, the slopes of all regressions were positive (Table X), which is consistent with physical principles, i.e. an increase in annually averaged sunshine duration will likely result in an increase in annually averaged global irradiance. Using a t-test with a significance level of 95%, seven stations have statistically significant regressions: Bloemfontein, Durban, Grootfontein, Port Elizabeth, Pretoria, Upington, and Windhoek. Of these stations, the variance in annual global irradiance G_a that can be explained by annual sunshine duration S_a ranged from 30.3% (at Upington) to 66.0% (at Grootfontein). With data from all stations pooled, the explained variance is 89.0%. The pooled slope coefficient b (Table X) suggests that a 1 h increase in annually averaged daily sunshine duration results in an increase in annually averaged daily global irradiance of 22.9 W m^{-2}. Similarly, a 1 h decrease in sunshine duration would effect a decrease in global irradiance of the same magnitude.

For annually averaged diffuse irradiance, the slopes of the regressions with annual daily sunshine duration were all negative (Table XI). Again, this is consistent with physical principles: an increase in sunshine duration implies fewer clouds, with less scattering of radiation by cloud droplets and ice crystals. Seven stations show statistically significant relationships between diffuse irradiance and sunshine duration: Alexander Bay, Cape Town, Grootfontein, Port Elizabeth, Pretoria, Upington, and Keetmanshoop. Of these seven stations, Grootfontein, Port Elizabeth, Pretoria, and Upington also had statistically significant relationships between annual global irradiance and sunshine duration. At the seven significant stations, the variance in diffuse irradiance explained by sunshine duration ranges between 12.6% (at Pretoria) and 46.6% (at Alexander Bay). With the pooled data, the explained variance is 50.4%. Thus, on average, sunshine duration explains more of the variance in global than diffuse irradiance. The regression slope b for the pooled data indicates that, for a 1 h increase in sunshine duration, we can expect a decrease in annually averaged daily diffuse irradiance of 5.2 W m^{-2}. A comparison of the slope coefficients in Tables X and XI suggests that a change in annual sunshine duration has a greater impact on annual global than it does on annual diffuse irradiance.

The slopes of annual direct irradiance versus sunshine duration were all positive (Table XII), implying that an increase in sunshine duration leads to greater direct irradiance, which conforms to physical principles.

Table X. Parameters of the least-squares regression between annually averaged global irradiance G_a and annually averaged sunshine duration S_a. Significant values ($p \leq 0.05$) are shown in bold; r^2 is the coefficient of determination. Summary statistics in row 'Mean' are for the data pooled from all stations

Station	Slope b (W m^{-2}h^{-1})	r^2 (%)	Significance level (%)
Alexander Bay	4.5	1.8	46.1
Bloemfontein	**25.1**	**64.9**	**100.0**
Cape Town	6.3	5.5	79.7
Durban	**19.9**	**56.8**	**100.0**
Grootfontein	**25.4**	**66.0**	**100.0**
Port Elizabeth	**15.2**	**49.7**	**100.0**
Pretoria	**18.9**	**60.2**	**100.0**
Upington	**14.5**	**30.3**	**99.6**
Keetmanshoop	9.4	8.5	85.1
Windhoek	**19.3**	**48.5**	**100.0**
Mean	**22.9**	**89.0**	**100.0**

Table XI. Parameters of the least-squares regression between annually averaged diffuse irradiance D_a and annually averaged sunshine duration S_a. Significant values ($p \leq 0.05$) are shown in bold; r^2 is the coefficient of determination. Summary statistics in row 'Mean' are for the data pooled from all stations

Station	Slope b (W m^{-2}h^{-1})	r^2 (%)	Significance level (%)
Alexander Bay	**−10.5**	**46.6**	**99.9**
Bloemfontein	−4.7	8.4	90.9
Cape Town	**−10.6**	**38.4**	**100.0**
Durban	−0.7	0.2	18.3
Grootfontein	**−5.3**	**20.4**	**96.0**
Port Elizabeth	**−10.6**	**17.2**	**96.8**
Pretoria	**−6.4**	**12.6**	**97.5**
Upington	**−7.7**	**35.0**	**99.9**
Keetmanshoop	**−17.0**	**42.5**	**100.0**
Windhoek	−7.0	8.3	85.5
Mean	**−5.2**	**50.4**	**100.0**

Table XII. Parameters of the least-squares regression between annually averaged direct irradiance B_a and annually averaged sunshine duration S_a. Significant values ($p \leq 0.05$) are shown in bold; r^2 is the coefficient of determination. Summary statistics in row 'Mean' are for the data pooled from all stations

Station	Slope b (W m^{-2}h^{-1})	r^2 (%)	Significance level (%)
Alexander Bay	**21.4**	**37.2**	**99.4**
Bloemfontein	**29.8**	**73.3**	**100.0**
Cape Town	**17.3**	**29.7**	**99.7**
Durban	**18.7**	**53.1**	**100.0**
Grootfontein	**30.7**	**72.4**	**100.0**
Port Elizabeth	**21.9**	**38.3**	**99.9**
Pretoria	**25.3**	**70.8**	**100.0**
Upington	19.9	9.4	87.2
Keetmanshoop	**20.1**	**19.0**	**97.4**
Windhoek	**27.2**	**45.6**	**100.0**
Mean	**28.7**	**89.5**	**100.0**

All stations except Upington showed statistically significant relationships between direct irradiance and sunshine duration. Explained variance in direct irradiance ranged from 19.0% (at Keetmanshoop) to 73.3% (at Bloemfontein), with a pooled variance of 89.5%. A 1 h increase in sunshine duration results in an increase in daily direct irradiance of between 17.3 and 30.7 W m^{-2}, and the pooled response is 28.7 W m^{-2}. On average, then, sunshine duration explains more of the variability in global and direct irradiance than in diffuse irradiance. The radiative response of direct irradiance to changes in sunshine duration is greater than for global and diffuse irradiance.

4. VOLCANIC IMPACTS ON RADIATION CLIMATOLOGY

Volcanic eruptions are known to have a major impact on the radiation budget, even at locations remote from the volcano itself (e.g. Herber *et al*., 1996; Nagel *et al*., 1998). In the last five decades there have been three volcanic eruptions of relatively large magnitude. Mount Agung, in Indonesia, erupted in March 1963 and added between 16 and 30 million tons of aerosols to the stratosphere (Deirmendjian, 1973; Cadle *et al*., 1976, 1977). In April 1982, Mexico's El Chichón added between 10 and 20 million tons of aerosol (Hofmann and Rosen, 1983; McCormick and Swissler, 1983; Mroz *et al*., 1983). And in June 1991, Mount Pinatubo, in the Philippines, contributed an estimated 30–40 million tons of aerosol to the stratosphere (McCormick and Veiga, 1992). (Mount St Helens (Washington, USA) erupted in 1980. Although the eruption was explosive, it did not inject much sulphur into the stratosphere and its global effects were considered small (Robock, 1981, 2000).)

The radiative changes following each of these three eruptions were evaluated at stations where the requisite irradiance data were available. Using monthly averaged irradiances, the mean irradiances for global, diffuse, and direct were calculated for the 24 months before and after each of the three eruptions. The change in irradiance was calculated in physical units, and as a percentage change relative to the 2 year pre-eruption mean.

Besides volcanic aerosols, changes in cloud cover will also have influenced the radiation climatology following each of the eruptions. Ideally, to separate the radiative effects of the volcanic aerosols from the radiative effects of changes in cloud cover, we would evaluate the irradiance changes during clear-sky conditions only. This, in turn, necessitates the availability of coincident hourly cloud cover and irradiance observations. However, hourly cloud cover observations over southern Africa are only available for 0800h, 1400h, and 2000h. We considered this frequency too limited for our purposes, especially since the third observation would be after sunset (i.e. when the irradiance is zero) at all sites for all months of the year. As an alternative, we evaluated the change in bright sunshine duration using the same procedure that we employed for the radiation components, i.e. we calculated the mean sunshine duration for the 24-month periods before and after each of the three eruptions and then determined the change. The relative magnitudes of changes in sunshine duration were compared with the changes in irradiance.

4.1. Mount Agung

The irradiance time series available for South Africa and Namibia permitted an assessment of the influence of the Mount Agung eruption at all stations except Upington and Grootfontein. At these two stations, irradiance observations did not commence until 1965 and 1969 respectively, i.e. after the 1963 eruption. The changes in global irradiance at the remaining stations were relatively small and inconsistent (Table XIII). Alexander Bay, Cape Town, Port Elizabeth, and Pretoria, for instance, showed decreases of between 0.2% (0.4 W m^{-2}) and 4.9% (11.3 W m^{-2}) in global irradiance following the eruption, whereas Bloemfontein, Durban, Keetmanshoop, and Windhoek showed increases of between 0.6% (1.5 W m^{-2}) and 3.7% (10.2 W m^{-2}). The average change across the eight stations was a decrease in global irradiance of 1.0 W m^{-2}, or 0.4% of the pre-eruption mean.

Changes in diffuse irradiance were larger and more consistent than for global irradiance. All eight stations showed increases in diffuse irradiance ranging between 13.9% (10.3 W m^{-2}) at Port Elizabeth and 44.3% (20.8 W m^{-2}) at Keetmanshoop following the Agung eruption. Figures 6 and 7 depict the monthly diffuse time series (with the seasonal trend removed) at Bloemfontein and Cape Town respectively, and illustrate the increase in diffuse irradiance following the Agung eruption. The average increase in diffuse irradiance across the eight stations was 21.9% (13.3 W m^{-2}). This increase in diffuse irradiance following an eruption is consistent with physical principles (i.e. more aerosols in the stratosphere results in more scattering of radiation (Iqbal, 1983; Robock, 2000)), as well as with other studies (e.g. Hay and Darby, 1984; Dutton and Christy, 1992; Blumthaler and Ambach, 1994; Olmo *et al*., 1999).

With regard to direct irradiance, all stations showed a decrease following the eruption, which is also consistent with physical principles and with other analyses (e.g. Hay and Darby, 1984; Dutton and Christy, 1992; Alados-Arboledas *et al*., 1997; Olmo *et al*., 1999). The reductions ranged between 4.7% (10.6 W m^{-2}) at Keetmanshoop and 17.4% (29.5 W m^{-2}) at Cape Town. The decreases in direct irradiance at Bloemfontein and Cape Town are illustrated in Figures 8 and 9 respectively. The average reduction in direct irradiance across the eight stations was 8.7%, or 15.5 W m^{-2}. In physical units, the largest mean radiative change following the Agung eruption was, therefore, in the direct component. This was partly compensated by the mean increase in the diffuse component of 13.3 W m^{-2}. As a percentage change, i.e. relative to the pre-eruption means, the

Table XIII. Change in global, diffuse, and direct irradiance and sunshine duration following the eruptions of Mount Agung, El Chichón, and Mount Pinatubo. Figures show the difference between the mean irradiances for the 24 month periods prior to and after the eruption expressed in physical units (W m^{-2}) and as a percentage change

	Global (W m^{-2})	Global (%)	Diffuse (W m^{-2})	Diffuse (%)	Direct (W m^{-2})	Direct (%)	Sunshine (h)	Sunshine (%)
Mount Agung								
Alexander Bay	−9.2	−3.6	9.0	15.8	−16.5	−8.5	0.0	−0.3
Bloemfontein	5.5	2.2	15.4	26.9	−10.0	−5.3	−0.1	−0.6
Cape Town	−11.3	−4.9	9.5	16.2	−29.5	−17.4	−0.4	−4.3
Durban	3.1	1.6	11.3	16.7	−7.6	−6.2	−0.1	−0.8
Port Elizabeth	−7.4	−3.5	10.2	13.9	−17.7	−12.8	−0.3	−3.6
Pretoria	−0.4	−0.2	14.6	22.9	−14.9	−8.7	−0.1	−1.2
Keetmanshoop	10.2	3.7	20.8	44.3	−10.6	−4.7	−0.1	−1.2
Windhoek	1.5	0.5	15.2	25.7	−16.7	−7.8	−0.1	−0.6
Mean	−1.0	−0.4	13.3	21.9	−15.5	−8.7	−0.1	−1.5
El Chichón								
Alexander Bay	−20.2	−7.6	4.7	7.6	−1.1	−0.6	−0.1	−0.8
Bloemfontein	−3.8	−1.5	10.2	19.8	−14.0	−7.0	−0.1	−0.8
Cape Town	0.6	0.3	2.3	3.7	−15.1	−8.6	−0.2	−2.7
Durban	−4.8	−2.5	1.0	1.5	−5.9	−4.8	−0.1	−0.9
Grootfontein	−1.3	−0.5	4.9	9.5	−6.2	−3.1	−0.1	−1.0
Port Elizabeth	−5.4	−2.6	4.4	6.9	−8.1	−5.5	−0.1	−1.8
Pretoria	6.9	3.0	−4.5	−6.7	11.4	7.1	0.3	3.3
Upington	−2.9	−1.1	3.2	6.8	−1.9	−0.9	−0.1	−1.4
Windhoek	−17.1	−6.2	1.0	1.7	−19.7	−9.0	−0.2	−2.4
Mean	−5.3	−2.2	3.0	5.1	−6.7	−3.7	−0.1	−1.0
Mount Pinatubo								
Cape Town	−21.6	−9.8	9.4	15.9	−23.8	−14.8	−0.9	−10.7
Pretoria	2.8	1.2	9.9	18.0	−7.2	−4.1	0.2	2.1
Upington	1.3	0.5	10.7	23.7	−8.1	−3.8	−0.4	−4.3
Mean	−5.8	−2.5	10.0	18.8	−13.0	−7.2	−0.4	−4.3

largest change was in the diffuse component (an increase of 21.9%) compared with a decrease in the direct component of only 8.7%. The variability in the magnitude of the changes in direct and diffuse irradiance explains the inconsistent changes in global.

All stations witnessed a decrease in bright sunshine duration following the Agung eruption (Table XIII); thus, we cannot rule out the possibility that an increase in cloud cover may have contributed to the observed increase in diffuse and decrease in direct in the 2 years following the eruption. However, the decreases in mean daily sunshine duration ranged between just 0.3% (0.0 h) at Alexander Bay and 4.3% (0.4 h) at Cape Town, with an average decrease of only 1.5% (0.1 h). These changes are small relative to the changes in diffuse irradiance (13.9 to 44.3%) and direct irradiance (4.7 to 17.4%). Furthermore, it is possible that the decrease in sunshine duration may, in part, be due to the increase in aerosols rather than solely due to an increase in cloud cover; the aerosols from the eruption would cause the sunshine recorder to reach the threshold irradiance later in the morning and earlier in the evening. This, in turn, would shorten the period of bright sunshine duration.

In Section 3.5 we determined from the pooled data that a 1 h decrease in sunshine duration would effect an average increase in annually averaged diffuse irradiance of 5.2 W m^{-2} (Table XI). Thus, with a mean decrease in sunshine duration of 0.1 h following the eruption, the expected increase in diffuse is approximately 0.7 W m^{-2}. Since the observed increase in diffuse was 13.3 W m^{-2}, it appears that the majority of that

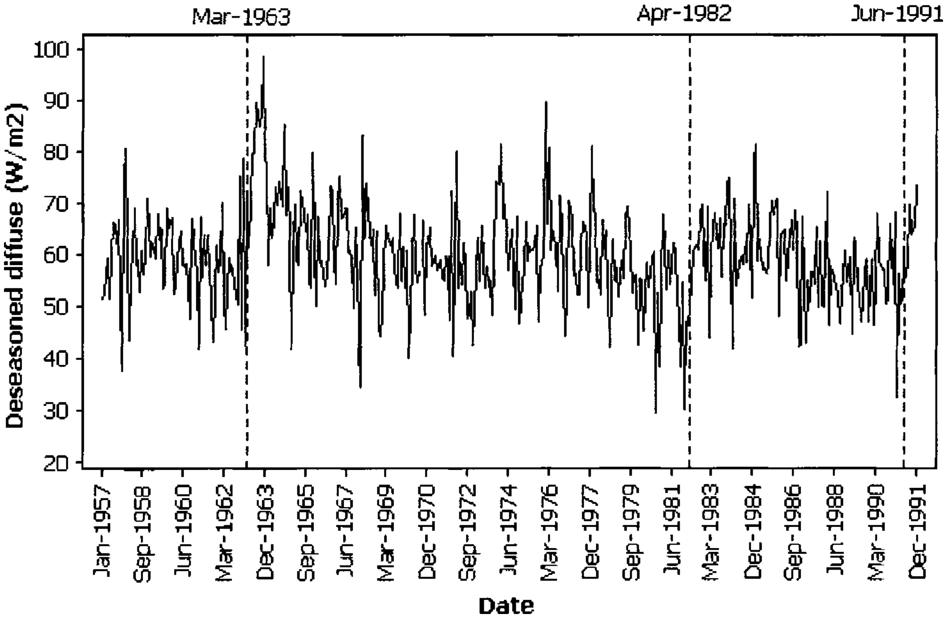

Figure 6. Deseasoned monthly diffuse irradiance at Bloemfontein, 1957–91. Vertical lines show the dates of the Mount Agung, El Chichón, and Pinatubo eruptions

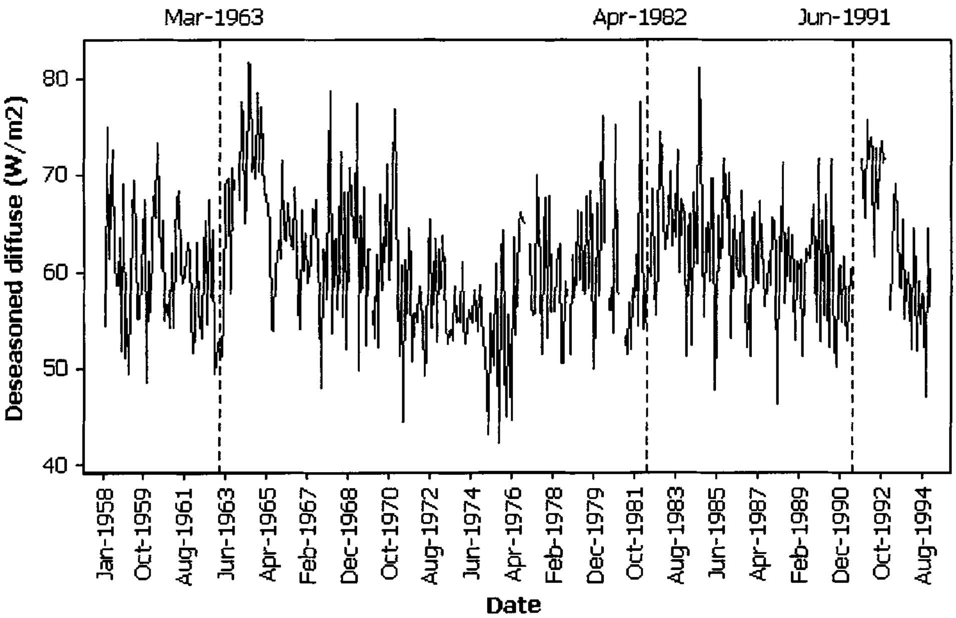

Figure 7. Deseasoned monthly diffuse irradiance at Cape Town, 1958–94. Vertical lines show the dates of the Mount Agung, El Chichón, and Pinatubo eruptions

increase is due to the volcanic aerosols; relatively little is due to the change in sunshine duration or clouds. Similarly, using the relationships established between sunshine duration and direct irradiance (Table XII), the expected decrease in direct irradiance for an average decrease in sunshine duration of 0.1 h is 4.0 W m^{-2}, which is considerably less than the observed decrease of 15.5 W m^{-2}.

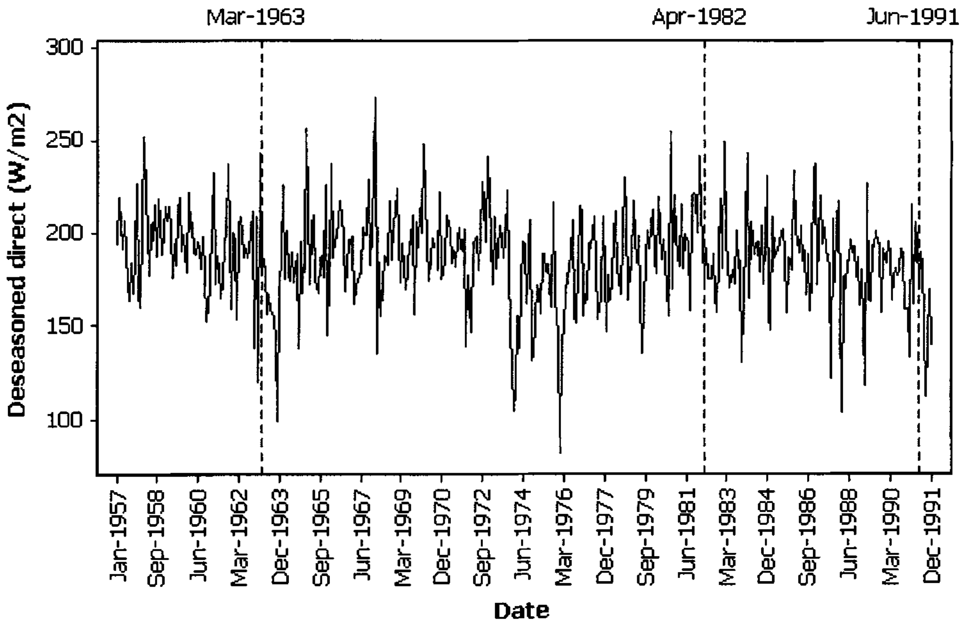

Figure 8. Deseasoned monthly direct irradiance at Bloemfontein, 1957–91. Vertical lines show the dates of the Mount Agung, El Chichón, and Pinatubo eruptions

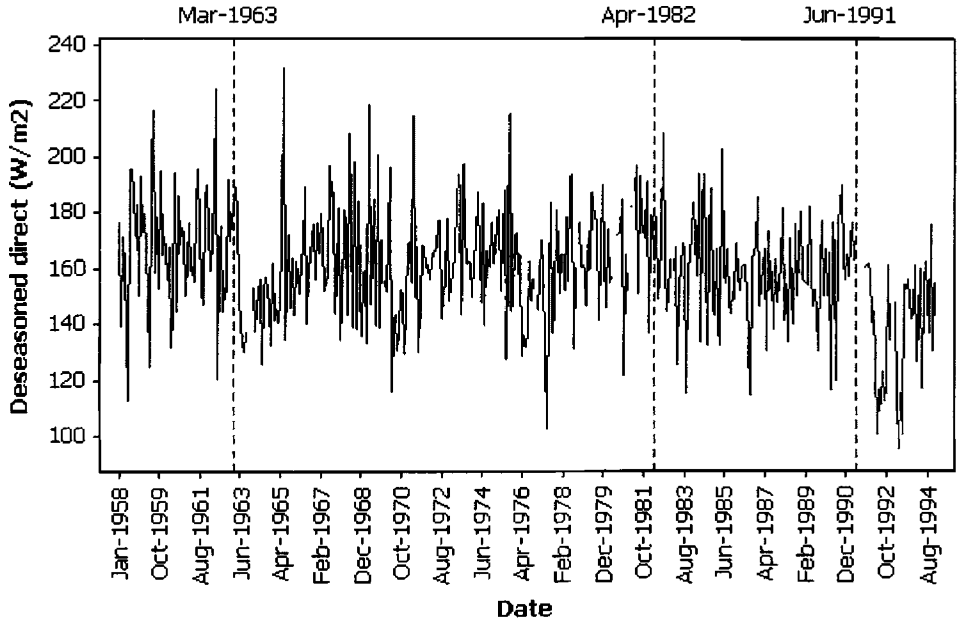

Figure 9. Deseasoned monthly direct irradiance at Cape Town, 1958–94. Vertical lines show the dates of the Mount Agung, El Chichón, and Pinatubo eruptions

4.2. *El Chichón*

The impact of the 1982 El Chichón eruption on the radiation climatologies was evaluated at nine of the 10 stations; at Keetmanshoop, the time series ended shortly after the eruption. As with Mount Agung, the changes in global irradiance following the El Chichón eruption were relatively small (Table XIII). At Cape Town and

Pretoria, global irradiance increased 0.3% (0.6 W m^{-2}) and 3.0% (6.9 W m^{-2}) respectively. At the remaining seven stations the global irradiance decreased between 0.5% (1.3 W m^{-2}) and 7.6% (20.2 W m^{-2}). These numbers are comparable in magnitude to the change in global irradiance following the Agung eruption.

Diffuse irradiance increased at all stations evaluated except Pretoria. Increases ranged between 1.5% (1.0 W m^{-2}) at Durban and 19.8% (10.2 W m^{-2}) at Bloemfontein. At Pretoria, there was a 6.7% (4.5 W m^{-2}) decrease in irradiance, which is anomalous given the expected increase in diffuse due to enhanced forward scattering. The average change across the nine stations was an increase in diffuse irradiance of 5.1% (3.0 W m^{-2}), which is substantially smaller than the average increase in diffuse following the Agung eruption (21.9%, or 13.3 W m^{-2}). For the eight stations that witnessed an increase in diffuse (i.e. excluding Pretoria), the average change was an increase of 7.2% (4.0 W m^{-2}), which is still considerably smaller than the average change following the Agung eruption. The changes in diffuse at Bloemfontein and Cape Town following the El Chichón eruption are illustrated in Figures 6 and 7 respectively.

Direct irradiance increased at Pretoria by 7.1% (11.4 W m^{-2}) following the El Chichón eruption. Again, this is contrary to expectations, in that direct irradiance typically decreases following a volcanic eruption due to enhanced backscattering. At the other eight stations, direct irradiance decreased between 0.6% (1.1 W m^{-2}) at Alexander Bay and 9.0% (19.7 W m^{-2}) at Windhoek, whereas the average change across the nine stations was a decrease of 3.7% (6.7 W m^{-2}; Figures 8 and 9). The average change across those eight stations with a decrease in direct was 5.0% or 9.0 W m^{-2}. As with the diffuse component, the mean decrease in direct irradiance following the El Chichón eruption is smaller than the decrease following the Agung eruption (8.7%, or 15.5 W m^{-2}).

At eight of the nine stations the daily bright sunshine duration decreased between 0.8% (0.1 h) and 2.7% (0.2 h) in the 2 years following the El Chichón eruption. At Pretoria, sunshine duration increased 3.3% (0.3 h). This may have contributed to the decrease in diffuse and increase in global and direct observed at that station. The average change in sunshine duration across all stations was a decrease of 1.0% (0.1 h). This change is relatively small compared with the changes in diffuse (5.1%) and direct irradiance (3.8%). Again, using the relationships established in Section 3.5 and Tables XI and XII, the average decrease in sunshine of 0.1 h likely contributed to an increase in diffuse irradiance of approximately 0.5 W m^{-2} and a decrease in direct irradiance of 2.6 W m^{-2}. These contributions are relatively small compared with the observed mean increase in diffuse (3.0 W m^{-2}) and decrease in direct irradiance (6.7 W m^{-2}).

4.3. Mount Pinatubo

To evaluate the radiative impacts of the Mount Pinatubo eruption, sufficient irradiance data were available at just three stations (Table XIII). Global irradiance decreased at Cape Town by 9.8% (21.6 W m^{-2}), and increased at Pretoria by 1.2% (2.8 W m^{-2}) and at Upington by 0.5% (1.3 W m^{-2}). On average, at these three stations the global irradiance decreased 2.5%, or 5.8 W m^{-2}. Diffuse irradiance increased at all three stations following the eruption, with increases ranging between 15.9% (9.4 W m^{-2}) at Cape Town and 23.7% (10.7 W m^{-2}) at Upington. The average increase was 18.8%, or 10.0 W m^{-2}. The increase in diffuse is evident at Cape Town (Figure 7) and, to a lesser extent, at Bloemfontein (Figure 6), where the time series ends just 6 months after the eruption. Direct irradiance declined at all three stations following the eruption, with decreases ranging between 3.8% (8.1 W m^{-2}) and 14.8% (23.8 W m^{-2}; Figures 8 and 9). The average change in the direct component was a decrease of 7.2%, or 13.0 W m^{-2}.

Following the Pinatubo eruption, annually averaged daily bright sunshine duration increased at Pretoria by 2.1% (0.2 h). The implied decrease in cloud cover may, therefore, have contributed to the increase in global observed at that station. However, diffuse irradiance increased and direct irradiance decreased; therefore, it is unlikely that changes in cloud cover contributed to these post-eruption trends in irradiance. Rather, the changes in direct and diffuse irradiance are more likely associated with the presence of the volcanic aerosols.

At Cape Town and Upington, bright sunshine duration decreased 10.7% (0.9 h) and 4.3% (0.4 h) respectively after the eruption. At these two stations, the variances in diffuse and direct irradiances that were explained by sunshine duration were quite low, ranging between 9.4 and 38.4% (Section 3.5). Thus, it is not appropriate to use the slope coefficients to calculate the expected change in irradiance due to the observed changes in sunshine duration. In other words, owing to the small number of stations, to the weak relationships between irradiance and sunshine duration, and to the inconsistent changes in sunshine duration across Pretoria, Cape Town, and Upington, we cannot determine the relative contributions of volcanic aerosols and changes in cloud cover to the observed changes in diffuse and direct at Cape Town and Upington.

Comparing the mean radiative changes following each of the three volcanic eruptions, it is evident that the largest change in both diffuse and direct was following the Mount Agung eruption in 1963, and the smallest change was following the El Chichón eruption in 1982; this comparison, however, is based on an assessment of only three stations following the Pinatubo eruption.

The largest change in global irradiance was following the Pinatubo eruption, and the smallest change was after the Agung eruption. Comparing the three irradiance components, after all three eruptions the largest percentage changes were in diffuse irradiance and the smallest changes were in global irradiance. In terms of the estimated magnitude of material that reached the stratosphere from each of these eruptions. El Chichón was the smallest of the three eruptions and Pinatubo was the largest (see Section 4). The large change in diffuse and direct irradiance over southern Africa after the Agung eruption is most likely because the eruption was in the same hemisphere. Furthermore, the aerosol cloud from Mount Agung was largely restricted to the Southern Hemisphere (Robock, 2000), implying less dilution of the cloud by circulation in the Northern Hemisphere. Similarly, the El Chichón cloud was mostly confined to the Northern Hemisphere (Strong, 1984; Robock, 2000) and the aerosols from this eruption were, therefore, less likely to influence the radiation climatology over southern Africa. The Pinatubo cloud, in contrast, was advected in both hemispheres (Bluth *et al*., 1992; Robock, 2000).

Using sunshine duration as a proxy, changes in cloud cover appear to have contributed a very small amount to the irradiance changes following the Mount Agung eruption. After El Chichón, changes in cloud cover may have accounted for, on average, approximately 16% of the observed change in diffuse irradiance and 38% of the observed change in direct irradiance. In other words, the majority of the observed changes in irradiance appear to be due to the eruption. Following the Pinatubo eruption, changes in cloud cover did not contribute to the observed changes in diffuse and direct irradiance at Pretoria. For Cape Town and Upington, it is not possible to determine the contribution of changes in cloud cover to the observed changes in irradiance.

5. SUMMARY AND CONCLUDING REMARKS

Temporal and spatial variability in global, diffuse, and horizontal direct irradiance and sunshine duration have been evaluated at eight stations in South Africa and two stations in Namibia. Interpolated surfaces created with an ordinary kriging algorithm demonstrate broad spatial trends in solar irradiance and sunshine duration. Global and direct irradiance and sunshine duration decrease from northwest to southeast, and diffuse irradiance increases toward the east. These trends are attributed to the presence of tropical–temperate troughs and associated cloud bands that extend from central southern Africa to the southeast and over the southwest Indian Ocean.

The time series at the 10 stations vary between 21 and 41 years. Statistically significant long-term trends in annually averaged global irradiance G_a are evident at five stations. At Bloemfontein, Cape Town, Durban, Pretoria, and Upington, G_a has decreased between 1.3% (2.8 W m^{-2}) and 1.7% (4.4 W m^{-2}) per decade. None of these five stations had significant trends in annually averaged diffuse irradiance D_a, but D_a did decrease 5.2% (3.0 W m^{-2}) per decade at Grootfontein and 4.2% (3.1 W m^{-2}) per decade at Port Elizabeth. Coincident with the decrease in G_a at Cape Town was a decrease in annually averaged direct irradiance B_a of 2.1% (3.5 W m^{-2}) per decade. Alexander Bay also had a decrease in B_a of 2.8% (5.7 W m^{-2}) per decade. Across the study region, there is greater variability in direct irradiance than in global and diffuse irradiance.

Discrete monthly averages of irradiance were evaluated to determine whether there were significant long-term trends in any particular month or season. Six stations showed long-term decreases in monthly averages of global irradiance G_m, and these decreases occurred in all months except January at at least one of the six stations. Five stations had decreases in monthly averaged diffuse irradiance D_m for at least 1 month of the year, and Alexander Bay showed an increase in D_m in March and September. Three stations had decreases in both G_m and D_m, but not for the same months. Five stations showed decreases in monthly averaged direct irradiance B_m. Bloemfontein is the only station with significant trends in G_m, D_m, and B_m, although these trends were not for the same months. All except one of the long-term trends in monthly irradiance were negative. However, there was no consistency in terms of the month, season, or station where the trends in irradiance were significant.

With regard to sunshine duration, statistically significant decreases in annually averaged daily sunshine duration S_a were evident at Alexander Bay (1.6%, or 0.2 h per decade) and Pretoria (1.1%, or 0.1 h per decade). The decrease in S_a at Alexander Bay may have contributed to the decrease in B_a observed at that station, and the decrease in S_a at Pretoria may have contributed to the decrease in G_a. None of the long-term trends in G_a, D_a, or B_a observed at other stations can be attributed to long-term trends in S_a. Based on modelled estimates of Ångström's turbidity coefficient, the observed decreases in G_a at Cape Town and Durban and the decrease in B_a at Cape Town may be due to an increase in aerosols. Similarly, the decrease in D_a at Grootfontein may be due to a decrease in aerosols at that station. At Bloemfontein, Cape Town, Pretoria, Upington, and Windhoek, decreases in monthly averaged daily sunshine duration S_m may have contributed to observed decreases in G_m and/or B_m for discrete months of the year. None of the trends in D_m could be attributed to trends in S_m.

Statistically significant regressions between G_a and S_a suggest that between 30.3 and 66.0% of the variance in annual global irradiance can be explained by variability in sunshine duration. On average, a 1 h increase (or decrease) in S_a results in an increase (or decrease) in global irradiance of 22.9 W m^{-2}. Variance in D_a explained by sunshine duration ranges between 12.6 and 46.6% and, for a 1 h increase (or decrease) in sunshine duration, one can expect an average decrease (or increase) in D_a of 5.2 W m^{-2}. Explained variance in annual direct irradiance B_a ranged between 19.0 to 73.3%, and the average response in B_a to a 1 h change in sunshine duration is 28.7 W m^{-2}. On average, sunshine duration explains more of the variability in direct irradiance than in global or diffuse irradiance, and the radiative response of direct irradiance to changes in sunshine duration is greater than for global and diffuse irradiance.

The radiative impacts of the 1963 Mount Agung eruption were evaluated at eight stations where the time series were of sufficient duration. In the 2 years following the eruption, the changes in global irradiance were small and inconsistent. On average, diffuse irradiance increased 21.9% (13.3 W m^{-2}) relative to the 2 year pre-eruption mean. Direct irradiance decreased at all stations, with an average decrease of 8.7% (15.5 W m^{-2}). In physical units, the largest mean radiative change following the Agung eruption was in the direct component. The contribution of changes in cloud cover to the observed changes in irradiance was small.

Following the El Chichón eruption in 1982, the changes in global were also relatively small. Seven stations showed a decrease in global irradiance; two stations showed an increase. Diffuse irradiance increased at eight stations, with an average increase of 5.1% (3.0 W m^{-2}), and direct irradiance decreased an average of 3.7% (6.7 W m^{-2}). Increases in cloud cover may have accounted for up to 38% of the observed changes in diffuse and direct irradiance. At Pretoria, diffuse irradiance decreased 6.7% (4.5 W m^{-2}) and direct irradiance increased 7.1% (11.4 W m^{-2}). With regard to the 1991 eruption of Mount Pinatubo, sufficient irradiance data were available for analysis at only three stations. Relatively small increases in global irradiance were evident at Pretoria and Upington, whereas global irradiance decreased at Cape Town. Diffuse irradiance increased and direct irradiance decreased at all three stations. The mean increase in diffuse was 18.8% (10.0 W m^{-2}) and the mean decrease in direct irradiance was 7.2% (13.0 W m^{-2}). Of the three eruptions, on average, the largest change in diffuse and direct irradiance was after the Agung eruption in Indonesia. The largest radiative change after the three eruptions, in relative terms, was in the diffuse component.

ACKNOWLEDGEMENTS

We appreciate the assistance of Danie Esterhuyse, Laimonis Kavalieris, Maria Garcia Quijano, and Lynn Shirley in conducting this research. Financial support from the National Science Foundation (grant 97-09667) is gratefully acknowledged. Climate data were kindly provided by the South African Weather Bureau.

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