Solar Irradiance, Air Pollution and Temperature Changes in the Arctic

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Solar irradiance, air pollution and temperature changes in the Arctic

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A highly significant decrease in the annual sums of global irradiance reaching the surface of the Arctic, averaging 0.36 W m^{-2} per year, was derived from an analysis of 389 complete years of measurement, beginning in 1950, at 22 pyranometer stations within the Arctic Circle. The smaller data base of radiation balance measurements available showed a much smaller and statistically non-significant change.

Reductions in global irradiance were most frequent in the early spring months and in the western sectors of the Arctic, coinciding with the seasonal and spatial distribution of the incursions of polluted air which give rise to the Arctic Haze.

Irradiance measured in Antarctica during the same period showed a similar and more widespread decline despite the lower concentrations of pollutants. A marked increase in the surface radiation balance was recorded. Possible reasons for these interpolar anomalies and their consequences for temperature change are discussed.

1. Introduction

Arrhenius (1896) first pointed out that any global warming resulting from increased atmospheric concentrations of CO_2 or other radiatively active gases will be enhanced in the polar regions. This has been confirmed by experiments with general circulation models in the equilibrium mode (Mitchell *et al.* 1990) although transient models indicate that the enhanced warming will be confined to the Arctic (Bretherton *et al.* 1990).

The importance of a substantial rise in the temperature of the Arctic is of wider significance than the local effects on the fragile ecosystems because of the many important, complex and interacting climatic feedback mechanisms involving the polar regions (Kellogg 1975).

Primary and secondary changes in the radiative exchange at the surface and in the atmosphere caused by the global increase in the concentration of radiatively active gases have been modified by incursions of polluted air reaching the Arctic from the industrial regions of the Northern Hemisphere.

In late winter and early spring, the influx and concentration of polluted, stagnant air give rise to the Arctic Haze phenomenon over large sectors of the region (Stonehouse 1986; Sturges 1991). Its effects on radiative exchange are complex, partly because they are strongly influenced by the shortwave reflectivity of the underlying surface. Calculations based on data gathered during research flights suggest that, in general, the Arctic Haze causes radiative cooling at the surface (Rosen & Hansen 1986; Valero & Ackerman 1986; Blanchet 1991).

Pollution-induced cooling, by offsetting the enhanced surface warming predicted

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for the Arctic by both equilibrium and transient general circulation models, could explain the absence of temperature increases in the Arctic demonstrated in several analyses of measurement series (Kukla & Robinson 1981; Kelley *et al.* 1982; Lamb 1982; Tsuchiya 1991; Jaworowski *et al.* 1992; Kahl *et al.* 1993; Walsh 1993).

Support for this explanation is provided in this study of changes in solar irradiance and net all-wave radiation balance at the surface which have been measured within the Arctic Circle during the last 40 years. The changes have been related to the seasonal and spatial patterns in air pollution and air temperature and contrasted with those derived from similar measurements in the Antarctic.

2. Changes in solar irradiance and radiation balance in the Arctic

(a) *Data*

Altogether 389 complete years of global irradiance $K\downarrow$ measurements were obtained from 22 sites. All-wave radiation balance Q_* was measured at 11 of these sites and 133 complete years of such data are available.

The coordinates of the measurement sites together with the periods covered are presented in table 1 with mean annual sums of $K\downarrow$, their interannual variations and cloudiness-indices – the fraction of extra-terrestrial irradiance. The references to data sources in most cases include details of the instruments used, their exposure and calibration.

The irradiance measurements analysed are all 24 h totals expressed either as mean monthly values or annual sums and corrected to the current World Radiation Reference scale (WMO 1981).

(b) *Results*

(i) *Global irradiance*

Annual sums of $K\downarrow$, averaged for each of the 43 years between 1950 and 1994 when data were available, are presented in figure 1. The calculated linear decrease of 0.36 ± 0.05 W m^{-2} per year was very highly significant, $p = 0.0001$; the addition of a quadratic term to the relationship did not increase its significance. The annual decrease of $K\downarrow$ calculated using the data from all sites, thus weighting each year for the number of measurements available, was 0.24 ± 0.06 W m^{-2} per year, less than that based on the average yearly values but equally significant, $p = 0.0001$.

Seasonal and annual trends in $K\downarrow$ at individual sites are given in table 2, expressed as the slope of linear regressions on the year of observation for those trends statistically significant at the 0.05 level or less; quadratic relationships yielded essentially similar results and therefore have not been presented.

Three-quarters of the Arctic sites showed significant linear trends in $K\downarrow$; one-quarter of both the monthly means and annual totals changed significantly. All but one of the significant annual changes were decreases; two-thirds of the significant monthly changes were negative in sign. In absolute terms, decreases in $K\downarrow$ were on the average twice as large as the fewer cases of increased irradiance.

Large seasonal and area differences in the distribution of the time trends in $K\downarrow$ were observed. One-third of all significant changes occurred in the two spring months, March and April, and one-half during the four months, February to May. Long-term trends in $K\downarrow$ were least frequent during the three midsummer months, June, July and August.

Table 1. *Global radiation measurements in the Arctic*

					mean annual values			
site	coordinates			period of measurement[a]	$K{\downarrow}$ (GJ m^{-2})	F_E[b]	CV (%)	data sources[c]
Alert Canada	81°30′ N	62°20′ W	62 m	1964–93 (16)	2.897	0.51	7.4	AB
Krenkel former USSR	80°37′ N	58°03′ E	21 m	1964–89 (25)	2.691	0.47	5.1	A
Eureka Canada	80°00′ N	85°56′ W	10 m	1970–93 (9)	3.003	0.52	6.0	AB
Ny Alesund Norway	78°50′ N	11°30′ E	17 m	1974–92 (11)	2.373	0.41	5.9	C
Chelyuskin former USSR	77°43′ N	104°17′ E	12 m	1964–90 (22)	2.789	0.48	4.3	A
Mould Bay Canada	76°14′ N	119°20′ W	15 m	1965–87 (7)	2.954	0.50	4.8	AB
Kotelny Is. former USSR	76°00′ N	137°54′ E	11 m	1964–91 (22)	2.674	0.45	9.9	A
Resolute Canada	74°43′ N	94°59′ W	64 m	1964–93 (13)	3.150	0.53	5.3	AB
Bjornoya Norway	74°31′ N	19°01′ E	16 m	1970–93 (8)	2.066	0.35	7.3	D
Dickson Is. former USSR	73°30′ N	80°10′ E	42 m	1964–90 (22)	2.736	0.45	4.6	A
Sachs Harbour Canada	71°59′ N	125°17′ W	84 m	1970–86 (7)	3.233	0.52	6.0	AB
Barrow USA	71°08′ N	156°47′ W	19 m	1951–92 (14)	3.183	0.51	8.5	AEF
Wrangel Is. former USSR	70°58′ N	178°32′ W	2 m	1964–91 (24)	3.151	0.50	4.5	A
Chetyrekhstolbovoi former USSR	70°38′ N	162°24′ E	32 m	1964–91 (24)	3.238	0.52	4.8	A
Cambridge Bay Canada	69°06′ N	105°07′ W	23 m	1971–93 (7)	3.337	0.52	3.0	AB
Hallbeach Canada	68°47′ N	81°15′ W	7 m	1970–93 (8)	3.482	0.54	2.3	AB
Olenek former USSR	68°30′ N	112°26′ E	127 m	1964–91 (17)	3.251	0.50	5.8	A
Inuvik Canada	68°19′ N	133°32′ W	103 m	1950–93 (26)	3.380	0.52	4.5	ABF
Kiruna Sweden	67°50′ N	20°26′ E	408 m	1952–91 (22)	3.080	0.47	11.1	GF
Verkoyansk former USSR	67°33′ N	133°23′ E	137 m	1964–91 (22)	3.395	0.52	3.0	AI
Sodankyla Finland	67°22′ N	26°39′ E	138 m	1953–93 (36)	2.928	0.45	8.9	AF
Reykjavik Iceland	64°08′ N	21°54′ W	56 m	1958–91 (27)	2.897	0.42	8.5	AI

[a] Figure in brackets is the number of complete years. [b] F_E is the fraction of extraterrestrial.
[c] See next page for data sources.

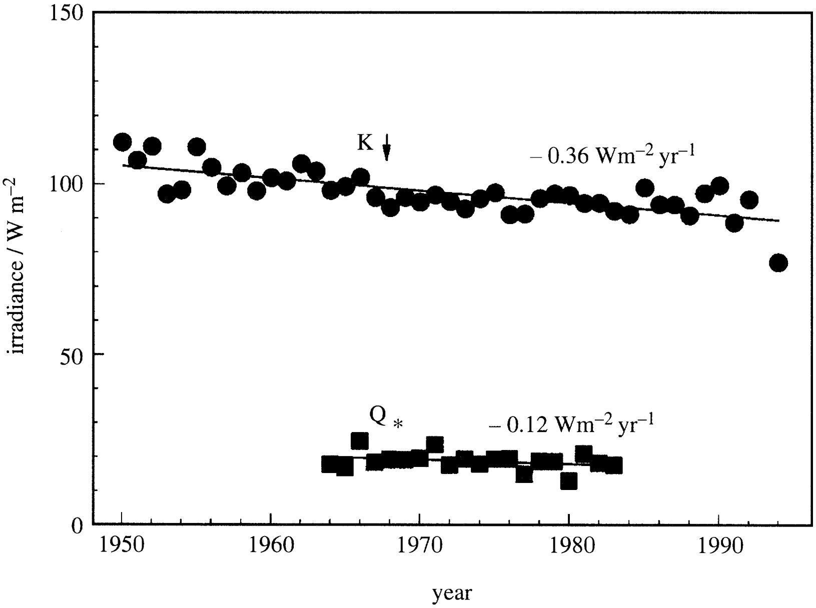

Figure 1. Changes in global irradiance and radiation balance within the Arctic Circle, 1950–1994. Average annual means for all complete years of measurements of the series listed in table 1.

The mean annual reduction in $K\downarrow$ within the Arctic Circle illustrated in figure 1 was 0.37% at individual sites. The average of annual reductions at individual sites was 0.15%. Decreases in monthly values of $K\downarrow$ were proportional to the irradiances and averaged 0.5% per year.

The area distribution of changes in $K\downarrow$, shown in figure 2, indicates reductions in the western sectors of the Arctic from Alaska to the Barents Sea; the small number of significant increases in irradiance were confined to central and eastern Siberia.

(ii) *Radiation balance*

Annual sums of Q_* averaged for each of the 21 years of data available between 1964 and 1984 are shown in figure 1. The calculated linear decrease of 0.12 W m^{-2} per year was not statistically significant.

The statistically significant trends found in monthly and annual values of Q_* at individual sites are presented in table 3 as the slope of linear regressions on year of measurement. As was the case with global irradiance, little statistical advantage was derived from substituting a quadratic in place of a linear relationship.

Ten out of the 11 Arctic measurement series had significant linear trends in Q_*; 29% of all changes in monthly means were significant, but only two of the 11 changes

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Data sources for table 1. [A] Monthly Bulletins, Solar Radiation and Radiation Balance Data (The World Network), Voeikov Main Geophysical Observatory, St. Petersburg, Russia (since 1964). [B] Atmospheric Environment Service, Ontario, Canada. [C] Norsk Polarinstitutt Arbok (1974–9); Meddel Nr 118 (1992, 1981–87); V. Hisdal, personal communication (1994, 1988–92). [D] Norsk Meteorological Institute Arbok (1970–9); Norsk Meteorological Institute (1994, 1980–92). [E] Climate Monitoring and Diagnostics Laboratory NOAA, E. G. Dutton, personal communication (1994). [F] Marshanova and Chernigorskii (1978). [G] Sverges Meteorological and Hydrological Institute, personal communication, W. Josefson (1994). [H] Finnish Meteorological Service (1994). [I] Global Radiation in Iceland, M. A. Einarsson (1969); Iceland Meteorological Office (1994).

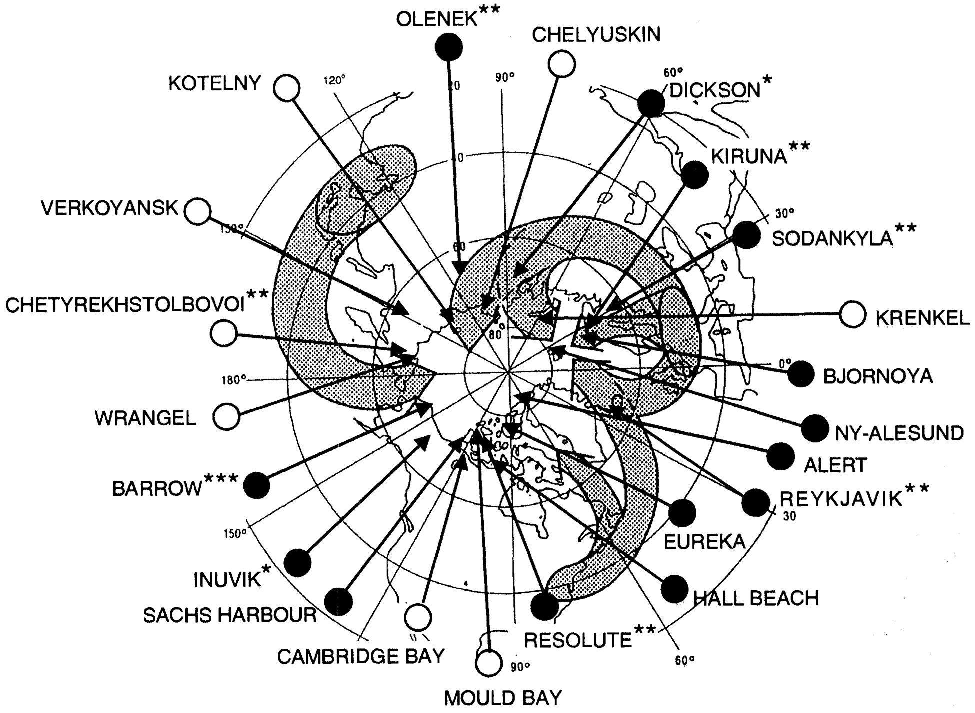

Figure 2. Mean annual changes in global irradiance within the Arctic Circle with location of pyranometer stations; closed circles indicate a decrease in irradiance, open circles an increase. The probability level of the fitted linear regression on year of measurement indicated by one star for $p = 0.05$, two for $p = 0.01$, and three for $p = 0.001$. Major sources and pathways for transport of pollutants between midlatitudes and the Arctic after Jaworowski (1989).

in annual sums were. Both of these trends in annual sums were negative, as were 60% of the significant trends in monthly values.

Neither the size nor the sign of the significant trends in Q_* were related to the size or sign of the radiation balance; the trends were of the same magnitude for increases and decreases.

The seasonal distribution of significant trends in Q_* was similar to that described for $K\downarrow$; 29% of the trends, nearly all of which were negative, occurred in March and April and 50% between February and May; only 3% of the significant changes occurred in September and October.

(*c*) *Discussion*

(i) *Causes of reduction in global irradiance*

The most common response to reports of large reductions in global irradiance is to question the accuracy of the measurements analysed. While instrumental errors cannot be excluded in individual cases, they are extremely unlikely to be the cause of the significant trends found in the large data base used in this study, which consists of measurements from a number of national meteorological services using a variety of pyranometer models of known accuracies, independently calibrated and operated. Many of the differences found in this data base exceed the random errors of measurement to be expected and the uncertainties of calibration procedures and of the standards on which these are based (WMO 1981).

Table 2. *Significant trends in global irradiance in the Arctic* (W m^{-2} a^{-1})

site	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	year
Alert Canada		**0.01**	**−0.17**	**−0.94**					−0.38	*−0.02*			
Krenkel former USSR		*0.01*	0.24		*−0.79*			1.02					
Eureka Canada		0.01											
Ny Alesund Norway													
Chelyuskin former USSR		*0.02*						*0.71*					
Mould Bay Canada		*−0.04*	**−0.45**		*−1.18*				**−0.69**		0.01		
Kotelny Is. former USSR			*0.25*							0.14			
Resolute Canada		*−0.04*	**−0.47**	−0.72	**−1.43**	**−1.85**			*−0.29*	−0.11			−0.52
Bjornoya Norway			−0.67	−2.40									
Dickson Is. former USSR													
Sachs Harbour Canada	**−0.002**				2.88								
Barrow USA	−0.03	**−0.30**	**−0.54**	**−0.81**	−0.84	*−0.87*							**−0.23**
Wrangel Is. former USSR													
Chetyrkhstolbovoi former USSR													
Cambridge Bay Canada			−0.16	−0.37						−0.49	*−0.06*		
Hallbeach Canada													
Olenek former USSR					*1.45*						*−0.06*	*−0.02*	
Inuvik Canada	−0.03	**−0.13**	−0.27	**−0.60**	*−0.57*					*−0.14*		*0.01*	*−0.06*
Kiruna Sweden	**0.06**	*−0.21*										**0.01**	**−0.06**
Verkoyansk former USSR		*0.02*		*0.30*					*0.42*			**−0.03**	
Sodankyla Finland			−0.38				−1.07					*0.01*	−0.11
Reykjavik Iceland							−1.69		0.17				−0.17

Bold values indicate significance at $P = 0.001$, plain at $P = 0.01$, *italic* at $P = 0.05$.

Changes in solar output, i.e. in the extra-terrestrial flux at the top of the earth's atmosphere, can also be excluded as the cause of the sometimes large but spatially variable reductions of $K\downarrow$ within the Arctic Circle. This is because of the spatial variation of the changes in $K\downarrow$, and also as the amplitude of the cyclic changes measured above the atmosphere are an order of magnitude less than the trends measured at the surface (Hartmann *et al.* 1993).

Increasing concentrations of radiatively active gases in the atmosphere can also be excluded as the cause of decreases in $K\downarrow$ as their prime effect on solar transmission will result from an increased water vapour concentration of the atmosphere following

Table 3. *Significant trends in radiation balance in the Arctic* (W m^{-2} a^{-1})

site	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	year
Alert Canada			**−0.75**				**−1.29**						
Krenkel former USSR			*−0.44*		*−0.88*		2.12				*−0.52*	*−0.54*	
Chelyuskin former USSR						**2.41**		*0.78*					
Mould Bay Canada			*−0.52*	*−0.89*			*−1.46*						-2.25
Kotelny Is. former USSR		**−1.20**	**−1.20**	**−1.76**	−1.56						**−1.16**	**−0.97**	**−0.82**
Resolute Canada	0.91	0.91	0.61	*−0.90*						**0.98**	**1.15**	**0.90**	
Dickson Is. former USSR		−0.41	−0.60	−0.75	*−1.09*		*−1.67*						
Wrangel Is. former USSR													
Chetyrekstolbovoi former USSR								*0.78*		**0.71**			
Olenek former USSR	**0.58**	0.41			*−2.23*						**0.65**	**0.57**	
Verkoyansk former USSR				*1.63*									

Bold values indicate significance at $P = 0.001$, plain at $P = 0.01$, *italic* at $P = 0.05$.

any heating which occurs. The simulated result of a doubling of CO_2 will be to reduce $K\downarrow$ by 5% (Wilson & Mitchell 1987).

Changes in the amount of cloud cover would have to be large to account for the reductions in $K\downarrow$ reported given the high transmissivity of Arctic cloud caused by their characteristically low water content and shallow depth (Gavrilova 1966). Using the mean value of transmissivity derived from three Arctic stations whose data are listed by Gavrilova, an annual increase of 0.4% in cloud cover is required to account for the average decrease in $K\downarrow$ of 0.36% a^{-1} shown in figure 1. An analysis of cloud cover observations made at seven Arctic stations during the last 50 years shows no evidence for any monotonic trends (Raatz 1981).

A substantial reduction in short wave irradiance reflected from the surface $K\uparrow$ would cause a decrease in $K\downarrow$ due to the close linkage between the two radiant fluxes under polar conditions (Hisdal 1982; Gardner 1987). Such a reduction could be caused by a lower surface reflectivity $K\uparrow\ K\downarrow^{-1}$ due to pollution or by a reduction in the area and duration of the Arctic sea ice cover. However, no evidence of a substantial or statistically significant interannual change – either in specific regions or in the total extent of Arctic sea ice – was found in an analysis of passive-microwave observations by satellites between 1978 and 1987 (Gloersen *et al.* 1992).

Aerosols brought into the Arctic atmosphere by incursions of polluted air from lower latitudes are almost certainly the major cause of the reductions in $K\downarrow$ reported in this paper. Their direct effect is to increase the scattering and absorption of short-wave radiation in the atmosphere and so reduce the flux transmitted to the surface. Indirectly, aerosol-cloud interactions modifying the microphysical properties of cloud and haze (Hobbs 1993) have the same effect. Another indirect and longer term effect of an increase in aerosol load, especially of carbon of anthropogenic origin, would result from their deposition on snow and ice surfaces, reducing their reflectivity and hastening their transformation into less reflective water surfaces. The results of five studies of the effects of Arctic aerosols on the solar irradiance absorbed at the surface have been tabulated by Blanchet (1991). Irradiance was reduced in all but one of the 19 model evaluations by amounts which ranged from +0.8 to −7.7 W m^{-2} and averaged −3.3 W m^{-2}. This corresponds to the measured mean reduction in Arctic $K\downarrow$ over a nine year period (figure 1).

Valero & Ackerman (1986) estimated the effect of Arctic haze on $K\downarrow$ at Barrow, Alaska, using a series of radiation profiles measured under cloud-free conditions in March 1983. They calculated a 20% reduction in net solar irradiance at the surface for both ice- and water-covered surfaces. This equals the reduction in $K\downarrow$ at Barrow measured between 1950 and 1983 (table 2).

(ii) *Causes of compensating changes in long-wave components of the radiation balance*

The radiation balance equation

$$Q_* = K\downarrow - K\uparrow + L\downarrow - L\downarrow,$$

where Q_*, $K\downarrow$ and $K\uparrow$ are as previously defined, and $L\downarrow$ and $L\uparrow$ are, respectively, the downwelling long wave atmospheric irradiance and the upwelling longwave terrestrial irradiance emitted from the surface, indicates that the 0.36 W m^{-2} mean annual reduction in $K\downarrow$ reported herein, must, in the absence of any significant change in the average value of Q_* (figure 1), be compensated either by increases in $L\downarrow$ or decreases in $L\uparrow$ and $K\uparrow$.

The increase in $L\downarrow$ due to the increased concentration of radiatively active gases in the atmosphere has been estimated to have averaged 0.06 W $\mathrm{m}^{-2}\ \mathrm{a}^{-1}$ over the last decade (Shine *et al.* 1990).

The decrease in radiating surface temperature required to compensate fully for the averaged observed reduction in $K\downarrow$, is 0.07 °C per year, far greater than that observed in the long-term measurements series of Arctic surface temperatures analysed.

A decrease in $K\uparrow$ can be excluded as the cause of the reduction in $K\downarrow$ in the absence of evidence for a substantial decrease in the extent of ice cover, and hence short wave reflectivity, in the Arctic (Gloersen *et al.* 1992).

Thus the mechanism whereby the radiation balance at the Arctic surface has remained unchanged despite the decline in global irradiance, is not clear.

3. Changes in Antarctic irradiance

Increases in the surface air temperature of Antarctica measured during this century are among the highest recorded in the world (Braaten & Dreschkhoff 1992; Jacka & Budd 1992; Jones 1990; King 1994; Raper *et al.* 1984); this is in marked contrast both to the absence of warming in the Arctic and current predictions of transient global circulation models (Houghton *et al.* 1992).

This interpolar anomaly could be caused by the lower concentrations of pollutants in the southern polar regions due to the lesser industrial activity, population and land area of the Southern Hemisphere. The distribution of anthropogenic sulphate aerosols over the globe supports this explanation; their calculated atmospheric burden over the Southern Hemisphere is one-third of that over the Northern Hemisphere

(Charlson *et al.* 1991). A similar ratio between the two hemispheres was found in the reduction of $K\downarrow$ between 1958 and 1985: -0.44 W m^{-2} a^{-1} for the Northern and -0.14 W m^{-2} a^{-1} for the Southern Hemisphere (Stanhill & Moreshet 1992).

Pollutant levels measured in the two polar regions show a somewhat smaller but significant difference. The results of 16 studies tabulated by Heintzenberg (1989) show the concentration of particulates measured at the South Pole during the summer to be half of that measured in the Arctic. A similar ratio was found between the number of condensation nuclei and their rates of increase between 1974 and 1990, as measured continuously at the South Pole and at Barrow, Alaska (Kane 1994).

If pollution caused the reduction in $K\downarrow$ found in the Arctic, changes in Antarctic irradiance should be smaller in magnitude and spatially and seasonally more uniform than in the northern polar regions, because of the much longer pathways for anthropogenic aerosols reaching the southern polar regions. To test this hypothesis, the limited measurements of $K\downarrow$ and Q_* available for Antarctica were analysed.

(*a*) *Data and results*

Altogether 174 complete years of global irradiance measurements were obtained from ten sites; radiation balance was also measured at five of these sites, yielding 71 complete years of data. All but two of the measurement sites were at the coast between 70° W and 170° E. The two inland sites were at the South Pole at an elevation of 2800 m, and at Vostok (78°27′ S, 106°52′ E, 3488 m) near the Pole of Inaccessibility of the contiguous continent.

Annual sums of $K\downarrow$, averaged for each of the 34 years between 1957 and 1991 when complete years of data were available, decreased significantly, $p = 0.05$, with year of measurement; the calculated linear decrease was 0.33 W m^{-2} per year.

Significant reductions in $K\downarrow$ were found at three-quarters of the Antarctic sites; no increases were found. At the individual sites one-fifth of the monthly and annual reductions in $K\downarrow$ were statistically significant. No seasonal difference in the reductions of $K\downarrow$ were apparent when expressed relatively. The largest annual reductions in $K\downarrow$ were found in the eastern sector of the continent between 30° E and 170° E.

Annual sums of Q_* averaged for each of the 25 years between 1957 and 1987 for which complete years of data were available, increased significantly, $p = 0.01$, with year of measurement: the calculated linear increase was 1.03 W m^{-2} a^{-1}. By contrast, at individual sites increases in annual sums of Q_* were apparent only at Faraday and Novolazarevskaya, two of the four sites with long and complete series of measurements.

Monthly values of Q_* and $K\downarrow$ were highly correlated, $r > 0.9$, at all four sites, without the hysteresis in the seasonal relationship found at Arctic sites. At Novolazarevskaya the slopes and offsets of the linear seasonal relationship between Q_* and $K\downarrow$ increased from 1964 to 1987, reflecting the 25% increase in Q_* and 2.3% decrease in $K\downarrow$ which occurred.

4. Interpolar anomalies

The overall decrease in $K\downarrow$ measured in Antarctica, 0.33 W m^{-2} a^{-1}, is surprisingly large. It is greater than that of the Southern Hemisphere as a whole (Stanhill & Moreshet 1992) and similar to that found in the Arctic, despite the lower levels of pollution and higher levels of surface heating occurring in the southern polar regions.

The reduction cannot be attributed to a large or significant increase in cloud cover, as no evidence for such a change was found in an analysis of observations from five Antarctic sites, including the continental radiation measurement station at Vostok, over the 1957–1985 period (Zav'ialova & Zhukova 1990). Nor is there any evidence for a large or significant decrease in the extent of Antarctic sea ice which, by reducing short-wave reflectance, could have caused a reduction in $K{\downarrow}$ (Gloersen *et al.* 1992).

The large overall increase in Q_* measured in Antarctica is even more surprising, although it is consistent with the anomalously rapid surface warming reported for the Antarctic. Moreover, this warming, averaging 0.028 °C per year at 15 coastal stations (Jacka & Budd 1992), would lead to a small decrease in Q_* through a greater emission of terrestrial irradiance from the surface.

The increase in Q_* is far greater than can be accounted for by the increase in long wave atmospheric radiation to the surface resulting caused by the greater concentration of radiatively active gases. Globally, this radiative forcing has increased by 0.97 $\mathrm{W\,m^{-2}}$ since 1960 and by 0.06 $\mathrm{W\,m^{-2}\,a^{-1}}$ during the last decade (Shine *et al.* 1990). These calculations do not, however, include the recently demonstrated effect of ozone depletion in reducing solar irradiance (Isaksen 1994).

Thus, in the Antarctic as in the Arctic, the cause of the changes in the components of the surface radiation balance are not clear: in part this uncertainty is attributable to the limited number and duration, as well as accuracy, of the measurement series available.

5. Conclusions

The magnitude of the reduction in global irradiance measured within the Arctic during the last four decades and its seasonal and spatial variation support the hypothesis that this decline was caused by incursions of polluted air. This reduced irradiance may, by compensating for radiative forcing due to the increased concentration of radiatively active trace gases, have prevented warming of the Arctic surface.

The absence of a corresponding decrease in the measured values of the surface radiation balance could not be explained by compensating changes in other components of the radiation balance.

Reductions in global irradiance measured in Antarctica were of similar magnitude to those found in the Arctic despite the lower level of pollutants in the southern polar region. This reduction in $K{\downarrow}$ was accompanied by a much larger increase in the surface radiation balance. Although this is compatible with the rapid surface warming reported in Antarctica, no explanation of these interpolar anomalies was found.

A better understanding of the changes in the polar radiation balances, which are of global as well as regional importance for climate change, will require a sustained program of measurements in which all of the components of the surface radiation and energy balances are monitored to the maximum accuracy currently attainable.

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Discussion

T. V. CALLAGHAN (*Centre for Arctic Biology, School of Biological Sciences, University of Manchester, UK*). Professor Stanhill has stated that there is no evidence of climatic warming so far in the Arctic. This observation conflicts with results from the collation of temperature data from official meteoroligical sations throughout the Arctic (Jones & Briffa 1992). Their definitive study has shown that some areas of the Arctic have experienced increases in annual mean temperature of up to 4.5 °C over the 30 year period 1960–1990. Jones & Briffa (1992) also show that other areas of the Arctic, such as Fennoscandia, have not experienced recent changes in temperature while the Baffin Bay–West Greenland region has sent recent cooling.

G. STANHILL. Thank you for drawing my attention to this valuable reference.

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