Recent Interannual Variations in Solar Radiation, Cloudiness, and Surface Temperature at the South Pole

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ABSTRACT

Incoming global solar irradiance measured at the surface at the South Pole unexpectedly decreased steadily by 15% from 1976 through 1987 during the late austral summer season, whereas no trend is apparent for September through December. February's irradiance trend, $-1.24\%\ \mathrm{yr}^{-1}$ on the average, is statistically significant at greater than the 99.9% confidence level. The irradiance observations were made continuously with the same calibrated sensor and are confirmed by a second simultaneous solar irradiance measurement series. Associated changes in seasonal sky cover (clouds) and surface air temperature were also observed. Seasonally increasing cloud cover is directly associated with the decreasing irradiance trends, whereas temperatures show a warming trend significant only in March, followed by a cooling trend significant only in May. Cloudiness and temperature records for 32 years suggest that the observed cloudiness trend began in the late 1970s, while the temperature trends become apparent only in the early 1980s. The observed sensitivity of total global solar irradiance to the change in sky cover is roughly six percent per one-tenth and is shown to vary spectrally. Although the annual averages of solar irradiance at the South Pole display an overall decrease between 1976 and 1989, the most recent years in this period show some recovery from earlier declines. Likewise, the downward trends in January and February irradiance diminished in 1988 and 1989.

1. Introduction

Clouds have two well-known important effects on the surface energy budget: shortwave cooling and infrared warming. Ramanathan et al. (1989) showed that globally the shortwave cooling effect of clouds is greater than the infrared warming. However, regionally, especially at high latitudes as suggested by Ramanathan et al., when highly reflective surfaces are considered, the net effect of clouds can be one of warming. This may particularly be true if horizontal and vertical advective heat transport are considered. Some evidence for this is observed at the South Pole region where our measurements between 1976 and 1987 show a nearly steady, large, year-to-year decrease in solar irradiance at the surface in the late austral summer (Jan–Mar). In this paper, we examine the year-to-year variability in the weekly, monthly, and yearly average solar irradiance observed at the South Pole for the period 1976–89, as well as monthly averages of observed sky cover and surface air temperature. Observed increasing sky cover is responsible for the irradiance decrease. Surface air temperatures show a slight warming and then a cooling trend in the 3 months immediately after those months with the greatest downward irradiance trends. March has the largest year-to-year warming trend; in April there is a transition leading to a cooling trend during May. The exact relationship, if any, between the irradiance and temperature trends is not known.

Observed changes in long-term solar irradiance associated with observed changes in total sky cover were reported recently by Russak (1990) for northern Europe. Russak attributes the observed changes to variations in atmospheric circulation. Long-term changes in cloudiness alone over North America and Europe were reported by Henderson-Sellers (1986a,b), who suggested that the increased cloudiness may be related to warming trends. A recent paper on the visually observed sky cover at the South Pole by Schneider et al. (1989) did not report any trends but noted the likelihood of daylight versus dark biases in the record. Specific effects of clouds on the surface radiation budgets at high latitudes were discussed by Cogley and Henderson-Sellers (1984) and Stone et al. (1990).

Recently much attention has been given to analyzing long-term temperature records for trends related to hypothetical radiation budget trends unrelated directly to cloudiness. Sansom (1989) looked at long-term surface temperature records in the Antarctic, and specifically at the South Pole, but did not note the interannual variations reported here. According to Sansom, the annual mean surface temperature at the South Pole

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does not show a significant trend, although some cooling is indicated. Jones (1988) showed that although the Southern Hemisphere is warming, much of the Antarctic plateau is cooling at the rate of about 0.25°C decade^{-1}, based on 1967–86 data. Trenberth and Olson (1989) looked at South Pole upper-air temperatures at levels above 500 mb and found noticeable downward trends between 50 and 100 mb during October and November but did not extend their analysis to the surface.

The purpose of our measurements at the South Pole is to determine the steady state and the variability of the surface radiation balance by making long-term continuous measurements. We have detected, and are reporting here, interannually autocorrelated variations in solar irradiance, cloudiness, and temperature, whose ultimate causes are unknown. Because of the gentle topography, the similar geography, and the radiation regime of the Antarctic plateau (Schwerdtfeger 1984), South Pole observations of cloudiness and solar irradiance should be representative of an extended region, although the actual extent of areal representativeness is not further explored in this paper.

2. Data description

Solar radiation data used in this study were collected by the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL) [formerly Geophysical Monitoring for Climatic Change (GMCC)]. Details of the observational procedures and some detailed data summaries were given by Dutton et al. (1989). The results of observations from two simultaneously operated pyranometers are used here. One of the pyranometers measures over the wavelength range of 0.3–2.8 μm (referred to hereafter as Q, for the quartz-filter pyranometer), and the other instrument measures over the wavelength range of 0.695–2.8 μm (referred to hereafter as RG8 because of the red RG8 Schott glass filter used). The instruments are identical except for the lower cutoff wavelength of the filters. Results from both instruments are used in this work for mutual verification of observed long-term signals. The instruments have operated side by side at the site since 1976.

The absolute calibrations of the solar radiometers were consistently maintained over the period of record by periodic side-by-side comparisons with recently calibrated instruments sent to the pole and by beginning- and end-point calibrations. The end-point calibrations were related directly to absolute active cavity radiometers (ACRs). The South Pole period of record begins before ACRs became accepted standards for solar irradiance measurements, but pyranometer calibrations before and after the advent of ACRs are traceable to the International Pyrheliometer Comparisons (IPC) sponsored by the World Meteorological Organization (WMO) in Davos, Switzerland (World Radiation Center, Davos, 1976). The IPC defined the modern international "absolute" scale to which the CMDL observations are referenced. The CMDL irradiance data have been corrected for all known calibration-scale shifts and long-term instrument sensitivity drifts. The long-term repeatability of the measurement, i.e., precision, is further improved when data are averaged over similar temperature and solar geometry conditions, as done in the analysis here. The maximum relative uncertainty due to instrument calibration in the monthly and annual average irradiance data used here, when compared with successive years, should be less than 1% or 3 W m^{-2}, whichever is largest, over the entire record. The absolute accuracy of the irradiance data is within the largest of 3% or 10 W m^{-2}, which is slightly worse than typically achievable. This is due in part to small solar elevation angles and extreme temperatures. However, no corrections to the irradiance data for temperature or cosine response errors were necessary for the current study, because those errors are small and constant, assuming that the ratio of diffuse to total irradiance does not change from year to year. The cosine error induced by changes in the ratio of diffuse to global irradiance due to increasing cloudiness is insignificant because of the excellent cosine response of the Q pyranometer used at the South Pole. The maximum correctable absolute error remaining in the monthly data given here is less than 4 W m^{-2}.

The time resolution of the data used here is 1 h based on averages of data sampled at 1 Hz and recorded as 1- or 3-min averages. Gaps of less than 10 min within an hour are filled by interpolation. This database for 1976–89 constitutes the primary CMDL irradiance database and is the starting point for the current study. There are, however, a few data gaps of up to several weeks in the record.

Data gaps present a particular problem when calculating monthly or yearly averages of a highly seasonally varying quantity such as high-latitude solar irradiance because a gap of just a few days can cause a large bias in the resulting average. This bias results because the expected values are not randomly distributed within the averaging time. For the purpose of examining monthly or yearly averages for long-term variations, it is desirable to remove the biases introduced by data gaps and hence reduce artificial variance in the record. We chose an interpolation method for filling the data gaps rather than using modeled or climatological values because interpolation is the most physically realistic means suitable in the presence of any long-term variation. Filled data obviously do not replace real data and cannot be used for analyses of short-term variations but are suitable for analyses presented here.

The data were filled as follows: gaps of 1 h were interpolated from adjoining hours. Gaps of greater than 1 h and less than 3 days were filled by interpolation from adjoining days. Gaps of greater than 3 days were filled by interpolation from adjoining years. The 3-day limit was chosen because after 3 days nearly all the autocorrelation in the hourly data is due to the annual cycle, and therefore, data from identical hours in adjoining years is more appropriate than from more distant days of the same year. Extrapolation from immediately adjacent hours, days, or years was used in the event that data were not available on both sides of the gap. A few hours remain unfilled because of insufficient adjoining data. Table 1 shows the percentage of data filled by each procedure for each year. A relatively small amount of data needed to be filled, except for 1976 and 1984, in which one-third of the data were filled from adjoining years. The missing data in 1976 were primarily in March, September, October, and November, and missing data in 1984 were mostly in March and December. Filling the 1976 and 1984 data primarily from adjoining years has little effect on the analysis except for September RG8 data discussed later. Table 1 also shows that the percentage of hours that remained unfilled is insignificant. By filling the data in the manner described here we avoid aliasing the annual cycle into interannual and long-term variability, which can happen as discussed by Trenberth and Olson (1989).

Two independent surface-temperature records were also used in the following analysis. One record is the continuous near-surface air-temperature measurement record maintained by CMDL since 1976, and the other is the routine synoptic surface air-temperature measurement, which is continuous since 1957. The observations at synoptic times are made by National Science Foundation (NSF) contract weather observers (US National Weather Service employees prior to 1974) using guidelines of the WMO for synoptic and climatic observations. The synoptic temperature data were obtained from the National Climatic Data Center (NCDC) in Asheville, North Carolina. Although both temperature records indicated the same major features, the two were averaged together for 1976–88 to get a better representation. The NCDC temperature record was also used in the previously mentioned study by Sansom (1989).

The sky cover observations are acquired visually by the South Pole weather observers who follow procedures consistent with the National Weather Service. The sky cover observations are made at synoptic reporting times and are also available from NCDC. The number of observations per day has varied over the years and within any given year, depending in part on local aviation activity. Visual cloud observations at any location are subject to several potential biases and have been discussed by Hoyt (1977), Henderson-Sellers (1986a,b), Schneider et al. (1989), and others. Individual observations of sky cover are reported in terms of tenths of sky covered by cloud or other visible sky obstruction from the vantage point of a single ground-based observer. The observations are somewhat subjective, and little confidence can be placed in differences of one- or two-tenths for a single observation. Also, individual observer biases may affect many observations. Most of these problems should not affect long-term variations in the observations, partly since the observers were generally replaced at the pole yearly.

TABLE 1. Annual percentage of data filled from the adjoining hour, day, or year, and of data unfilled. Percentages based on the total number of hours that the sun is above the horizon each year.

	Hour	Day	Year	Unfilled
1976	0.8	6.7	38.7	0.8
1977	0.5	6.1	10.2	0.3
1978	0.2	1.7	2.2	0.0
1979	1.2	3.2	8.1	0.0
1980	2.4	2.5	11.4	0.0
1981	2.4	3.5	15.0	0.04
1982	1.5	2.3	2.6	0.0
1983	2.2	2.8	0.3	0.0
1984	1.4	1.7	30.4	0.0
1985	1.7	1.4	3.6	0.0
1986	2.0	2.0	4.5	0.0
1987	2.0	1.4	0.1	0.0
1988	0.7	2.7	1.0	0.0
1989	0.1	3.1	1.6	0.0

3. Analysis of solar radiation data

The processed solar-irradiance data are in the form of hourly averages in units of watts per meter squared. After the missing hours were filled by the procedure described in section 2, monthly and yearly averages were calculated. Figures 1a and 1b show the annual Q and RG8 solar irradiance averages, respectively, for all hours when the sun was above the horizon (refraction is neglected, which results in several sunlit hours per year being excluded from the averages). The apparent features in the Q data show a decrease between 1978 and 1980 and partial recovery between 1985 and 1989. The RG8 data show similar variation.

The significance of the apparent multiyear decrease and then increase in the annual irradiance can be better assessed by examining the quality of a least squares fit to the data by a suitable smoothly varying analytical function. Some amount of autocorrelation in the data is apparent. Since there is an obvious decrease and subsequent increase in the data, a second-degree polynomial was chosen to be fit to the data. This is not to suggest that a quadratic process is responsible for the observed data or that the resulting fit has any meaning beyond the observed data. The resulting least squares fits are plotted in Fig. 1. The similarity between the two data records is evident in the values of coefficients of the fitted curves given in Table 2. The fitted curves account for 81% and 90% of the interannual variance for the Q and RG8 spectral regions, respectively. Therefore, nearly all the interannual variability is ac-

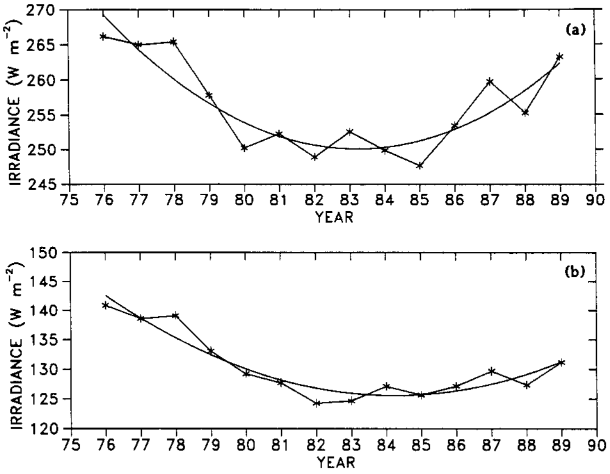

FIG. 1. Annual average solar irradiance at the South Pole and a second-degree polynomial least squares fit, 1976–89: (a) Q wavelengths; (b) RG8 wavelengths.

counted for by a gradual decrease and subsequent increase over the period of record.

To examine further the interannual autocorrelated variation in the South Pole solar-irradiance data, we plotted the monthly average Q and RG8 irradiances for 1976–89 (Figs. 2 and 3). Visual inspection of Figs. 2 and 3 suggests a general decrease in irradiance during the months of January and February from the beginning of the record until around 1986 or 1987 with the other months showing no consistent changes. Both the Q and RG8 display strikingly similar variability. The significance of the January and February decrease is examined by least square fitting a straight line to the 1976–87 portion of the record for each month. Table 3 gives results of the least squares linear fit for both the Q and RG8 irradiance data for 1976–87. The significance levels are based on normality of the residuals and the Student's t statistic for small sample sizes. The slope for January and February Q irradiance is less than zero at the <0.003 level of significance, whereas the percentage trend for March, when the sun sets, is the largest but is not statistically significant. It is seen that the RG8 data generally repeat the Q results in Table 3, except for September where a significant negative trend is indicated for RG8. The indicated September RG8 slope is, however, erroneous because all of September 1976 was missing and was filled from anomalously high 1977 values (Fig. 3). September also has the weakest signal and is subject to greater percent uncertainty. Nonetheless, this demonstrates the potential for incorrect trend results if the data-filling procedures are not monitored. Also demonstrated is the sensitivity of the present analysis to individual data points because of the small sample size.

The RG8 results independently verify the Q results. It should be noted that although the Q and RG8 data are acquired from separate instruments that are individually calibrated and edited, common data acquisition and processing computer hardware and software are used. Additional confidence is given to the observed seasonal and monthly irradiance variations because the same instruments were used over the entire period and observing conditions are nearly symmetrical about 21 December.

Examination of the monthly average irradiance time series suggests that the decrease in the annual averages are caused mostly by reductions in the late summer between 1976 and 1987, whereas the recovery in the last half of the annual average record is due to a tendency towards higher values (note points above the trend line in Figs. 2 and 3) for most months since about 1985.

Better identification of the yearly onset of the anomalous late summer solar-irradiance decrease between 1976 and 1987 is obtained by analyzing weekly average irradiance data from successive years for trends in a manner similar to the monthly analysis. The magnitude and the 95% confidence intervals for the trends in the weekly Q data are given in Fig. 4. The first two weeks after sunrise and the last two before sunset were not included because of large sample variances resulting in large confidence intervals. The slopes first became consistently and significantly negative during the second week in January (16 weeks after sunrise). Once the weekly trends made the transition to significantly negative they remained negative. Therefore, January is a transition month, and its monthly average irradiance slope statistics (Table 3) are not as representative as those for other months such as February or December.

4. Analysis of cloud data

Because the magnitudes of the observed trends in monthly solar irradiances between 1976 and 1987 are so large, changes in clouds, rather than aerosols, water vapor, or other trace gases, are suspected of being the cause. Solar irradiance models like LOWTRAN 6 (Kneizys et al. 1983) and that of Bird and Riordan (1986) have been used to show that even extreme amounts of water vapor are unable to produce a 15% decrease in global solar irradiance and that only unrealistic aerosols could account for such a decrease. Separate and independent remote sensing measure-

TABLE 2. Second-degree polynomial fit results for the annual average Q and RG8 pyranometer data, 1976–89. Annual average irradiance (W m^{-2}) = $a + bt + ct^2$, where t is 2-digit year. SL is significance level and R^2 is the correlation coefficient squared for the fit.

	a	SL	b	SL	c	SL	R^2
Q	2794	<0.001	−61.1	0.001	0.367	0.001	0.81
RG8	1903	<0.001	−42.2	<0.001	0.251	<0.001	0.90

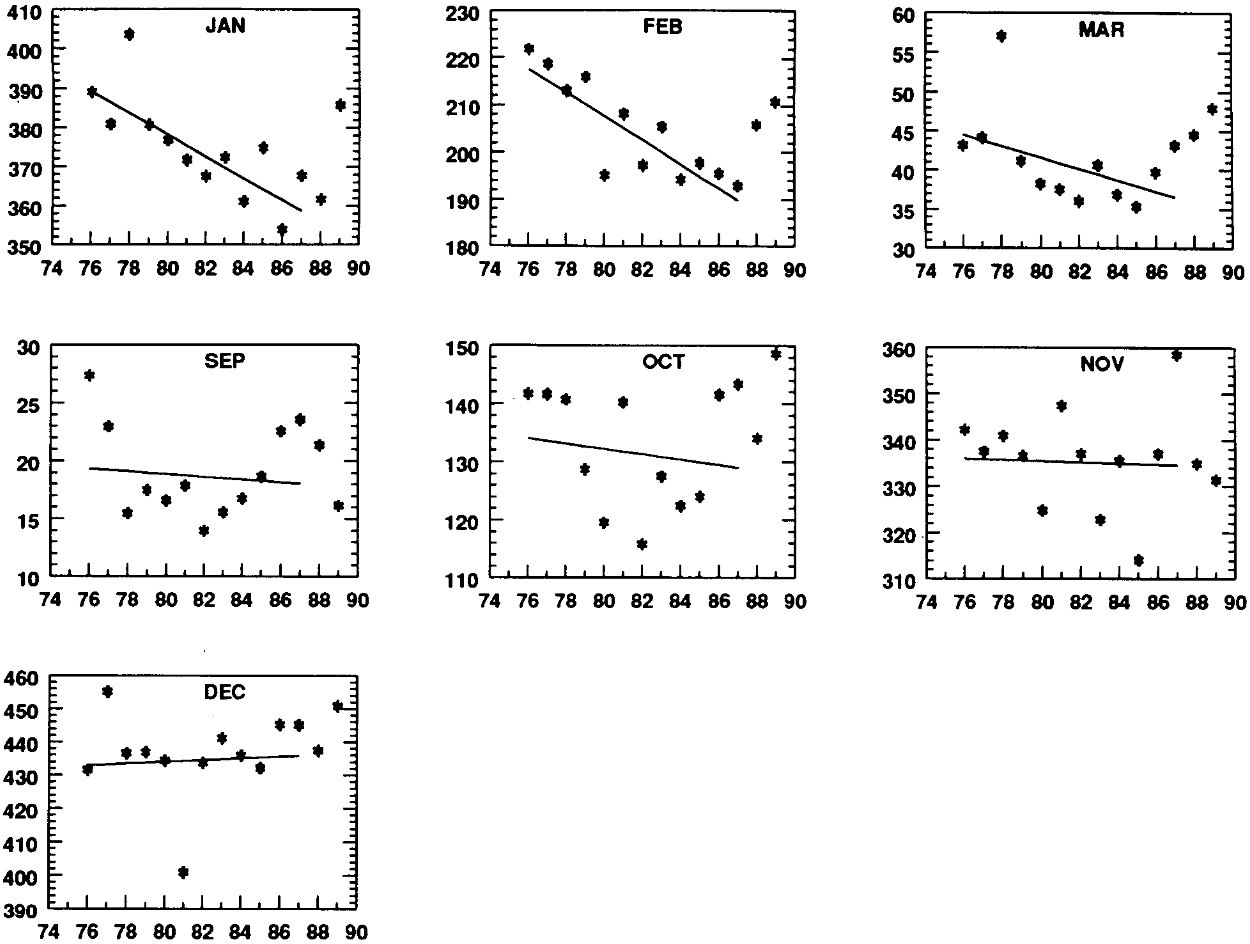

FIG. 2. Time series of monthly average Q solar irradiance in W m^{-2} versus year, 1976–89. One time series is plotted for each month as indicated, and a linear least squares line is fitted to each series through 1987. Note that each month is scaled differently according to the range in the data. See Table 3 for statistics relating to the least squares fits to the 1976–87 time period.

ments of clear-sky aerosol and water vapor attenuation are maintained by CMDL at the South Pole and indicate no changes since 1976 except for a 0.04 aerosol optical depth increase in 1983 following the 1983 eruption of El Chichón (Bodhaine 1988).

The most consistent routine digital information about clouds at the South Pole is the synoptic observations of clouds and sky cover. Although the visual cloud observations are not adequate for accurately quantifying cloud radiative effects, monthly and seasonally averaged sky cover amounts are used here to determine if there is any relationship with the solar irradiance measurements. Time series of individual monthly averages of South Pole sky cover were first examined. Positive trends in sky cover significantly larger than zero at the 0.005 level were detected for the January and February averages from 1976 to 1988. To illustrate changes in sky cover data, we show in Fig. 5 the 3-month averages of the sky cover data with a 1–2–1 running annual smoother applied. An increase of sky cover by two-tenths over the 12-yr period is indicated for January–March, but the other three 3-month intervals show no such tendencies. Although the sky cover data are subjective in nature, there is a strong suggestion of an observed increase in cloudiness for the late summer months that corresponds to, and is responsible for, the observed decrease in solar irradiance. However, there is sufficient natural noise in both datasets that the direct correlation between the two on any shorter time scale is low.

The available information is insufficient to determine if the 1988 and 1989 cloudiness data correspond to the recovery in the January and February irradiance record.

The sensitivity of the observed solar irradiance to an actual change in cloud cover at the South Pole can be estimated by dividing the 12-yr decrease in solar irradiance by the corresponding sky cover increase, using the indicated change in cloudiness from Fig. 5a. The sensitivity for the observed January and February irradiance decrease between 1976 and 1987 is 5.9% and 7.3% (±1%) for a one-tenth increase in sky cover,

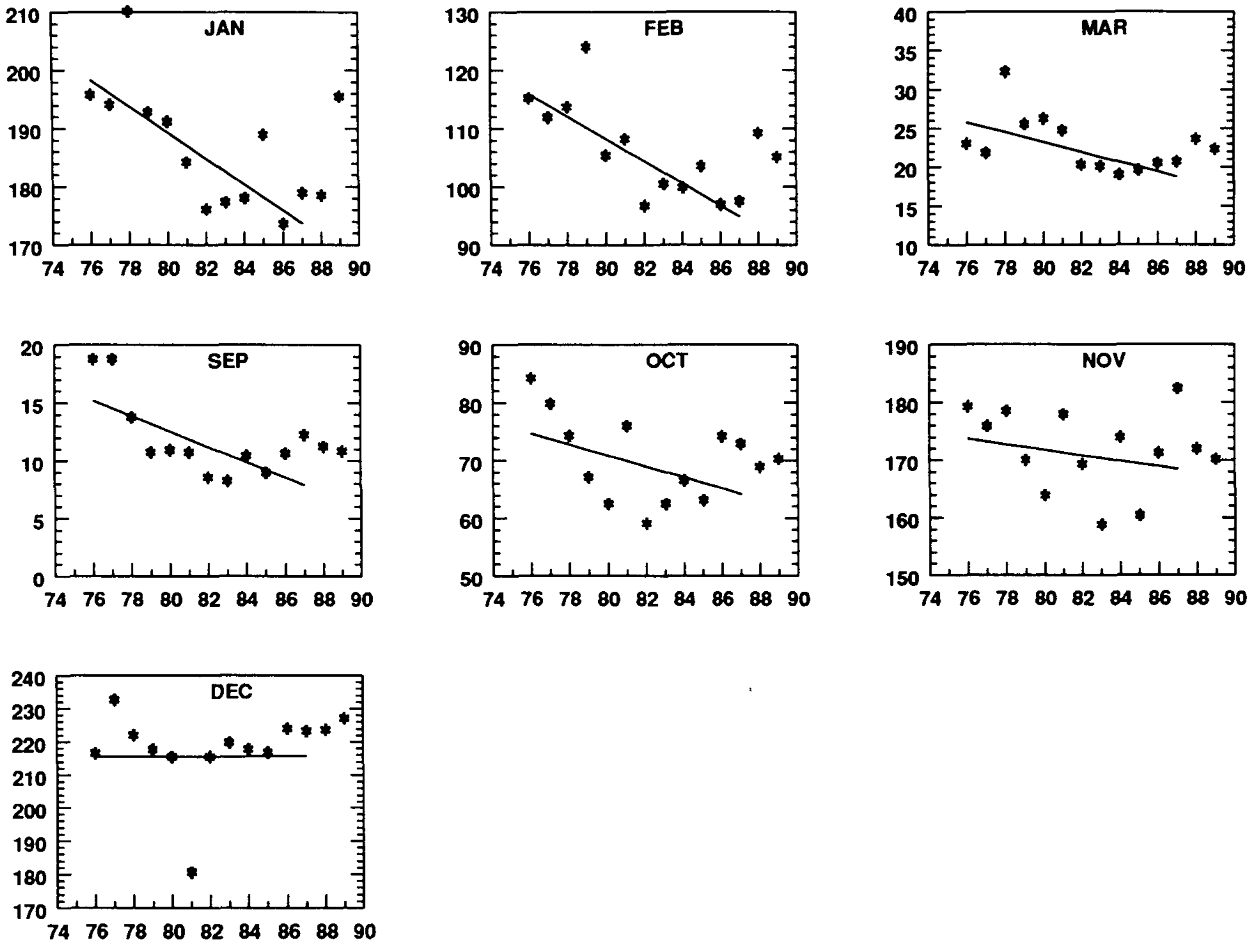

FIG. 3. Same as Fig. 2, but for RG8 solar irradiance.

for Q and RG8 data, respectively. This is about half of the value reported by Russak (1990) for Estonia in northern Europe, but the difference is easily accounted for by the difference in the average surface reflectance at Estonia and the South Pole.

The indicated irradiance sensitivity to cloud cover is not valid over the entire range of sky cover (0–10) because the additional cloudiness may have different optical properties than the clouds originally present. This sensitivity is related not only to cloud amount but also cloud optical depth and absorption as well as surface reflectance; all of which vary spectrally. It is

TABLE 3. Monthly irradiance linear trends and statistics, 1976–87 (SL is significance level). Problems with the September RG8 values are discussed in the text.

	Jan	Feb	Mar	Sep	Oct	Nov	Dec
			Q Values				
Slope (W m^{-2} yr^{-1})	−2.76	−2.52	−0.72	−0.11	−0.46	−0.10	0.26
SL	0.003	<0.001	0.14	0.75	0.61	0.91	0.81
Mean irradiance (W m^{-2})	373	203	40	19	132	335	434
			RG8 Values				
Slope (W m^{-2} yr^{-1})	−2.15	−1.40	−0.46	−0.52	−0.78	−0.34	0.22
SL	0.002	0.015	0.08	0.02	0.16	0.52	0.80
Mean irradiance (W m^{-2})	185	105	22	11	69	171	216

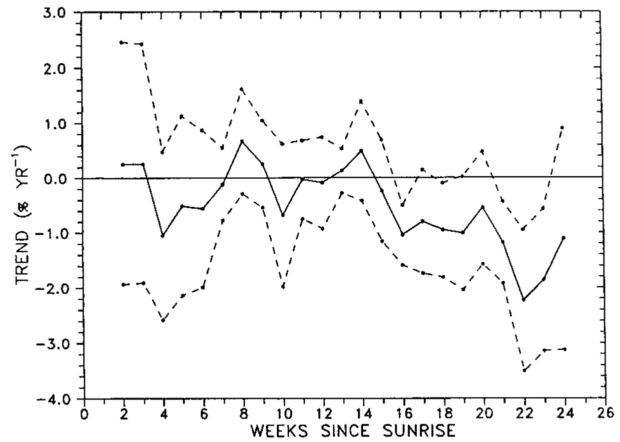

FIG. 4. Linear slopes of least squares fits to time series of weekly average Q solar irradiance (solid line) measured at the South Pole from 1976 to 1987, and the 95% confidence interval for the plotted slopes (dashed line). Week 2 begins 7 days after sunrise, 20 September.

expected that the RG8 sensitivity would be greater than Q because the RG8 band is more sensitive to water substance absorption, which affects cloud transmission and surface reflectance. The irradiance in the spectral band obtained by subtracting the RG8 from the Q (0.30–0.69 μm) should be much less sensitive to cloud effects than even the Q band because the 0.3–0.69 μm band has little cloud absorption and the snow surface reflectance is higher (Wiscombe and Warren 1980). Subtracting the monthly average RG8 values from the Q data in Figs. 2 and 3 provides a record of the solar irradiance in the Q–RG8 band, which exhibits only a small and statistically insignificant change in irradiance during all months (not shown). The best estimate irradiance–cloud sensitivity, calculated as before, in the Q–RG8 band is only 2.7% per tenth. This is much less than either Q or RG8. This result substantiates that clouds are mainly responsible for the observed decreases in the Q and RG8 bands.

The effect of clouds on the annual average irradiance record was also investigated. Sky cover averaged over all the sunlit months is shown in Fig. 6. Comparison of the second-order fitted curves in Figs. 1 and 6 shows that the maximum in sky cover coincides within a year of the minima in irradiance; the irradiance sensitivity to this sky cover change is 5.5% ± 1.5% per tenth for the Q and RG8 irradiances, with the difference between

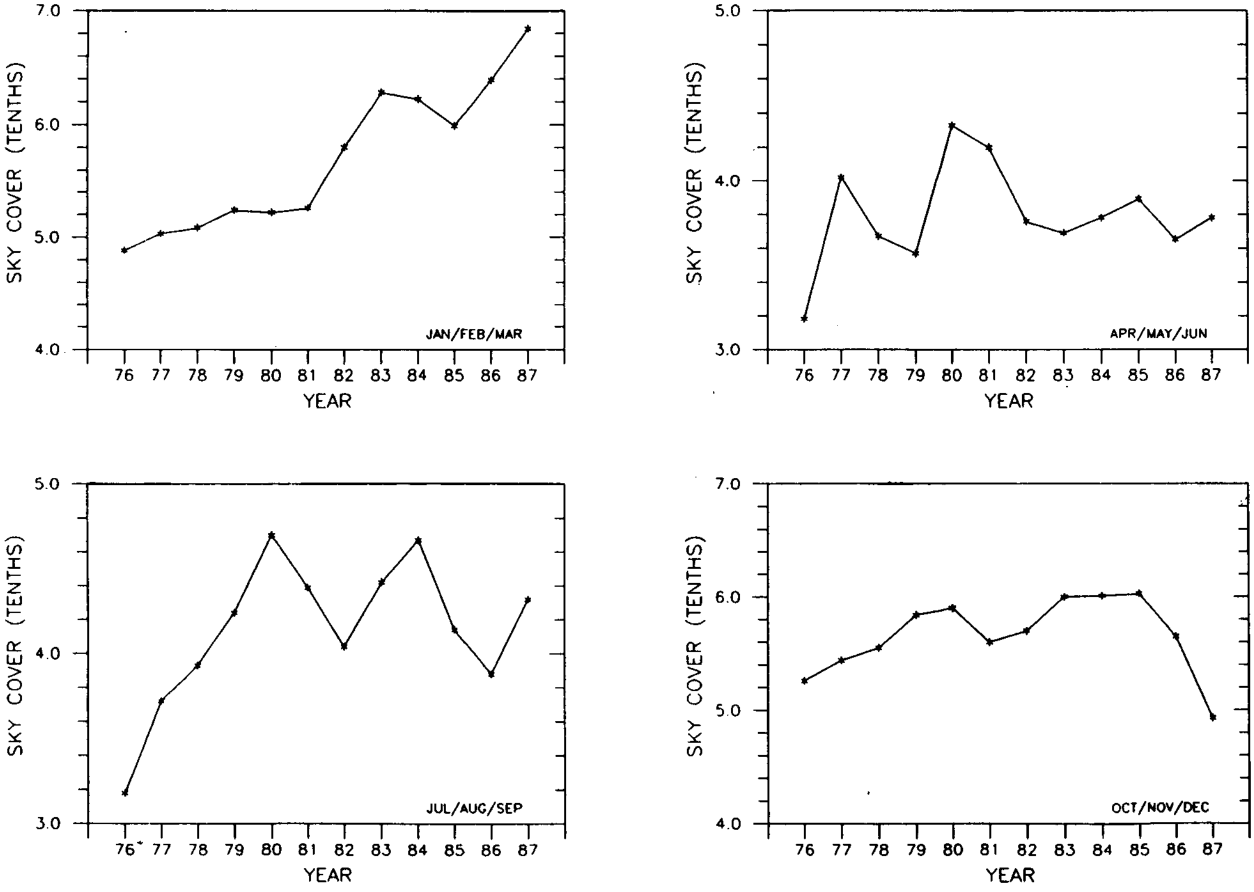

FIG. 5. Three-month averages of visually observed South Pole sky cover after a 1–2–1 annual smoother was applied.

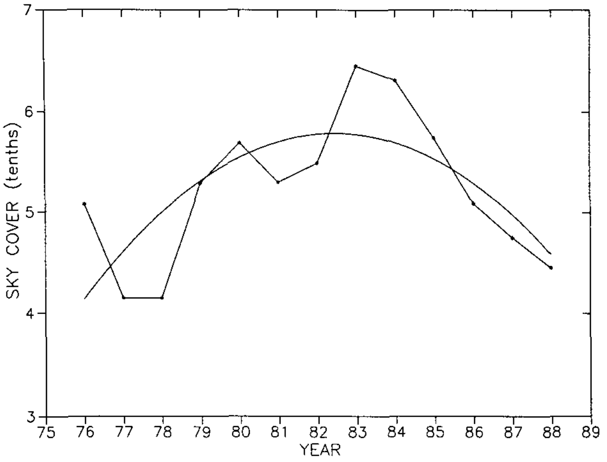

FIG. 6. Annual average (fully sunlit months only): South Pole sky cover observed.

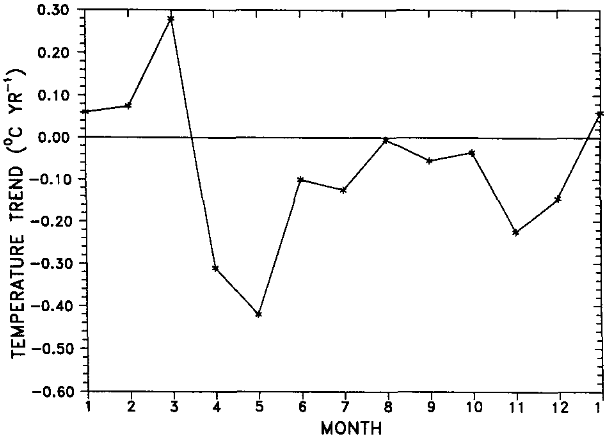

FIG. 7. Slope values for linear least squares fits to separate time series of each months' average surface air temperature at the South Pole, 1977–88.

Q and RG8 lost in the uncertainty. This irradiance/cloud sensitivity is expected to vary from that reported for January and February because different solar zenith angles are included. Again, it can be shown that there is virtually no correspondence between the Q–RG8 band and the cloud record.

Unfortunately the record of cloud types and heights at the South Pole has not been reported in the NCDC database since 1978, so it is not possible to perform an analysis of the possible changes in the type of cloud that may be responsible for the cloud cover changes reported here.

5. Temperature record

Any decrease in surface solar irradiance tends to cool the surface, whereas an increase in clouds increases the downward thermal infrared irradiance, which has a warming influence at the surface. The results of linear analysis of the 1976–88 time series of monthly average South Pole combined CMDL and NCDC surface temperatures are given in Table 4, and the fitted linear slopes are summarized in Fig. 7. Small statistically insignificant positive temperature increases are shown for January and February, but a positive slope significant at the 0.02% level is shown for March. The slopes become negative at the 0.1% and then 0.01% significance level for April and May, respectively, and remain slightly negative for the rest of the year. The significance levels given are for analysis of individual months, but the consistent character of the results further increases the credibility of the indicated slopes. The abrupt reversal in temperature trend from March to April and May constitutes the major feature in the temperature record. Although there is no certain connection between this temperature feature and the observed irradiance variations, significant changes in temperature are important in determining the climatic impact of radiation budget variations.

6. Discussion

Between the mid-1970s and the late-1980s, a year-to-year decrease in solar irradiance has occurred in the late summer season at the South Pole, with an associated increase in cloudiness. Occurring over many of the same years but about a month later in the season is a weak surface warming followed by a cooling during April and May. As a result, over the past decade at the South Pole and possibly for some larger portion of the Antarctic polar plateau, surface air has remained warmer near the end of the summer but has cooled more quickly to the "coreless" winter temperatures, discussed by Schwerdtfeger (1984), once the winter season arrives. Decreasing cloudiness would help explain the May cooling, but no correlated cloud variations are suggested in the sky cover data. The lack of a correlated change in May cloudiness cannot, of course, be verified in a solar irradiance record, but the nighttime cloud observation bias shown by Schneider

TABLE 4. Monthly average surface air-temperature trends and significance levels (SL), 1977–88, for the combined CMDL and NCDC record.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Slope (°C yr⁻¹)	.07	.10	.31	−.29	−.42	−.09	−.13	−.02	−.04	−.01	−.21	−.14
SL	.78	.58	.02	.11	.01	.65	.52	.93	.81	.94	.25	.32

et al. (1989) could explain the lack of an observed correlation between cloud cover and temperature, even if one actually existed. [Downward thermal infrared irradiance, which is sensitive to cloudiness at the South Pole (Stone et al. 1990), could be used to detect nighttime cloudiness. However, this variable has been measured by CMDL at the South Pole only since 1986 (Dutton et al. 1989) and is therefore not useful relative to the time period of the observed trends.]

The observed linear trends in monthly solar irradiance, cloudiness, and temperature are all too large to have existed for much more than a few years before the time period examined. There is no basis for extrapolating the observed trends beyond the time period for which there is data. In fact, there currently is an indication of a reversal in the downward irradiance trends in the last 2 years of monthly data, and the annual averages show a distinct recovery from earlier decreases. Whatever has occurred over the pole could be a specific decadal time scale "event"; also, possible cyclic behavior can not be ruled out. Unfortunately the irradiance record does not go back far enough to determine when the current trends began or if there are any complete cycles.

Earlier solar irradiance measurements were made at the South Pole and were used by Viebrock and Flowers (1968) to look at the effects of Agung, a major Southern Hemisphere volcanic eruption. The earlier data are available from NCDC for complete years for 1960, 1961, 1962, 1964, and 1965. The absolute level of the annual and monthly averages of the 1960–65 observations is in general agreement with the early CMDL data and definitely eliminates the possibility of the $-1.25\%\ \mathrm{yr}^{-1}$ February trend existing back to 1965 or earlier. However, the 12-yr gap and instrumental and procedural differences make the combination or comparison of the two datasets for further analysis impractical.

Fortunately the NCDC sky cover and surface temperature records go back continuously to 1957. These records can be examined for indications as to when currently observed (1976–87) trends began. Figure 8 shows the entire 32-yr record of the 3-month-average cloud amounts with a 1–2–1 smoother applied. The upswing in the cloud amounts in January–March begins in the mid-to-late 1970s, and there is no similar feature in the other seasons, although the random variability is large.

It was suggested from Fig. 7 that there is a significant contrast between March and April–May surface air temperature trends. Since the positive temperature trend occurs just subsequent to (and may overlap with) the months when irradiance and sky cover trends are present, there is a possibility of some relationship between temperature and irradiance trends. To determine when the opposing March–May temperature trends began, the 32-yr NCDC record of March and May average South Pole air temperatures is shown in Fig. 9. It is seen from this figure that the upswing in the March temperatures, reported in Fig. 7, is due mostly to steady increases after 1983. Similarly, the persistent decreases in May began in 1981. The anomalous years of 1978 and 1979 conceal whether or not the observed temperature tendencies actually began a few years earlier. It is also seen in Fig. 9 that the smoothed March and May average temperatures generally track each other except for a brief period around 1960 and since about 1981. If the diverging March–May temperature records are somehow related to the solar and cloudiness trends in January and February, the temperature signal did not emerge from the masking variability until a few years after the cloudiness trend began, as indicated in Fig. 8.

7. Summary and conclusions

The long-term variability of continuous total solar irradiance measurements, surface temperature records, and several-times-daily visual sky cover observations for the South Pole have been examined. The results show a large and previously undetected seasonal decrease in year-to-year solar irradiance during the months of January and February, and possibly into March, between 1976 and 1987 while the rest of the sunlit months show no linear variation over the same years. February's solar trend between 1976 and 1987, $-2.5\ \mathrm{W\ m^{-2}\ yr^{-1}}$ (or averaging $-1.24\%\ \mathrm{yr}^{-1}$), is statistically significant at >99.9% confidence level. The magnitude of the late-summer irradiance decrease is so large that only changing clouds could account for the observations. These results are essentially duplicated by the RG8 solar irradiance measurement series at the pole with a slightly greater percentage decrease in the RG8 record. Irradiance in the spectral band defined by Q–RG8 shows little or no significant reduction as would be expected if clouds were responsible for the reductions in the Q and RG8 over a snow surface.

Examination of the long-term visual sky cover (cloud amount) record for the South Pole reveals a negative correlation to the Q and RG8 solar measurements. The cloud amounts have shown a steady increase since the mid-1970s during January, February, and March, but have shown only random changes during other months.

Time series of South Pole monthly average temperatures for the same years show small year-to-year warming tendencies in January and February and statistically significant warming during March, followed by transition during April and then significant cooling in May. However, the March-to-May trend contrast does not become apparent until a few years after cloudiness begins to increase. The remaining months show slight and individually insignificant cooling tendencies. It is not possible to tell from the current analysis to what extent the temperature changes might be associated with radiative forcing due to cloud changes or with horizontal advection and/or vertical mixing

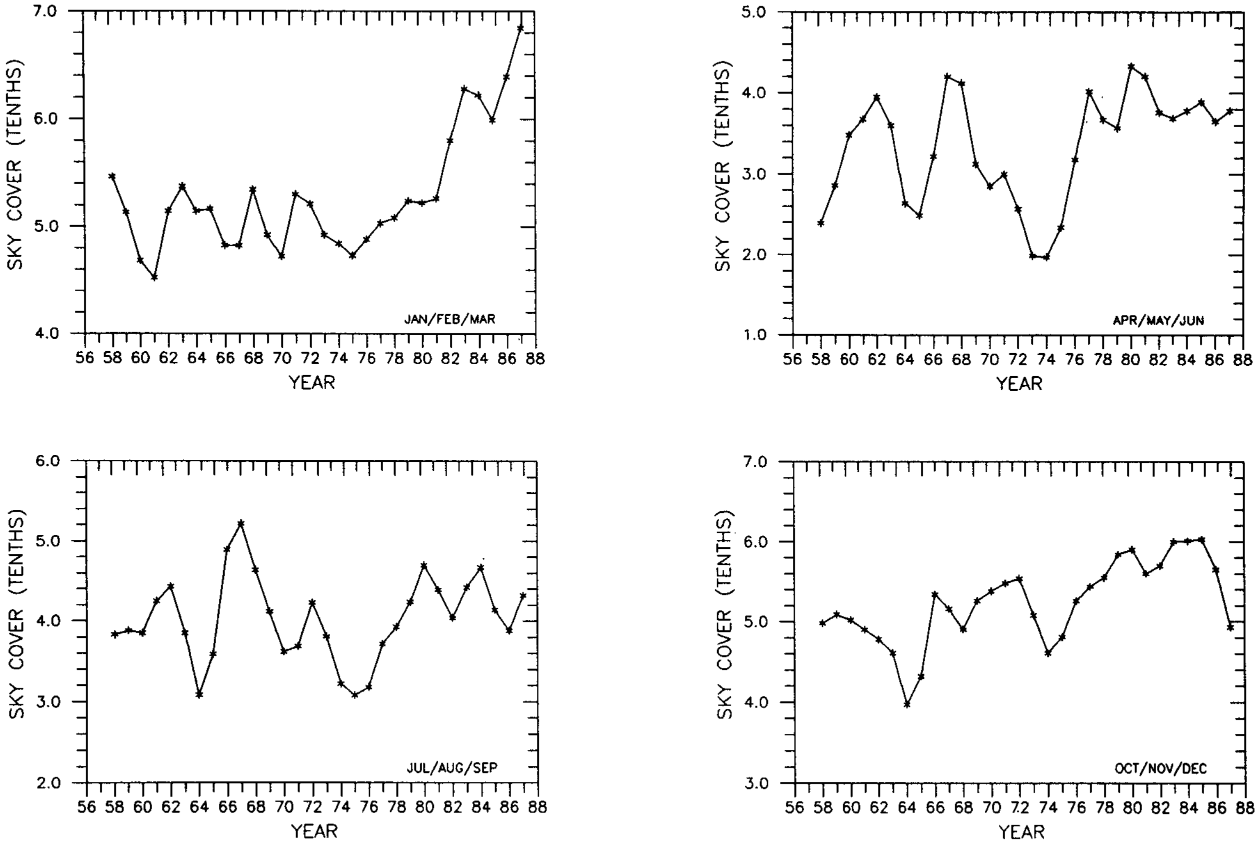

FIG. 8. Same as Fig. 5, but for the 1958–87 time period.

of sensible heat. All these processes strongly influence the intensity of the omnipresent surface inversion at the South Pole and thus are expected to contribute to surface temperature variations in response to varying synoptic weather events as noted by Stone and Kahl (1990).

The warming in March lags by 1 month the most significant solar-irradiance decrease. The physical significance of this lag or even whether or not there is a cause and effect relationship between the two events is not known. The cooling expected from the decreased solar irradiance does not result in an observed surface cooling. Apparently the downward thermal emission, horizontal warm air advection, and vertical-mixing warming associated with increased cloudiness more than compensate for any cooling tendencies. Also, the high surface albedo effectively reduces the usual cooling potential relative to a given loss of solar irradiance over darker surfaces.

As opposed to the obvious and statistically significant linear features observed in the monthly average irradiance records, the annual averages of solar irradiance show an overall temporal decrease with reversal of this tendency in about the middle of the record. The annual averages decrease from 1976 to about 1982/83 and then increase. Again, these results are essentially duplicated in the RG8 measurement record. Sky cover amounts averaged over the sunlit months for each year (Fig. 6) show features corresponding inversely to annual irradiance variations. The variability in the annual averages is only partially accounted for by the major features observed in the monthly data. No related temporal reversal is detected in the annual or monthly average temperature record or the seasonal cloud cover data, although the cloud and temperature data are complete only through 1988.

No conclusions have been made as to what has caused the seasonal change in cloudiness. Many other questions remain, including the following: Why do the observed trends only exist in certain months? Are the increases in cloudiness caused by changes in the synoptic advection patterns or by some nonadvective cloud producing process such as increased vertical motions or enhanced nucleation and cloud drop (or crystal) growth? To what extent is the surface warming caused by increased infrared emissions from the clouds or by advection of warmer air bearing more clouds? Why did the detected seasonal trends begin in the mid-to-late 1970s, and what is ultimately controlling the variability? Is there a link to lower latitude or higher altitude processes? Obviously, further research is needed to better define possible relationships, to understand rel-

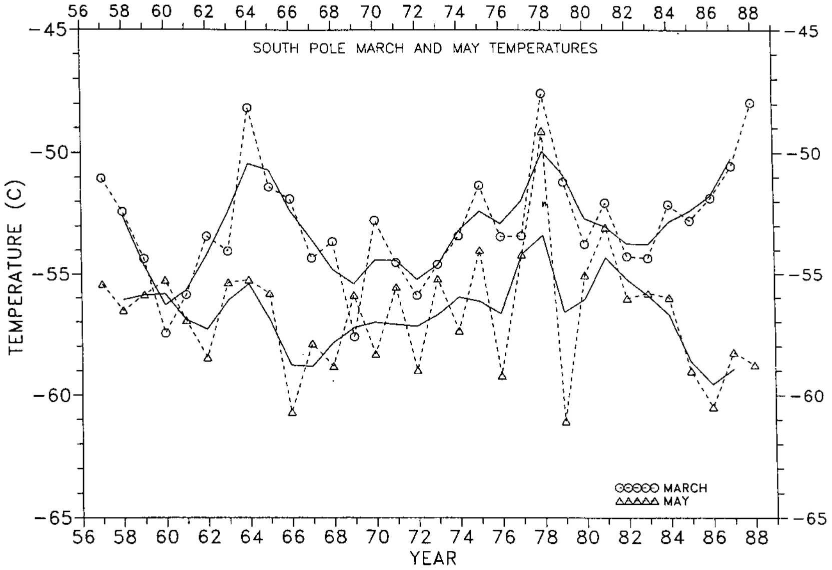

FIG. 9. Time series of monthly average temperatures for March and May at the South Pole, 1957–88. Dashed lines connecting symbols, circles for March and triangles for May, are for actual data, and solid lines are for the 1–2–1 annual smoother.

evant mechanisms, and to explore the relevance to the larger problem of global climate change.

Ongoing South Pole monitoring observations will reveal the more complete nature of the radiation and meteorological variability discussed here.

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