Systematic Error in the Synoptic Sky Cover Record of the South Pole

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ABSTRACT

Astronomers have long recognized that it is far more difficult to detect thin and scattered clouds visually when the nighttime sky is dark than when the moon contributes significantly to the sky background. An analysis of the nighttime synoptic total sky coverage data from the Amundsen-Scott South Pole station, for the period 1976–85, shows a systematic error in the observational record which we believe is due to this effect. We will show that the nighttime mean total sky cover at the South Pole has been underestimated by a factor of at least 1.5 (55% as opposed to the reported 37%). The percentage of time that the sky was reported to be clear has been overestimated by a similar amount. With the recognition of this systematic error we conclude that the seasonal variations in sky cover at the South Pole, as determined from these synoptic observations, are not nearly as significant as previously believed.

1. Introduction

The integrity of the synoptic meteorological record of the South Pole is important both to the continuing effort to understand the climatology of the Antarctic plateau (Dalrymple 1966), and to a number of interdisciplinary studies being conducted at the Amundsen-Scott South Pole station (Reuning 1985). Indeed, these data are often evoked in global heat budget models where effects such as radiative heat loss trapping due to cloud cover over the polar plateau are considered. Schwerdtfeger (1984) has shown that observational data from the winter of 1965 strongly support a correlation between the variation in the long wavelength net radiative flux and reported cloudiness. Of particular concern to nighttime upper atmospheric and astronomical studies at the South Pole is the accuracy of the synoptic Total Sky Cover (TSKC) record. These data can provide correlative cross checks to anomalous observations in areas of inquiry as diverse as stellar photometry (Chen et al. 1986) and monitoring of dayside auroral dynamics (Eather 1984).

This site provides a well-controlled environment to investigate the often-stated (and accepted) claim that it is easier for an observer to see thin, broken and scattered clouds at night when the moon is bright than when the sky is dark. During the austral polar night the moon remains above the horizon continuously for intervals of more than two weeks as it cycles through its phases. Also during this time, the moon is intrinsically brightest when it is above the horizon.

Our investigation was driven by the concerns of establishing an astronomical observing site at the South Pole (Taylor 1988). Therefore, we have focused our attention on the dark periods bounded by nautical and astronomical twilights, when the sun is at least 12 and 18 deg below the horizon, respectively. These periods are commonly thought of as "total darkness" and correspond, approximately, to 21 April–22 August, and 13 May–1 August. We note that the solar illuminance at the earth's surface on the boundary dates for nautical twilight is only 0.00831 and 0.000651 lm m^{-2} at the boundaries of astronomical twilight (Kingslake 1965). The latter illuminance is comparable to that of starlight integrated over a complete hemisphere. Comparatively, at the height of the South Pole summer, when the sun is at an elevation of +23.4 degrees, the solar illuminance is 33 700 lm m^{-2}. Obviously, during the prolonged periods of continuous night, variations in heating by direct solar insolation play no significant role in the process of cloud formation.

Schwerdtfeger (1984, p. 23) has also noted that "the quality of cloud observations during the polar winter night depends upon the presence of moonlight. Nevertheless, experienced observers can well distinguish a relatively dense low cloud deck from less dense clouds. . . ." Our study certainly supports both his first statement and the ability of observers to detect dense clouds regardless of moonlight. Yet, we will show that even

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experienced observers have difficulty detecting thin and scattered sky cover when the sky is dark.

If the conjecture concerning the detectability of sky cover being influenced by sky brightness (due to the moon) is indeed true, then one might expect that the nighttime TSKC data (for nonopaque sky cover) might be biased. Indeed, if nonopaque sky cover is more difficult to detect when the moon is dark, then a systematic underestimation in the nonopaque TSKC data would be expected. Our analysis of the TSKC data from the Amundsen–Scott South Pole station shows that such a systematic error, resulting in an underestimation in the mean sky cover during the austral polar winters, has occurred.

2. Data analysis

The dataset we have studied was obtained from the National Climatic Data Center (NCDC) and contains TSKC observations for the years 1976–85. These observations are visual estimates of the degree of obscuration of the sky due to clouds made by in situ observers every 6 h. The observations were originally recorded in octas, but were converted to tenths by the NCDC before distributing these data. The obscuration due to both totally opaque clouds (such as dense cumulus) and nonopaque clouds (such as thin cirrus) were reported separately. No information about cloud type or height beyond this distinction of "opaque" and "nonopaque" sky cover is made in this record. While other data records were structured to contain this information, an examination of these records revealed that few entries were actually recorded during the polar winters.

The TSKC observations are in the form of two time series, spanning 10 yr, but do not include the period of February–December 1983. A small percentage of the observations (0.43% of the nonopaque data, and 11.4% of the opaque data) were recorded as "not available" throughout the 10 yr interval. During the polar night, a similar percentage of the nonopaque observations (0.46%) and a smaller number of the opaque observations (5.9%) were not available. While observations of the opaque data apparently were made more reliably during the winter, the distribution of not available entries in the summer and winter seems to be random. Hence, the lack of this small subset of the data is not statistically significant.

A Fourier spectral analysis was performed on the TSKC data for all available nonopaque entries in the study period. The resulting power spectrum, shown in the top section of Fig. 1, contains a number of strong peaks. Most of these are harmonics of the predominant annual component (with a period of 365.25 days), which itself appears near the left end of the spectrum going off-scale. One peak, however, corresponds to a period of 29.575 days. This is extremely close to the period of the mean lunar synodic cycle. It is interesting to note that this is the second strongest peak in the power spectrum, when the aliased peaks due to the annual component are discounted. The temporal data were not prewhitened to remove aliases resulting from the annual component in order to allow us to compare the relative strengths of other power peaks to the annual component.

The power in each of 1753 discrete frequencies in this periodogram have been plotted relative to the power in the annual component. The mean power is indicated by the solid horizontal line. The dashed horizontal lines correspond to the 1σ noise level of the periodogram. The lunar synodic peak is 2.8σ above the mean power level; hence, there is 99.7% certainty that this peak is not spurious. The lunar elongation (the angular separation of the sun and moon, measured topocentrically) varies with the synodic period. The presence of this strong component in the power spectrum then suggests that the reported level of obscuration due to sky cover may have been affected by the lunar elongation. One could conjecture that this was a real physical effect (which we emphatically do not suggest), and that the lunar elongation does indeed influence the amount of sky cover at the South Pole.

If this farfetched hypothesis were true then the effect should be independent of the time of year. To test this, we segmented the TSKC data into two subsets. The first, which we will refer to as "day," contains only midsummer data, when the sun was at elevations of $\geqslant 12$ deg. The second, henceforth called "night", contains only those data recorded during the polar dark period bounded by nautical twilight. Hence, these two data subsets are symmetrical with respect to solar elevation. Power spectra of these two subsets of the annual data were then computed.

The power spectrum of the daytime data, illustrated in the middle section of Fig. 1, shows no appreciable lunar synodic component. The power peak which appears close to the lunar synodic period is only 1.5σ above the mean power level, and hence is not statistically significant. The power spectrum of the nighttime data, however, indicates a strong component at the lunar synodic period, as can be seen in the bottom part of Fig. 1. This component, 3.2σ above the mean power level, is the third strongest in the nighttime power spectrum.

During the 6-month-long polar day, and for most of the twilight periods, the background sky illumination due to moonlight is insignificant in comparison to the sky brightness due to the sun. The dominance of the azimuthally averaged sky brightness due to the sun holds until the end of nautical twilight. Therefore, one would expect the lunar illuminance to have a significant effect on the reported sky cover only when the sky is dark.

The sky brightness may be dominated by moonlight only during the less than 4 months yr^{-1} during the polar darkness. The amplitude of the lunar synodic power peak in the periodogram derived from data taken over all seasons is therefore reduced in comparison to

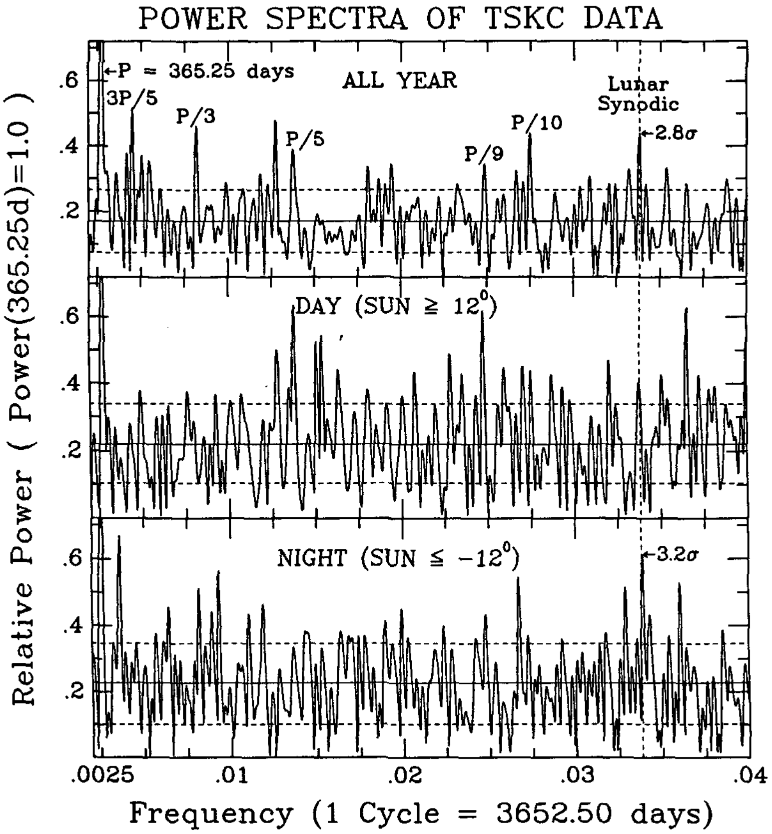

FIG. 1. Power spectra of the 6-h total sky cover observations from the Amundsen-Scott South Pole station for the years 1976–85. The range of the components illustrated, in period space, is from 500 to 20 days. The top spectrum is derived from all TSKC observations. The middle spectrum is from daytime (midsummer) observations, and the bottom spectrum is from observations during the polar night.

the nighttime-only power spectrum. The mechanism which is hypothesized to be responsible for this peak is operative for less than ⅓ of the year.

The Nyquist cutoff for these data, which span a decade, corresponds to a period of 5 yr. The TSKC observation sets studied, however, were noncontiguous due to sampling dropouts, data unavailability for most of 1983, and by subdividing the time series into daytime and nighttime regimes. Therefore, in order to circumvent the problems often encountered in time series analysis with such discontinuous datasets, all of the discrete transformations were postprocessed and reconstructed by a one-dimensional analog to the CLEAN algorithm often employed in the reduction of radio astronomical observations (Roberts et al. 1987).

We are not arguing here for the recognition of the existence of a systematic error in the observational record on the basis of these power spectra. Our principal reason for examining the power spectra was simply to determine if such a bias might exist. If no power peak was found at the lunar synodic period, then any further investigation would probably not have been warranted.

We questioned whether the obvious lunar synodic power peaks appearing in the all-year and nighttime periodograms arose from an observational bias due to moonlight-induced variations in sky brightness during the polar night. The sky brightness will vary with the lunar elongation at the lunar synodic period. To test this hypothesis, we binned the 9 yr of available nighttime sky cover data by the relative sky brightness due to lunar illuminance.

The moon is neither an isotropic scatterer, nor at a fixed distance from the earth. Therefore, in looking for a possible systematic error in the sky coverage record due to lunar brightness, it was not sufficient to examine the data simply as a function of lunar phase or elongation. For each reported sky cover observation we computed the relative sky brightness, due to the moon, in the following manner:

(i) The topocentric lunar declination and elongation were computed using lunar and solar ephemerides with precisions of a few seconds of arc throughout the period of study.

(ii) The first ephemeris also was used to determine the topocentric lunar distance to the nearest kilometer.

(iii) The measured relative brightness of the moon as a function of elongation (thereby incorporating albedo effects, and nonisotropic scattering) was obtained according to photometric results given by Bond and Henderson (Radio Corporation of America 1974).

(iv) The relative brightness *B* determined in (iii) was attenuated by an inverse-square falloff based on the lunar topocentric distance, normalized using the closest perigee distance of the moon in the reporting period.

We note that the mean lunar synodic period (from new moon to new moon) of 29.53 days is not commensurate with the mean anomalistic period (from perigee to perigee) of 27.56 days. Hence, in the 10-yr period considered, lunar perigees are well distributed in phase. Further, the synodic period is not commensurate with the year, nor quite commensurate with the calendar month. Therefore, over a multiyear period, the relative sky brightness due to the moon will be uniformly distributed with respect to the time of year, and hence uncorrelated with both the calendar date and the seasonal cycle. This is illustrated, for the austral polar night, in Fig. 2. These histograms show the number of observations reported as a function of time of year, and sky brightness due to the moon, binned on a weekly basis. The histograms span the period of time from the end of nautical twilight to the beginning of nautical twilight. The boundaries of the polar night as defined by astronomical twilight are indicated. As can be seen, during the polar night, times of increased sky brightness due to the moon are not seasonally biased.

The topmost histogram, labeled "NO MOON," sums all observation made when the moon was below the horizon, and therefore not contributing significantly to the sky brightness. The moon will not be in the sky (above the horizon) at all times for all elongations. This, indeed, is a function of both the time of year and the lunar topocentric elongation, as illustrated in Fig. 3. This figure shows the percentage of time the moon was above the horizon as a function of time of year and relative lunar brightness for all reported TSKC observations. For example, on 1 June, when the moon was waxing and at least 42% of its maximum brightness, it was always above the horizon. Also on this date, during

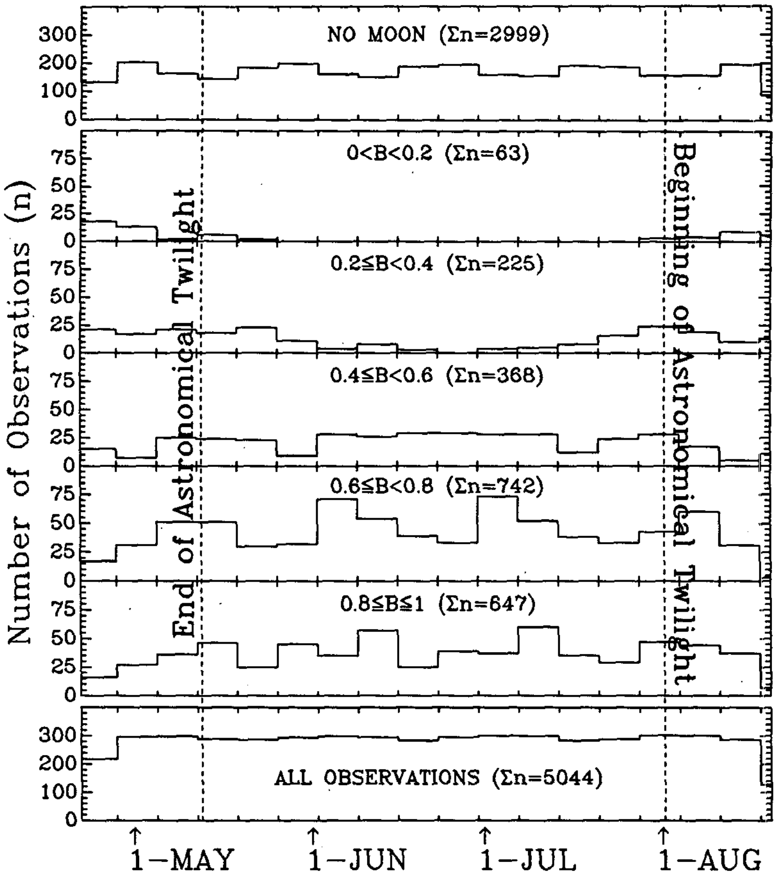

FIG. 2. The number of TSKC observations reported as a function of date for incremental levels of sky brightness due to the moon (*B*). The total number of observations (Σn) for each brightness level is also indicated.

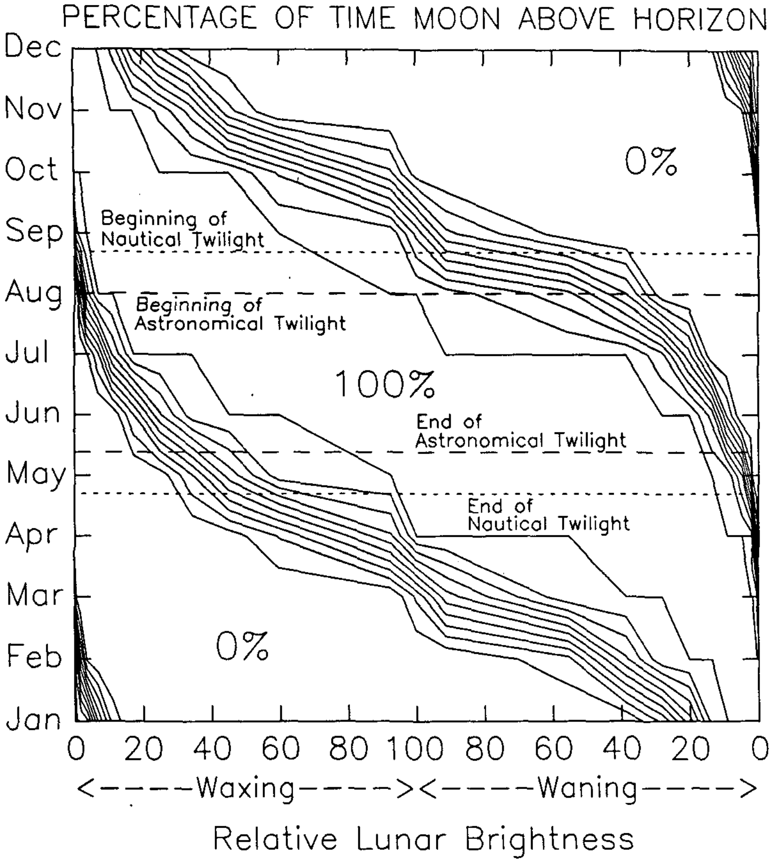

FIG. 3. The visibility of the moon (percentage of time the moon is above the horizon) at a given relative lunar brightness level as a function of the time of year. During the midwinter at the South Pole the moon is always above the horizon when brightest, and below the horizon when faintest. This is illustrated for the times of all reported TSKC observations during 1976–85. The isotemporal contours are shown at 10% intervals.

its waning phases, the moon was always above the horizon unless it was less than 28% of its maximum attainable brightness.

As is apparent, during the darkness of the polar winter, when the moon is bright it is always above the horizon. Conversely, when the moon is faint (near new phase) it is always below the horizon. This is also exhibited in Fig. 2. Note that for $0 < B < 0.2$, the moon is never in the sky during midwinter. This also means that when the moon is below the horizon, during the winter, it is intrinsically faint. Hence, the contribution to the sky brightness from scattered moonlight with the moon below the horizon is negligible.

Next, the TSKC observations were binned into 25 classes of 4% width in relative sky brightness; the means of the reported total sky cover, total opaque sky cover, and percentage of observations reported as clear were computed for each bin. For the sky to have been considered clear, both the total sky cover and total opaque sky cover entries must have been reported as zero. Obviously the visibility of the moon must be taken into account when computing the relative sky brightness. Therefore, elongation-dependent binned data were rebinned based upon the percentage of time the moon was above the horizon. The relative sky brightness due to lunar illuminance, then, also includes a "duty cycle" incorporating the lunar visibility. While this was done for the sake of rigorous completeness in the treatment of the data, this effect is small during the polar night. The distribution of the data is only minimally affected by lunar visibility during the polar night.

3. Results and conclusions

Both the periods bounded by nautical and astronomical twilight were considered independently in our analysis. For each of these periods, the data were binned as previously discussed. The results of the binning process are presented in Fig. 4. The solid lines in each of the figures represent the best fit to the binned data resulting from a weighted linear least-squares regression. Each point in the regression was weighted simply by the number of points in the bin. The dashed lines on

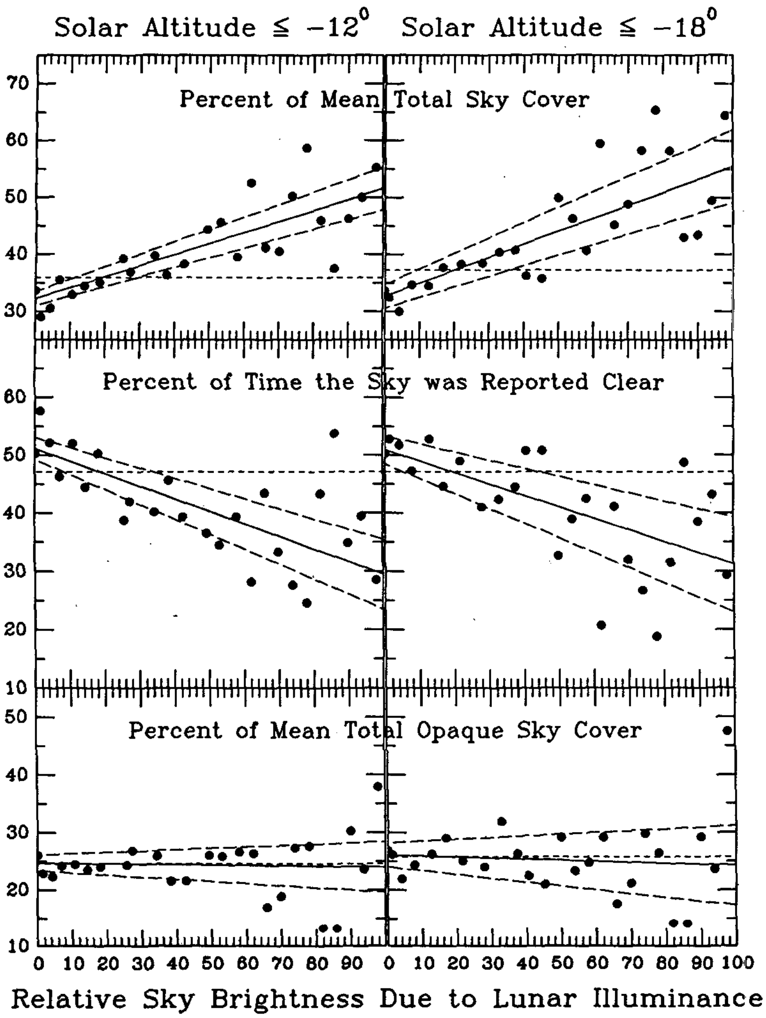

FIG. 4. The dependencies of the reported mean total sky cover, percentage of time the sky was reported clear, and percentage of reported mean opaque sky cover on the sky brightness due to moonlight during the austral polar winter, are shown in the top, middle and lower sets of figures, respectively. Results are plotted for times bounded by nautical (left column) and astronomical (right column) twilights. The significance of the solid and dashed lines are explained in the text.

either side of the best fit represent the one-sigma uncertainty (confidence) levels of the fit. The fact that the uncertainty in the solution broadens toward higher relative illuminance is a natural consequence of the lunar brightness variation as a function of elongation. The dashed horizontal lines show the mean values of all reported observations in the sample (independent of the sky brightness).

The trend toward underestimating thin and scattered cloud cover when the sky is dark is rather obvious and striking. It is interesting to note that the reported total opaque sky cover seems unaffected by the sky brightness. This, we believe, supports the idea that totally obscuring clouds are seen with equal ease regardless of the level of the background sky illumination.

We emphasize here that the data were binned according to the sky brightness from the lunar illuminance. As previously noted, the period of lunar phasing is not commensurate with the annual (and seasonal) cycle. Thus, the sky cover reported for a given lunar illuminance, when binned throughout the austral polar winters of our study, is independent of date. Any seasonal bias which might exist during the protracted dark periods bounded by twilight are, therefore, of no concern, since the lunar illuminance over many lunar cycles is not correlated with the time of year.

As can be seen, during the polar winter when the sky is bright, observers have consistently reported higher levels of sky cover, and fewer periods of clear skies. We emphasize that we do not believe this is a physical effect in the level of obscuration, but rather a systematic error made by the observers. Because the thin and scattered sky cover is seen more easily with the sky bright, we believe that the true percentage of sky cover and incidence of clear skies are indicated by times of high lunar illuminance and not by the reported seasonal means. When this systematic error is taken into account, the mean total sky cover in the period bounded by astronomical twilight is at least 55.6 ± 5.3% (corresponding to 100% lunar illuminance), not 37% as reported in the NCDC data record. Our analysis also indicates that the sky was clear no more than 31.2 ± 8.1% of the time, rather than the 47% indicated by seasonal averages. Similar results are found for the period bounded by nautical twilight, with the mean total sky cover 51.6 ± 3.8% and the percentage of time the sky was reported clear 29.6 ± 5.0%.

As a check on this procedure, we performed a similar analysis on the daytime periods when the sun was at least 12 and 18 deg above the horizon, centered on midsummer (for symmetry). As may have been anticipated, and as was first intimated by the daytime power spectra, no statistically significant correlation could be found between the lunar illuminance and the reported sky cover. This was expected since the moon, even when full, is 4×10^5 fainter than the sun.

This study can only set a limit on the magnitude of the systematic error which apparently has been made. Indeed, if the nighttime sky could brighten beyond the 100% level due to lunar illuminance then the visual detection of thin and scattered sky cover might be easier still and the incidence of reported sky cover correspondingly increased. It is obvious that this cannot be extrapolated indefinitely, as at some physical level of sky brightness the true degree of obscuration would be visually perceived correctly.

Figure 5 shows the distribution of reported total sky cover and percentage of time the sky was reported clear as a function of the time of year for the TSKC data. The solid lines in each of the histograms indicate the monthly means of the raw data reported by the NCDC. The horizontal dashed lines represent the mean sky cover and percentage of time the sky was clear corresponding to the values found for 100% lunar illuminance for the dark periods spanning both nautical and astronomical twilights. This illustrates the effect that the observational bias due to moonlight has on the nighttime (polar winter) observations. Since our study addresses the apparent systematic error found in the reported sky cover during the austral polar night, this figure indicates the effect of correcting those data, in the manner noted, only for that period.

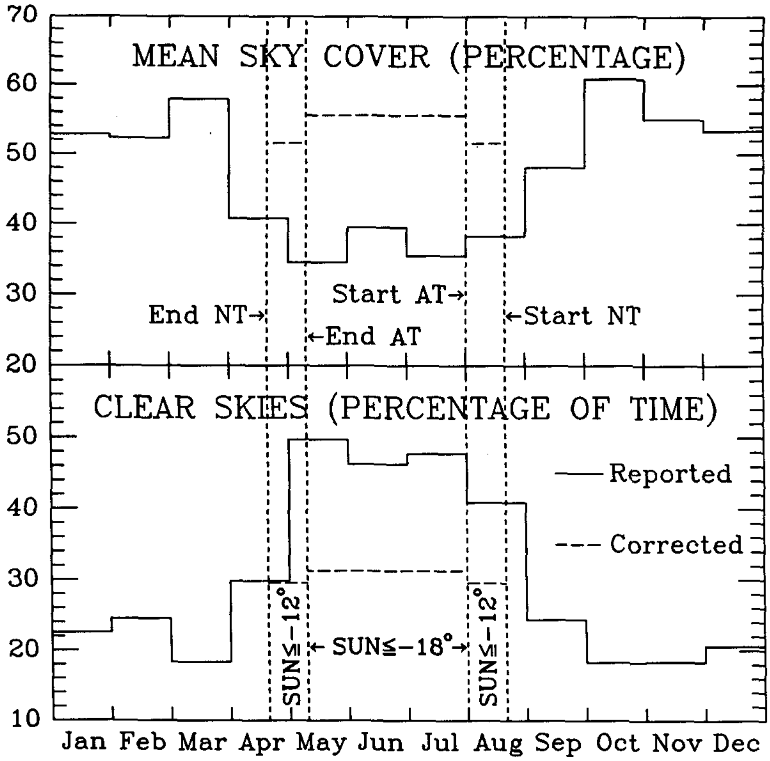

FIG. 5. The mean reported total sky cover and percentage of time the sky was reported as clear, during the years 1976–85 at the South Pole, as a function of time of year are indicated by the solid lines. The dashed lines show the corrected distribution functions after a systematic error due to sky brightness during the polar night is removed. The dark periods bounded by astronimical twilight (AT) and nautical twilight (NT) are noted.

If one accepts that the reported values are biased, and that the degree of sky cover is more correctly indicated by times of high lunar illumination, then, as shown in Fig. 5, the nonopaque sky cover at the South Pole is not significantly different in the winter than in the summer. This result was unanticipated, since one might expect stronger seasonal variations in cloud cover, given the large annual variation in incident solar flux at the South Pole. Independent verification of this systematic error might be found by attempting to quantify the sky cover as a function of lunar-induced sky brightness from the nighttime auroral all-sky photographic programs conducted by Eather (1984), Mende (1984) and Rosenberg (1985). This is a matter for future investigation.

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REFERENCES

Chen, K-Y., J. Esper, D. McNeill, J. P. Oliver, G. Schneider and F. B. Wood, 1986: An automated South Pole Stellar telescope. *Instrumentation and Research Programs for Small Telescopes, Int. Astron. Union Symp.*, Vol. 118, 83–84, IAU, Reidel.

Dalrymple, P. C., 1966: A physical climatology of the Antarctic Plateau. Studies in Antarctic Meteorology, *Antarctic Res. Ser.*, **9**, 195–231, AGU, Washington, DC.

Eather, R. H., 1984: Dayside Auroral Dynamics. *J. Geophys. Res.*, **89**, 1695–1700.

Kingslake, R., 1965: Light: Its generation and modification, *Appl. Opt. Opt. Eng.*, **1**, 243.

Mende, S. B., 1984: Monochromatic imaging of the 6300 Angstrom emissions from South Pole station. *Antarct. J. U.S.*, **19**, 235–236.

Radio Corporation of America, 1974: *Electro-Optics Handbook.* RCA, 225 pp.

Reuning, W. M., Ed., 1985: *Antarct. J. U.S.*, **20**, 272.

Roberts, D. H., J. Lehar and J. W. Drehar, 1987: Time series analysis with CLEAN. I. Derivation of a spectrum. *Astron. J.*, **93**, 968–989.

Rosenberg, T. J., 1985: Poleward surges of auroral phenomena over the South Pole. *Antarct. J. U.S.*, **20**, 227–228.

Schwerdtfeger, W., 1984: *Weather and Climate of the Antarctic.* Elseviere, 261 pp.

Taylor, M. J., 1988: Observing from the South Pole. *Sky and Telescope*, **76**, 351–353.

Wood, F. B., K-Y. Chen and G. Schneider, 1984: South Pole Astronomical Observatory. *Antarct. J. U.S.*, **19**, 237–238.