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Interannual variability of United States cloudiness

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Abstract. United States cloudiness data for 1950–1992 show quasi-biennial (QBO) and quasi-triennial (QTO) oscillations which match partly with the QBO and QTO of the Southern Oscillation (SO) index (the Tahiti minus Darwin pressure), but not with the QBO of the 50-mb equatorial zonal wind. Cloudiness also shows significant periodicities near 4.2 and 7.5 years, and probably a sunspot cycle effect (periodicities 11–14 years), with minimum cloudiness at or soon after sunspot minima, though this could also be due to periodicities of 10 and 17 years observed in the SO index. During 1955–1970, cloudiness increased by about 1%. Thereafter, it remained almost steady for the eastern and central parts of the USA, but continued to rise until about 1980 for the western USA.

1 Introduction

Cloudiness variations are of growing interest because of their possible relationship with greenhouse warming. For the United States, Angell *et al.* (1984) reported variations in cloudiness and sunshine, and Angell and Korshover (1987) studied the relationship with El Niño. Angell (1990) reported results for 1950–1988, showing a high correlation (− 0.86) between annual values of USA cloudiness and sunshine duration, and relationships with the strong El Niños of 1972 and 1982. In this note, we examine the same data updated, and demonstrate two characteristics, viz. a solar cycle variation and a quasi-biennial oscillation (QBO).

2 Data

The data for 1950–1992 were obtained by US observers at 100 first-order National Weather Service Stations. Dr. J. K. Angell averaged the monthly mean values by season (DJF, MAM, JJA, SON), and kindly supplied us with the cloudiness values for a few individual locations, and also for six broad regions viz. the north-west (NW), north-central (NC), north-east (NE), south-west (SW), south-central (SC), and the south-east (SE), and for the whole of the United States. The representativeness of the cloudiness estimates are discussed by Merritt (1966), and many other details are given in Angell *et al.* (1984), Angell and Korshover (1987), and Angell (1990).

3 Results from a visual inspection

To eliminate seasonal variations, running averages were obtained over four consecutive seasons, thus yielding 12-monthly means, centred 3 months apart. The top part of Fig. 1 shows a plot of the 12-monthly running means (full lines) for three individual locations (arbitrarily chosen, not representative of any region), viz. Boston (Mass), Washington (DC) and Brownsville (Texas). Considerable year-to-year variations are seen. The crosses represent 3-year running averages and bring out long-term changes better. The fourth plot is for sunspot numbers and the vertical lines indicate years of sunspot minima (1953–1954, 1964, 1975–1976, and 1986). There is a slight indication of a relationship between sunspot cycle and cloudiness. For Boston and Washington, cloudiness is minimum near sunspot minimum in 1954 and 1976, but not in 1986. For Brownsville, the indication is not at all clear. Quantitative measures are discussed later.

Total ozone variations are known to have a solar cycle dependence as well as a QBO. The fifth plot in Fig. 1 shows ozone variations for Resolute, Canada and the sixth plot shows the average ozone variation for North America (data provided by Dr. J. K. Angell). In both the cases, ozone values are larger during sunspot maxima, and there is a superposed QBO. Thus cloudiness variations seem to be similar to the well-known ozone variations.

The lower part of Fig. 1 shows the cloudiness variations for the six broad regions (NW, NC, NE, SE, SC, and SW), and for the whole USA. For almost all regions there is a variation parallel to the sunspot cycle, with

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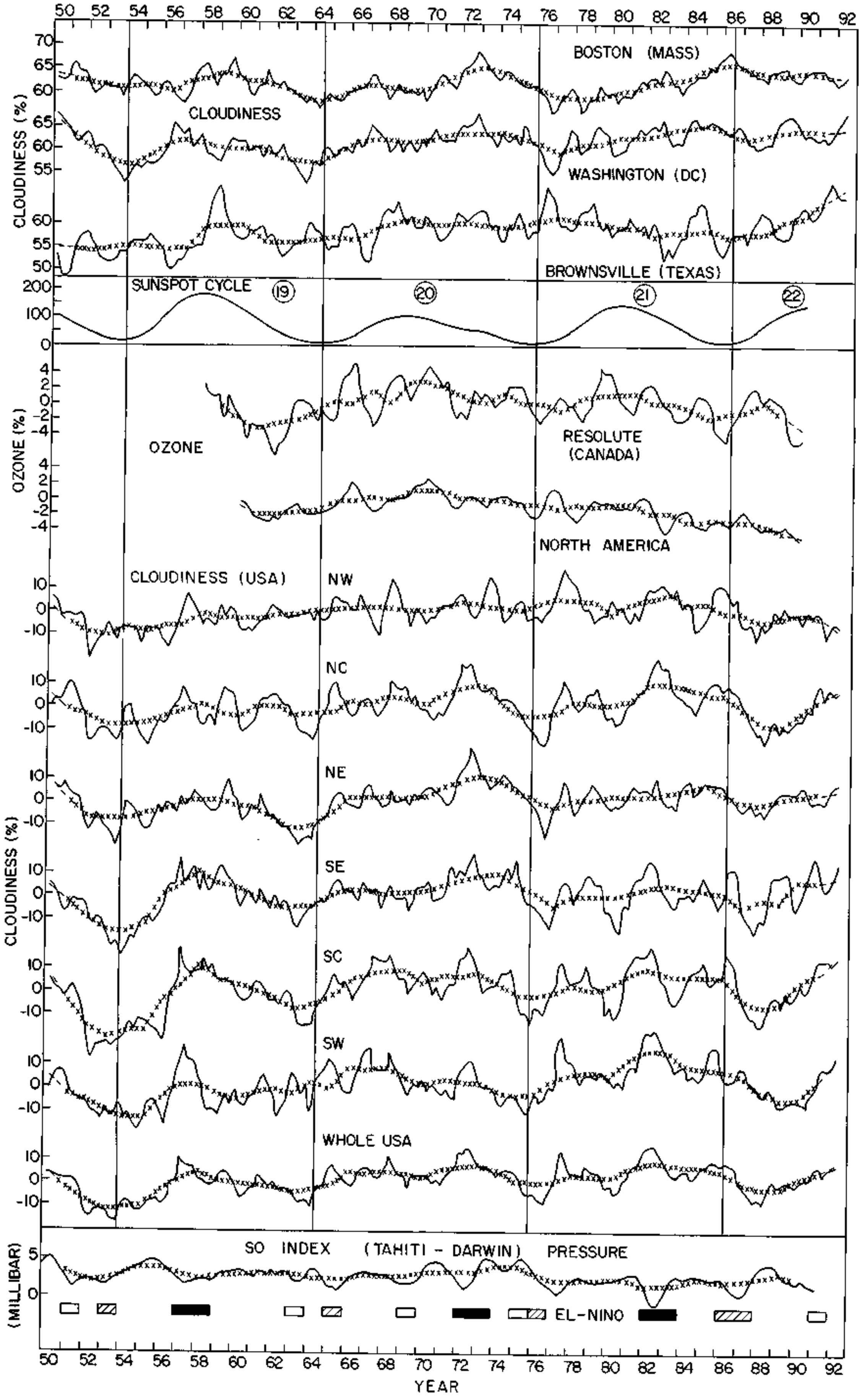

Fig. 1. *Upper panel*: Plots of 12-month running averages (*full lines*) and 3-year averages (*crosses*) of cloudiness (percentage of the sky covered by clouds) at Boston (Mass), Washington (DC) and Brownsville (Texas) in the USA, the total ozone at Resolute (Canada), and the average for North America. Sunspot numbers for cycles 19, 20, 21, and 22 are also shown. *Lower panel*: Cloudiness for different regions (north-west, north-central, north-east, south-east, south-central and south-west) of the United States. The bottom plot shows the Southern Oscillation index SO (Tahiti minus Darwin sea-level atmospheric pressure), and El Niño events as *rectangles* (*full*, strong; *hatched*, moderate; *open*, weak)

ranges as large as almost 20% (from maximum to minimum) in some cases. However, there is a complication here. Angell (1990) indicated larger cloudiness during the strong El Niños of 1972 and 1982. The bottom part of Fig. 1 shows a plot of the Southern Oscillation (SO) index represented by Tahiti minus Darwin (T − D) sea-level atmospheric pressure. The low values of this index are associated with El Niño events, as indicated. Now it happens that during the solar maxima of all the three sunspot cycles 19, 20 and 21, there were strong El Niños (full rectangles, 1957–1958, 1972–1973, 1982–1983). Thus, a doubt could be raised as to whether the cloudiness increase was related to sunspot maxima or to El Niños. However, the smooth rise of cloudiness from near sunspot minimum to near sunspot maximum probably indicates a relationship with sunspot cycle also. Additionally, there were moderate El Niños (hatched rectangles) during the sunspot minima of 1953, 1965, 1976 and 1986–1987, but the cloudiness remained low during these years. Incidentally, during the recent solar minimum of 1986, the cloudiness seems to have attained a low about 2 years later (1988, a drought year).

If the 3-year averages (crosses) are subtracted from the 12-month averages (full lines), only short-term variations will be seen. Fig. 2 shows a plot of these variations for the six regions and the whole of the USA. The bottom plots are for the SO index and the 50-mb equatorial zonal wind (Venne and Dartt, 1990), treated in an exactly similar way (12-month averages minus 3-year averages). The vertical lines mark the 50-mb westerly wind maxima. The following may be noted as general indications from a visual inspection.

1. The 50-mb wind has a very striking QBO, with successive maxima separated by about 20–36 months (average spacing about 28 months).
2. The cloudiness QBO is irregular. Some maxima tally with the 50-mb QBO maxima, but many others do not. The number of cloudiness maxima is smaller, indicating a larger average spacing. Thus the cloudiness QBO seems to be qualitatively and quantitatively different from the 50-mb wind QBO. Recently Kane (1992) reported similar differences for the QBOs of several other parameters. Spectral analysis of the cloudiness data is discussed later.

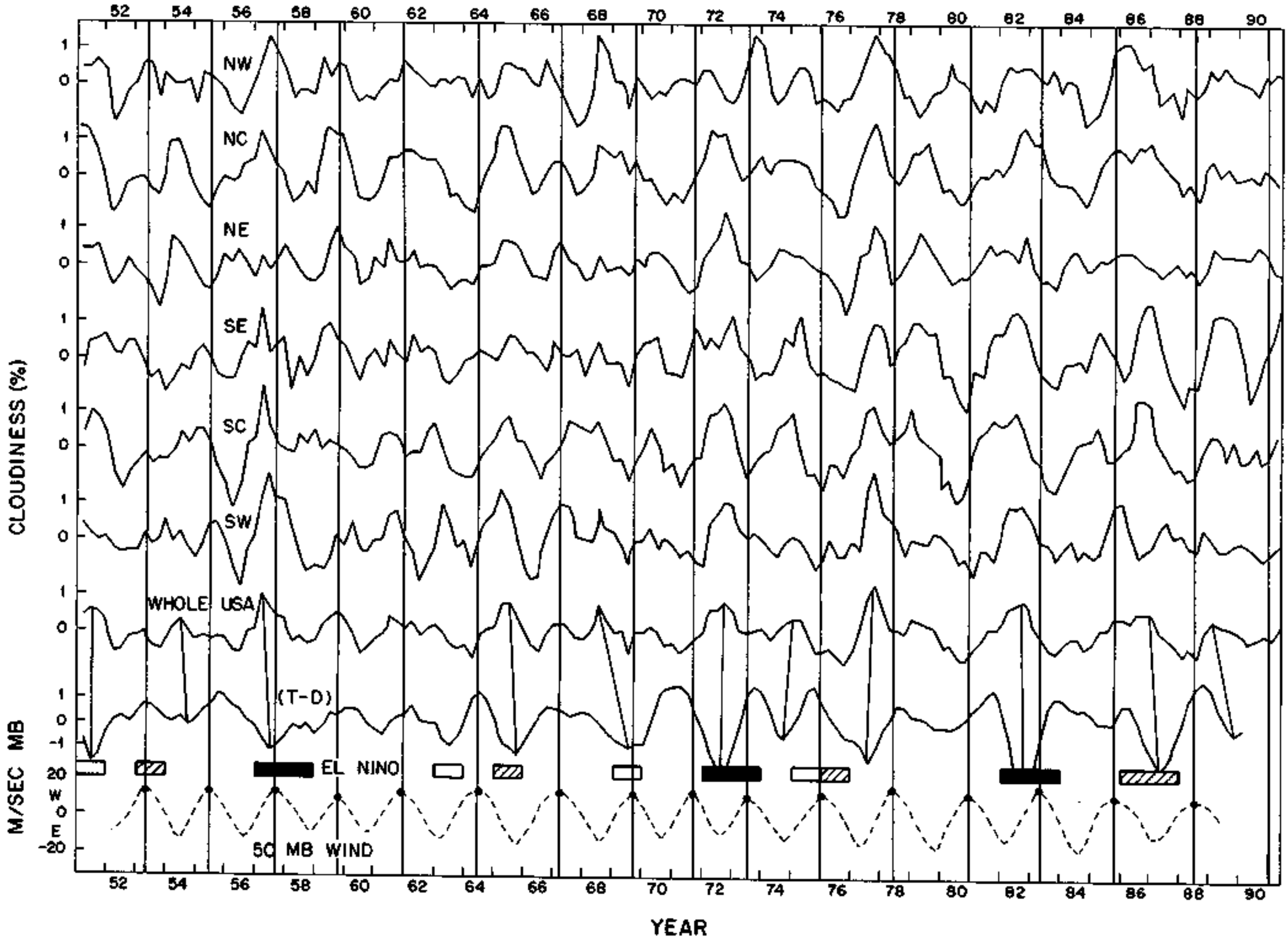

Fig. 2. Plots of the differences of 12-monthly averages and 3-year averages of cloudiness for NW, NC, NE, SE, SC, and SW regions, and the whole of the USA. The lower plots show the SO index (T − D), and the 50-mb equatorial zonal wind. El Niño events are also indicated

3. The SO index also shows a QBO, but its nature is different from that of the 50-mb wind QBO. In fact, the QBO maxima of cloudiness for the whole USA seem to roughly match the minima of the SO index, as shown by the connecting lines. It would thus seem that the cloudiness variations (2–4 years) are related to the SO index and not to the 50-mb wind. The differences between the cloudiness variations of the six regions (some peaks not matching in time or amplitude) may be due to data inaccuracies or differing influences of the El Niño on geographically different regions.

Let us now examine the spectral characteristics of the various series.

4 Spectral characteristics

The 12-month running averages shown in Fig. 1 (full lines) were subjected to power spectrum analysis by the method of maximum entropy spectral analysis (MESA), which was discovered by Burg (1967) and reviewed by Ulrych and Bishop (1975). This method locates periodicities much more accurately than the earlier conventional method of Blackman and Tukey (1958). However, the amplitude estimates in MESA are not very accurate (Kane, 1977; Kane and Trivedi, 1982). Hence, MESA was used only to locate possible peaks $T_k (k = 1\text{–}n)$ in years, and these T_k were then used in the expression

$$f(t) = A_0 + \sum_{k=1}^{n} \left[a_k \sin\left(2\pi \frac{t}{T_k}\right) + b_k \cos\left(2\pi \frac{t}{T_k}\right) \right] + E$$

$$= A_0 + \sum_{k=1}^{n} r_k \sin\left(2\pi \frac{t}{T_k} + \phi_k\right) + E \,, \qquad (1)$$

where $f(t)$ is the observed time series, and E is the error factor. A multiple regression analysis (MRA) (Bevington, 1969) was then carried out, which uses a least-square fit to give the best estimates of A_0 and (a_k, b_k). Further, the method of residuals was used to estimate the standard errors of these quantities which are the same for all (a_k, b_k). From these, the amplitudes r_k and their standard error σ_r (same for all r_k), and also the phase ϕ_k can be calculated. Amplitudes r_k exceeding $2\sigma_r$ are significant at an a priori 95% confidence level.

Figure 3 illustrates the maximum entropy spectra for the whole USA cloudiness series, consisting of 170 trimestral data points (12-month running means centred 3 months apart) during 1950–1992. Corresponding to the parameter lag in the Blackman and Tukey method, MESA has the length of prediction error filter (LPEF) parameter. Small LPEFs resolve smaller periods while larger LPEFs resolve larger periods. In Fig. 3, the four plots correspond to LPEFs of about 30%, 40%, 50% and 60% of the full data length (170 points). The various peaks (T_k) were used in Eq. (1). Since the basic unit of data is 3 months, the folding frequency (0.5) corresponds to 6 months. Hence all periods exceeding 6 months can be revealed. However, as can be seen from Fig. 3, there are virtually no strong peaks near or below 1 year (4 trimesters), mainly because the data consist of 12-month running averages. In the very large periodicity region, a peak near 60 years is indicated. This is not very meaningful and only

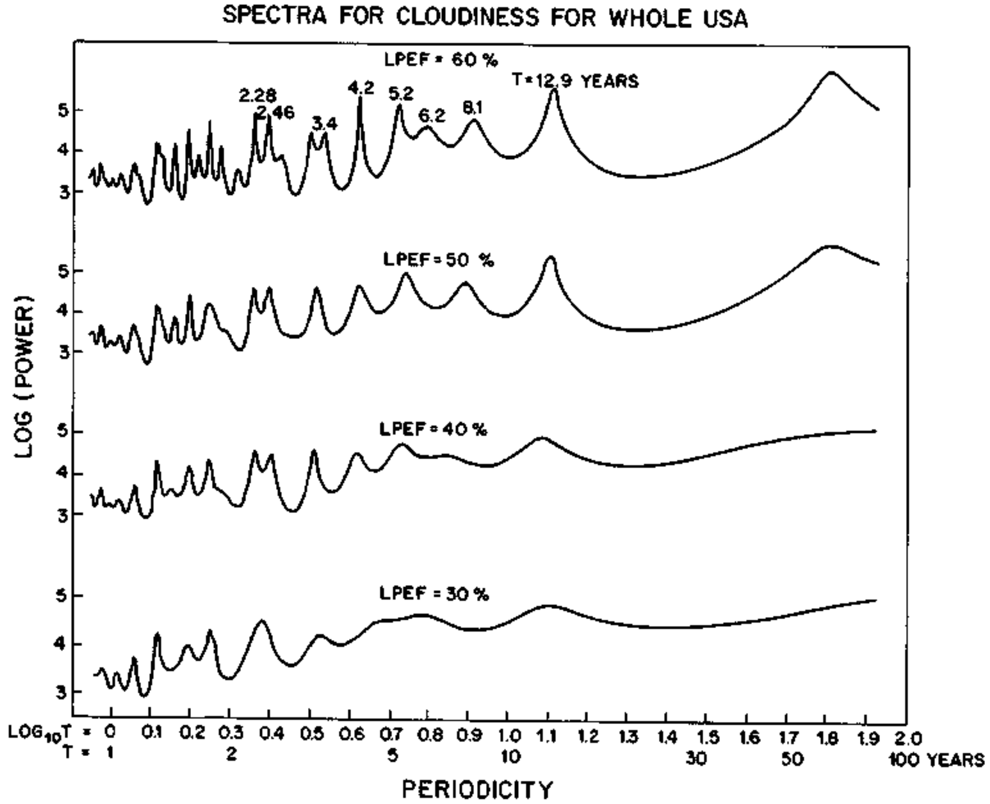

Fig. 3. Maximum entropy spectra for cloudiness for the whole USA for LPEF = 30%, 40%, 50%, and 60% of the data length of 170 points (~43 years, 1950–1992). Prominent peaks (years) are indicated for LPEF = 60%

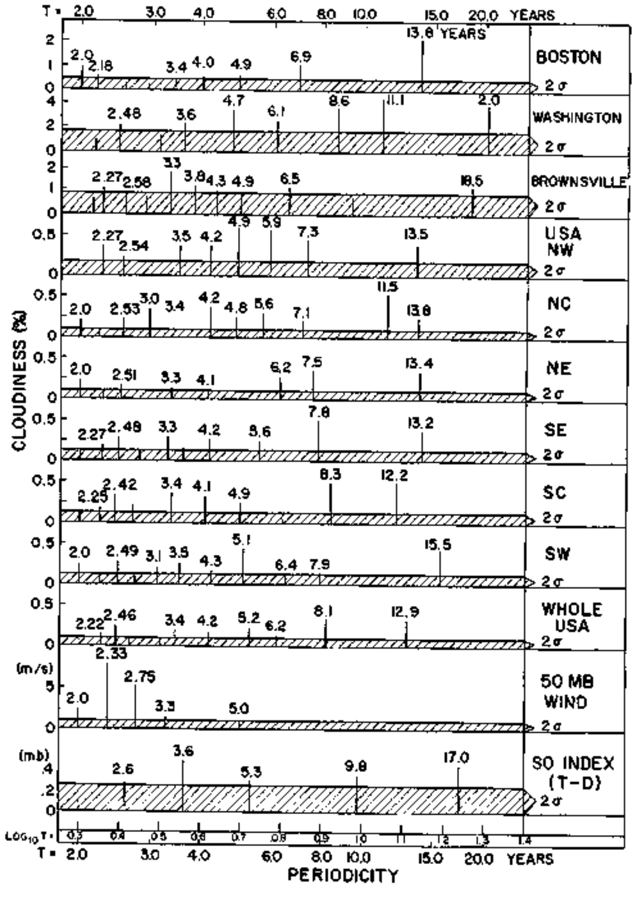

Fig. 4. Amplitudes of the various periodicities detected by maximum entropy spectral analysis for the percentage cloudinesses at various locations, and also for the 50-mb wind and SO index

indicates that long-term trends may be involved. These trends are discussed later. Here, in the interval 2–30 years, periods significant at more than the 2σ level were at $T = 2.28, 2.46$ (QBO region), 3.4, 4.2, 5.2, 6.2, 8.1, and 12.9 years. Figure 4 shows a plot of the amplitudes of the various periodicities noted in the various series, using MESA with LPEF = 60% of the data length. The following points may be noted.

1. In the top three plots for individual locations, Boston shows a very strong peak at 13.8 years, and Washington (DC) at 11.1 years. Both these could be solar cycle effects. However, Brownsville does not show such a peak. In the QBO (2–3 years) and QTO (3–4 years) regions, significant peaks are seen at all three locations. In addition, peaks are seen near 4.8 and 6.5 years.
2. In the next six plots for the six regions (NW, NC, NE, SE, SC, and SW) of the USA, a significant QBO near 2.5 years is seen in all regions, in addition to significant peaks near (3.3–3.5), (4.1–4.3), (7.1–8.3), and (11.5–13.8) years. Whether the ~13-year peak is a solar cycle effect is a moot question. The method is accurate enough to distinguish between 11 and 13 years.
3. The lower part of Fig. 4 shows similar results for the 50-mb wind and SO index (Tahiti minus Darwin pressure). The 50-mb wind has a very strong peak at 2.3 years with two subsidiary peaks at 2.0 and 2.8 years, a pattern not reflected in the cloudiness data except for NW-USA which shows a strong peak at 2.3 years. The SO index shows a strong peak at 3.6 years which is reflected well in the cloudiness data. However, the ~4.2- and ~7.5-year peaks in cloudiness have no match either in 50-mb wind or SO index.

It would thus seem that the cloudiness variations are mostly unrelated to 50-mb wind variations, but partly related to the SO index. The origin of the ~4.2- and ~7.5-year peaks in cloudiness needs further investigation. In Fig. 2, the strong and moderate El Niños are shown (by connecting lines) to be generally related to cloudiness maxima for the whole USA, some of which can be extended to some individual regions also. For example, during the strong El Niño of 1957–58, all regions except NE showed cloudiness maxima. During the 1972–73 strong El Niño, all regions except NW showed cloudiness maxima. During the 1982–1983 strong El Niño, all regions showed cloudiness maxima. These El Niño events occurred with spacings of 15 and 10 years and might have been partly responsible for the 11–13-year periodicity.

5 Long-term trends

Angell (1990) estimated the long-term trends in cloudiness as 2.0 ± 1.3% between 1950–1968 and 1970–1988 (the first and last halves of the total record 1950–1988) for an average value of 58% sky cover, thus yielding a percentage increase of 3.5% between these two intervals (2.0 in 58.0 is 3.5%). Earlier, Henderson-Sellers (1986) obtained a percentage increase of 7.0% between 1950–1968 and 1970–1984, almost double that of Angell (1990), who states that the two data sets had only half the stations in common, and hence that the representativeness of both data sets becomes doubtful. Nevertheless, both the studies certainly implied an appreciable increase in cloudiness in the USA during the last four decades. In our plots in Fig. 1 there is some indication of a solar cycle relationship. To minimize this, 11-year running averages were calculated. These are shown in Fig. 5 for NW, NC, NE, SE, SC, and SW, and for the whole USA. The bottom plot shows the 11-year running averages of sunspots. The latter show an average value of about 100 for 1955–1961, dropping to about 65 by 1966, remaining steady at that level up to about 1974, rising thereafter steadily to about 100 again in 1984. The various regions show a rise in cloudiness from 1955 to 1970 by about 1% and a more or less steady level thereafter, except for NW and SW regions, where the increase continued up to 1980 or later. Thus the cloudiness increase has not been uniform in the last few decades. Angell (1990) has shown that these increases are seasonally dependent, being minimum in spring and maximum in autumn. In our analysis, only 12-monthly averages are considered and the seasonal differences are suppressed.

Angell (1990) has compared the annual variations in cloudiness with precipitation and temperature, and reports a correlation of +0.79 between cloudiness and precipitation and a correlation of −0.43 between cloudiness and temperature. From satellite data, Ramanathan

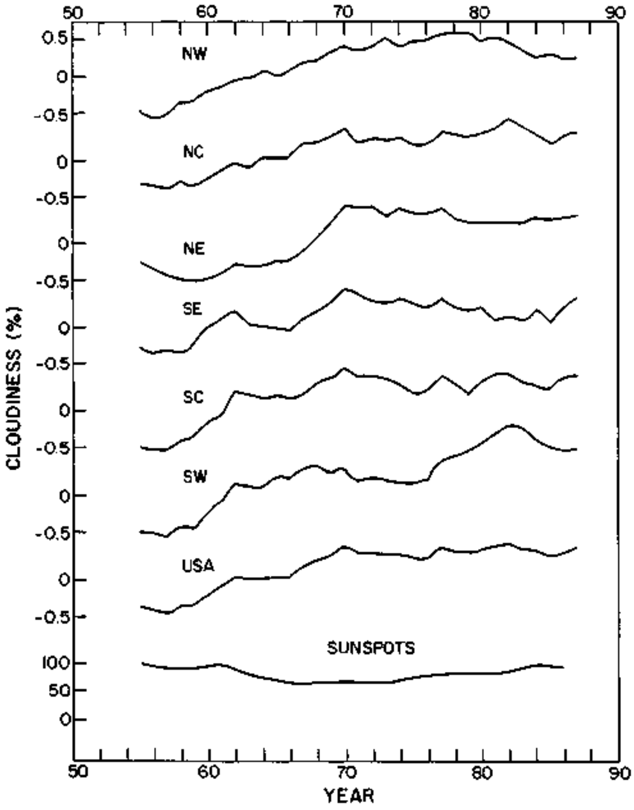

Fig. 5. Plots of 11-year running averages of cloudiness for various regions of the USA. The bottom plot is for sunspots

et al. (1989) show that clouds do have a net cooling effect on a global scale, due to radiative energy balance. Earlier, from a short period of meteor satellite observations, Mokhov (1985) had indicated a tendency for an increase in cloudiness with increases of the global-scale surface temperature.

6 Conclusions

This analysis of USA cloudiness (percentage of the sky covered by clouds) has revealed the following.

1. There is a slight indication of a solar cycle relationship, with lower cloudiness values soon after the sunspot minima of 1953–1954, 1964, 1975–1976 and 1986. For some regions the range could be as large as 20%. A spectral analysis showed strong peaks in the 11–14-year region.
2. Spectral analysis of the 12-month running averages revealed significant QBOs. These did not match with the 50-mb equatorial zonal wind QBO, but did partly match variations of the SO index. Incidentally, the SO index (related to El Niños) shows periodicities near 10 and 17 years, which might have appeared in cloudiness as 11–14-year periods, which might have been misinterpreted as solar cycle effects.
3. Cloudiness showed significant peaks near ~4.2 and ~7.5 years which had no equivalent in either the 50-mb wind or SO index.
4. There was about a 1% increase in cloudiness from ~1955 to ~1970 for NC, NE, SE, and SC regions, and a steady level thereafter. For NW and SW regions, the increase continued up to ~1980.

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