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88 DENSITY TEMPERATURE
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Seasonal dependence of stratospheric temperature variations

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Abstract. Stratospheric temperatures show distinct trends, not necessarily monotonically upward or downward. At the North Pole, trends were large only during winter and spring and were different for different months; downward for November, December, mixed for January and upward for February, March and April. For the 10°–90°N belt, the trends were variable, viz., downward during 1971–1975, upward during 1975–1978 and downward again from 1978 onwards up to date, opposite to the upward trend of ground temperature in the Northern hemisphere in recent years. Twelve-monthly running averages revealed strong QBO (quasi-biennial oscillation). For the North Pole, the QBO showed colder (lower) temperatures during 50-mb wind QBO westerly phase maxima. For the 10°–90°N belt, the QBO was similar for 30 mb and 50 mb but the QBO phases did not match well with 50-mb wind QBO phases.

1 Introduction

In a recent communication (Kane, 1992), we analysed the stratospheric (30 mb) temperature data for the North Pole as given in Labitzke (1987) and also data for further periods. It was shown that evaluating running averages over three consecutive values and then further over two consecutive values eliminated QBO (quasi-biennial oscillation, period 2–3 years) and the resulting series for northern winter months (November, December, January, February) indicated solar cycle variations with probable lags or leads of about 0–2 year for temperature maxima with respect to sunspot maxima. Further running averages over 11 years indicated long-term trends, different for the different winter months. In this note, we reexamine the long-term trends and show that these are not monotonically up or down but are mixed. Also, we compare these results with those for 30-mb and 50-mb temperatures for other latitudes, viz. area averages for 10°–90°N as given in Labitzke and van Loon (1991).

2 Data

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3 North Pole stratospheric temperature

Figure 1a shows a plot of the North Pole 30-mb temperatures for various months. The full lines represent original values and the thick lines are "3–2 year" running averages, i.e., running averages over three consecutive values and then further over two consecutive values of these 3 year averages. This is equivalent to a four point filter of weights 1, 2, 2, 1 and the results are very similar (even in phase location) to those obtained by using more sophisticated filters like binomial or Gaussian filters. The bottom plot is for sunspots and the vertical lines mark sunspot minima. The original values (thin lines) show QBO in the winter months (November–February) with a range of several degrees, far above the standard deviation of about 1°. The fluctuations are smaller in March and April, still smaller in May and October and very small in June, July, August,

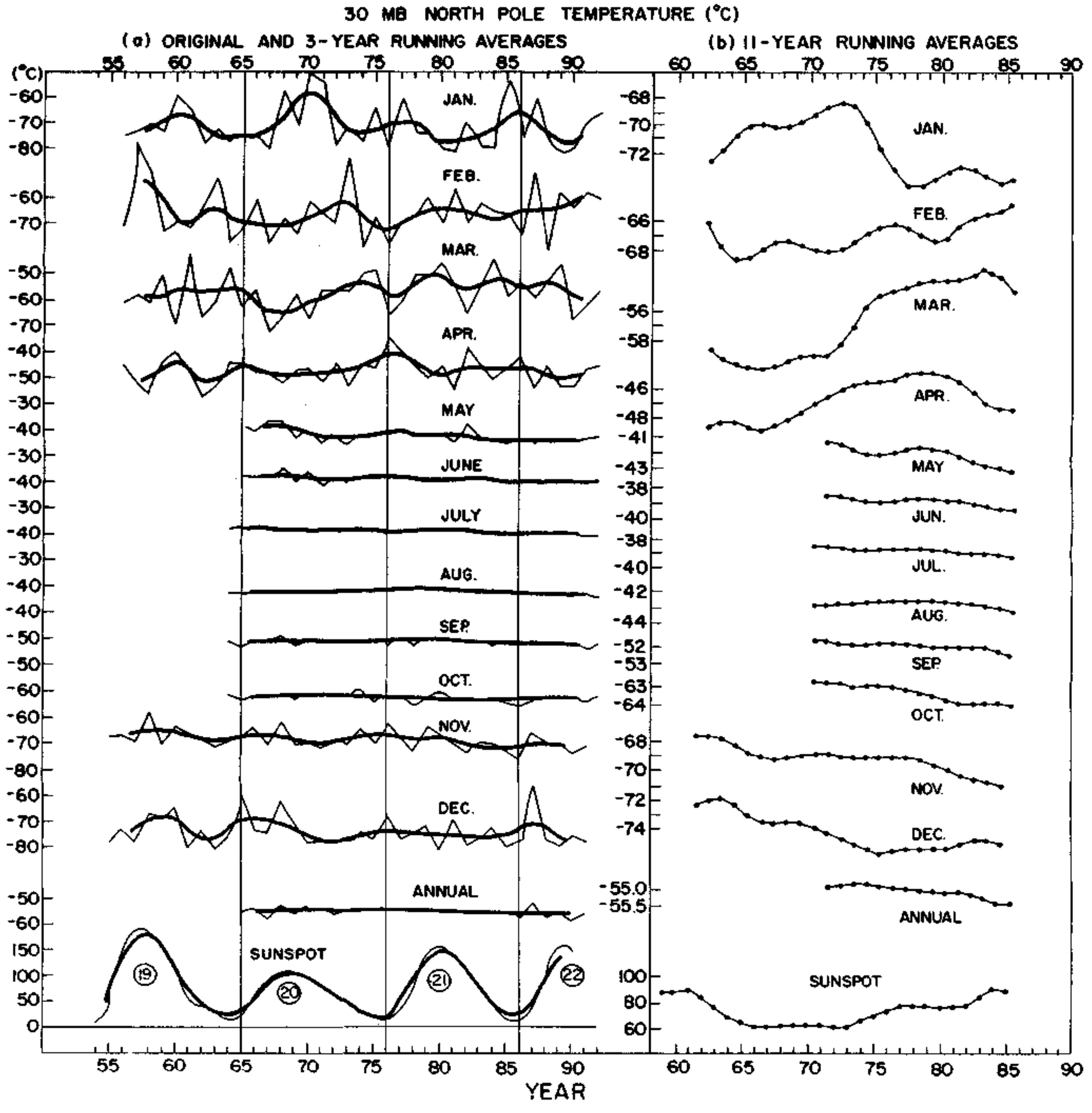

Fig. 1. a North Pole 30-mb temperatures (*full lines*) and their 3–2 year running averages (*thick lines*) for various months; **b** 11-year running averages. The *bottom plot* is for sunspots. *Vertical lines* mark sunspot minima

September (summer). When QBO is eliminated, the thick lines do not show any resemblance to sunspot cycle except perhaps for January values which show maxima for cycles 19 (1960) and 20 (1970) only. The annual means have very little year-to-year fluctuations. In winter, there seems to be a 5–6-year (half solar cycle?) periodicity also.

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1967 to 1978 (11 years) and a drop of about 2° thereafter. December shows a drop of about 2° from 1963 to 1975 (12 years) and a steady level thereafter. Thus, the changes are very different for the different months. As a result, the annual means hardly show a 0.5° drop from 1974 to 1985 (11 years). If the variations in linearity are ignored and a straight line is fitted to the 11-year running averages, the decadal trends (°K per decade) are as given in Table 1. There is a significant difference between the trends in November, December, January (negative) and February, March, April (positive).

It must be remembered, however, that the monthly mean temperatures at the North Pole are greatly affected by major mid-winter warmings which occur during December to March. If these occurred more often in the earlier (or later) years, apparent down (or up) trends would result and may result in different trends for different winter months. The warming occurred in December of 1965, 1968, 1987, January of 1968, 1970, 1971, 1977, 1985, 1987, February of 1957, 1958, 1963, 1966, 1973, 1979, 1981, 1987, 1989, March of 1959, 1961, 1964, 1974, 1975, 1980, 1984, 1986, 1988 and April of 1976, 1982. Thus, these were well spread over earlier as well as later (recent) years and could not have affected very much the overall long-term trends. However, the differences in trends of different winter months (e.g. the abnormally high values for January during 1969–1973) may be due to such abnormal warmings.

4 Stratospheric temperature at other latitudes

Naujokat (1981) showed that trends may be different at different latitudes. Labitzke and van Loon (1991) reported results for the latitude belt 20°N–50°N but for October–November only. For a wider belt, (10°N–90°N), they reported results for all months. Figure 2 shows the trends for 30 mb temperatures for 2-month means (JF, . . ., ND).

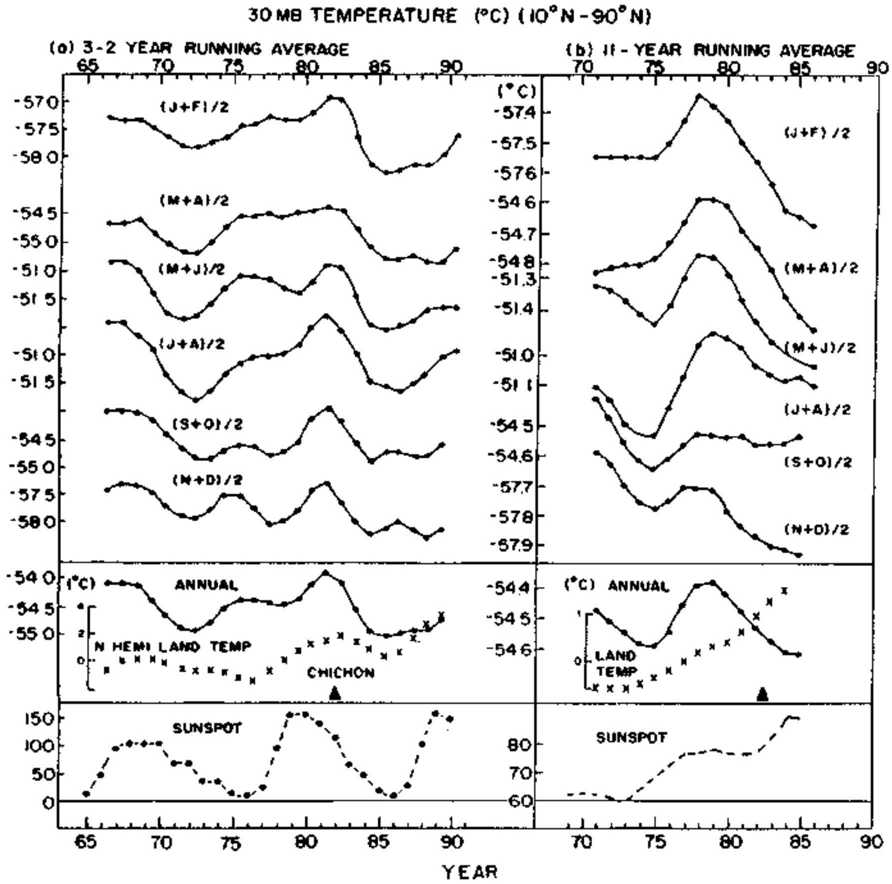

Fig. 2. **a** 3–2-year running averages of (10°–90°N) belt 30-mb 2-monthly mean temperatures as also for the whole year (annual), where the *crosses* show northern hemisphere land temperature; **b** 3–11-year running averages. *Bottom plots* are for sunspots

The left half (Fig. 2a) shows the 3–2-year running averages. When compared with the sunspots (bottom curve), the temperatures do indicate some resemblance with sunspots, with maxima near 1969, 1980 and probably near 1989–90. However, the temperature peak in 1982 (and not in 1980 sunspot maximum) may also be related to the El Chichon volcanic eruption. Also, the temperature plots show an additional peak near 1975 (sunspot minimum) in varying degrees for the various months, probably indicating a 5–6-year periodicity. The right half (Fig. 2b) shows the 11-year running averages. For almost all months, there was a negligible or downward trend from 1970 to 1975 (about 0.1° in 5 years), an uptrend from 1975 to 1978–79 (about 0.1°–0.2° in 3–4 years) and a sharp down trend from 1978 up to date except for September–October for which the change from 1978 up to date was negligible. As a result, a similar pattern is indicated for the annual means also (seventh plot). The crosses indicate the behaviour of northern hemisphere ground (land) temperatures (Jones *et al.*, 1986, updated). It appears that the recent (1979 onwards) drop in stratospheric temperatures in opposition to the rise in ground temperature. This is compatible with theoretical predictions (e.g. Ramanathan, 1988) that a tropospheric warming should be associated with stratospheric cooling. It is interesting to note, however, that the 11-year running averages of sunspots are not constant but show a rising trend from 1973 to date (Fig. 3b, bottom plot). Thus, the ground temperature rise and stratospheric temperature fall seem to vary in similar fashion to sunspot activity.

There is a quantitative difference between the changes at North Pole and changes in the 10°–90°N belt. In Fig. 1a, the year-to-year temperature variations in January–February were about 15 °C in the North Pole stratosphere. In contrast, Fig. 2a shows variations of only about 1 °C in the 10°–90°N belt. Correspondingly, the long-term changes also were several degrees at the North Pole stratosphere (Fig. 1b) but only fractions of a degree in the 10°–90°N belt stratosphere (Fig. 2b). Assuming linear fits, the decadal trends were as shown in Table 1.

Figure 3 is a plot of 50-mb temperatures in the 10°–90°N belt. The magnitudes of temperature variations are slightly smaller at 50 mb as compared to those at 30 mb (Fig. 2). Striking dissimilarities are: (i) For 1970–1975, the 50-mb plots of Fig. 3b show mostly downward trends while those of Fig. 2b show upward trends, no trends or downward trends depending on season; (ii) For September/October, Fig. 2b shows a steady level for 1978 onwards, while Fig. 3b shows a clear downtrend. The downward trend from 1978 onwards is in opposition to the upward trend of ground temperature in recent years, in agreement with theoretical predictions

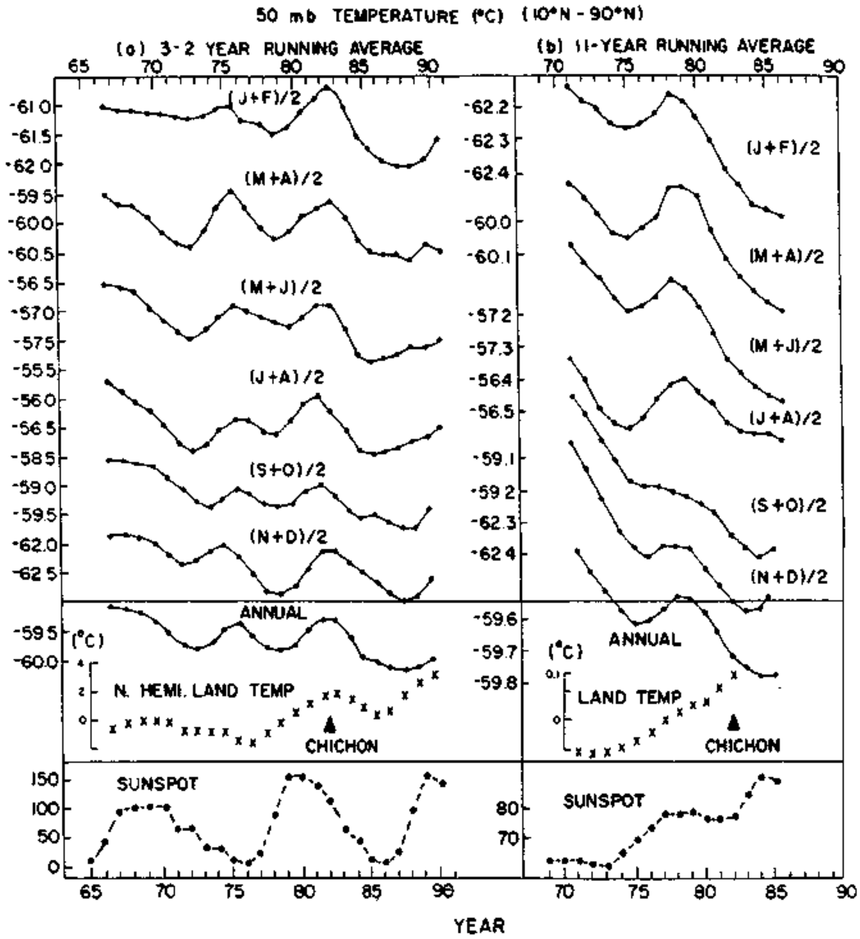

Fig. 3. a 3–2-year running averages of (10°–90°N) belt 50-mb 2-monthly mean and annual temperatures. The *crosses* show northern hemisphere land temperature; b 11-year running averages. *Bottom plots* are for sunspots

(Ramanathan, 1988). The linear gradients are given in Table 1.

5 Quasi-biennial oscillations

The zonal winds in the tropical stratosphere (16–40 km) exhibit a strong QBO. Several studies have tried to link this tropical QBO to interannual variations in the extra-tropical stratosphere. Holton and Tan (1980, 1982) showed that the equatorial QBO modulated the mean zonal wind and planetary wave components of the geopotential field in the northern hemispheric stratosphere in winter. Examining the polar stratospheric temperature data during the easterly and westerly phase years of the equatorial QBO separately, Labitzke (1982, 1987), van Loon and Labitzke (1987) (and many others) found that the polar vortex in northern winter was stronger and colder in the westerly phase. However, recently, Labitzke and van Loon (1992) have showed with an expanded data base that their earlier results are not statistically significant. In our earlier paper (Kane, 1992), it was shown that, whereas the winter month values showed large QBOs, these QBOs were intermittent, different for different months and not matching in phase with the equatorial 50-mb wind QBO. However, one value per year is not an ideal set to study QBO (2–3 years). Since we have now data for all months, 12-month running averages (to eliminate seasonal variation) centered a few months apart would be expected to reveal a better picture. Combining data for 4-monthly intervals (JFMA, MJJA, SOND, three values per year), running averages over three successive intervals were calculated, yielding 12-monthly means, centered 4 months apart (February end, June end, October end). Figure 4 shows the plots; the top plot for 30-mb North Pole temperature, the second plot for 30-mb (10°–90°N) belt temperature, the third plot for 50-mb (10°–90°N) belt temperature and the fourth plot for 50-mb equatorial wind (Venne and Dartt, 1990, upper half westerly, W; lower half easterly, E). The vertical lines mark the maxima of westerly (W) equatorial 50-mb wind. Whereas the equatorial wind QBO is fairly regular (in amplitude) and has peak separations in the range 22–34 months, the QBOs in the other parameters, though quite evident, are somewhat irregular with amplitudes sometimes large and sometimes small. For the North Pole temperatures (first plot), the peaks of largest (negative) temperatures (cold extremes) seem to match the QBO westerly-phase peaks within 4 months (in agreement with earlier results of Labitzke, 1982, 1987 who, incidentally, had used only one value per year, hence direct comparison is not possible) but not always in the same sense (lag or lead). For example, for the 1969 and 1970–71 peaks of North Pole negative temperature, the spacing was 32 months for the negative temperature peaks while it was 24 months for the wind QBO (westerly-phase) peaks. In 1989 end, the North Pole negative temperature shows a strong peak while wind QBO has no corresponding westerly-phase peak. For the 10°–90°N belt temperatures, the plots for 30 mb and 50 mb are similar except during 1977, 1978, 1979 and 1990. The peaks match between one another but do not always match with the North Pole temperature peaks or the 50-mb equatorial wind QBO peaks. This is understandable, because there is a phase shift of QBO

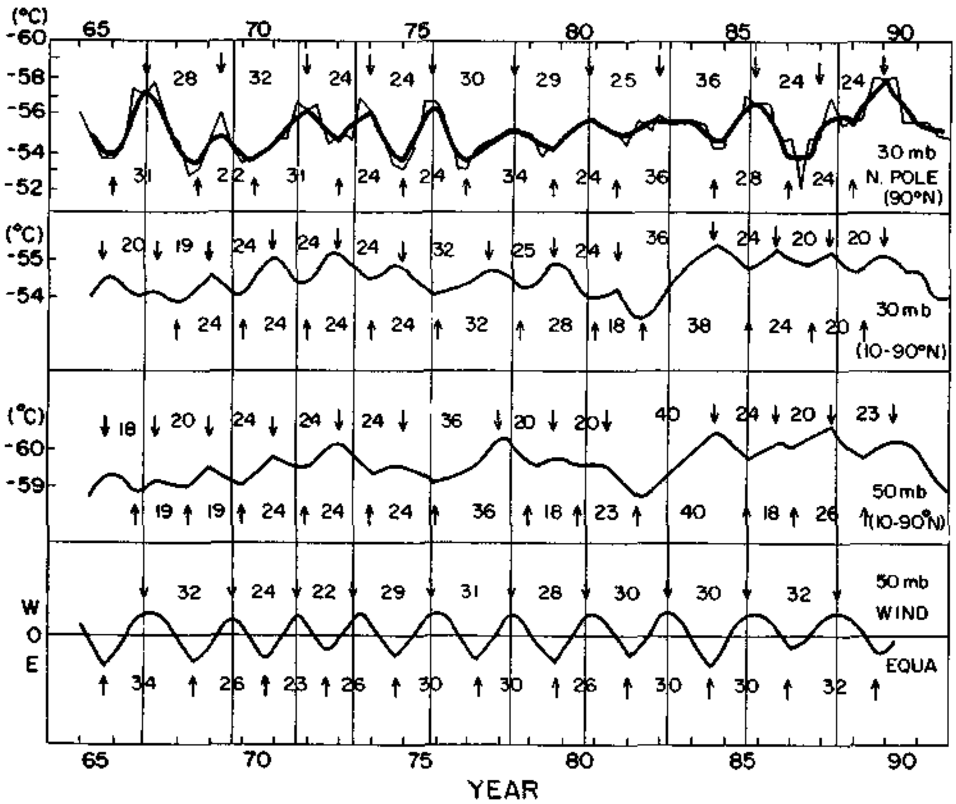

Fig. 4. 12-month running averages, centered 4 months apart, for North Pole 30-mb temperatures, (10°–90°N) belt 30-mb and 50-mb temperatures (watch negative scale) and 50-mb equatorial wind (westerly W and easterly E). The *arrows* indicate QBO peaks and the numbers indicate the spacings between successive QBO peaks (or troughs) in months. *Vertical lines* indicate westerly phase maxima of 50-mb wind QBO

from equatorial to subtropical and high latitudes. Hence, an average of such a wide belt as 10°–90°N would certainly have a complicated QBO. Dunkerton and Baldwin (1991, 1992) have studied the QBO modulation of planetary wave fluxes in the northern hemisphere winter and observed that whereas the stratosphere temperature and circulation varied interannually on time scales from 2–12 years, a substantial portion of the December–February interannual variance was due to QBO. According to them, additional variance could be due to a QDO (quasi-decadal oscillation) and QBO/low-frequency modulation.

6 Conclusions

The stratospheric temperatures show distinct trends. These are not always monotonically upward or downward.

1. At the North Pole, the trends are larger in winter months but different winter months (November, December, January, February) show very different trends, even qualitatively. Roughly, November and December show downward trends, January does not show a monotonic upward or downward trend, February, March and April show upward trends and other months have small downward trends. In winter, polar vortexes are formed which end up in final warmings and polar vortex breakdown which occurs in February–March in the North Pole region. It would thus seem that the North Pole vortex is getting colder in the last few years. This could be one of the causes for the ozone depletion there, reported by Bunn *et al.* (1991). In contrast, the temperatures after the North Pole vortex breakdown in March–April seem to have increased during the last few years, probably maintaining an overall heat balance. However, the temperatures in subsequent months (May–October) have a slightly decreasing tendency, indicating an overall cooling of the North Pole region. This needs further exploration.
2. For the 10°–90°N belt, there are slight differences in the trends of different months. During 1971–1975, the 30-mb temperatures show upward, downward or no trend, depending upon season, whilst 50-mb temperature trends are monotonically downward. During 1975–1978, the trend seems to have turned upwards at both 30 mb and 50 mb. For 1978 onwards, trends are predominantly downward at 50 mb for all months and at 30 mb for all months except September–October. This downward trend is in opposition to the recent upward trend showed by ground temperature in the northern hemisphere, thus it is in agreement with theoretical expectations (Ramanathan, 1988). The overall trend is slightly downward at 30 mb and considerably downward at 50 mb.
3. When seasonal variations are eliminated by calculating running averages over 12 consecutive months, the temperature plots show prominent QBO, though not as regular as that of 50-mb equatorial wind. For North Pole temperatures, 50-mb wind QBO west-phase maxima seem to be associated with colder polar temperatures, confirming earlier results of Labitzke (1982, 1987). For 10°–90°N belt, the 30-mb and 50-mb temperature variations are almost alike but their QBO phases do not match well with 50-mb wind QBO phases, probably because QBO phase shifts with latitude. Dunkerton and Baldwin (1992) have shown that the correlation between the equatorial QBO wind and the winter stratospheric temperature is positive in the 20°N–50°N belt and negative in the 50°–90°N belt. Thus, 10°–90°N is too wide a belt to show clear QBO features. A study with finer latitude belts is necessary and will be conducted as and when such data are available to us. However, since we are dealing with long-term temperature trends and have used running averages over several years, the differences due to different QBO effects are expected to have been wiped out.

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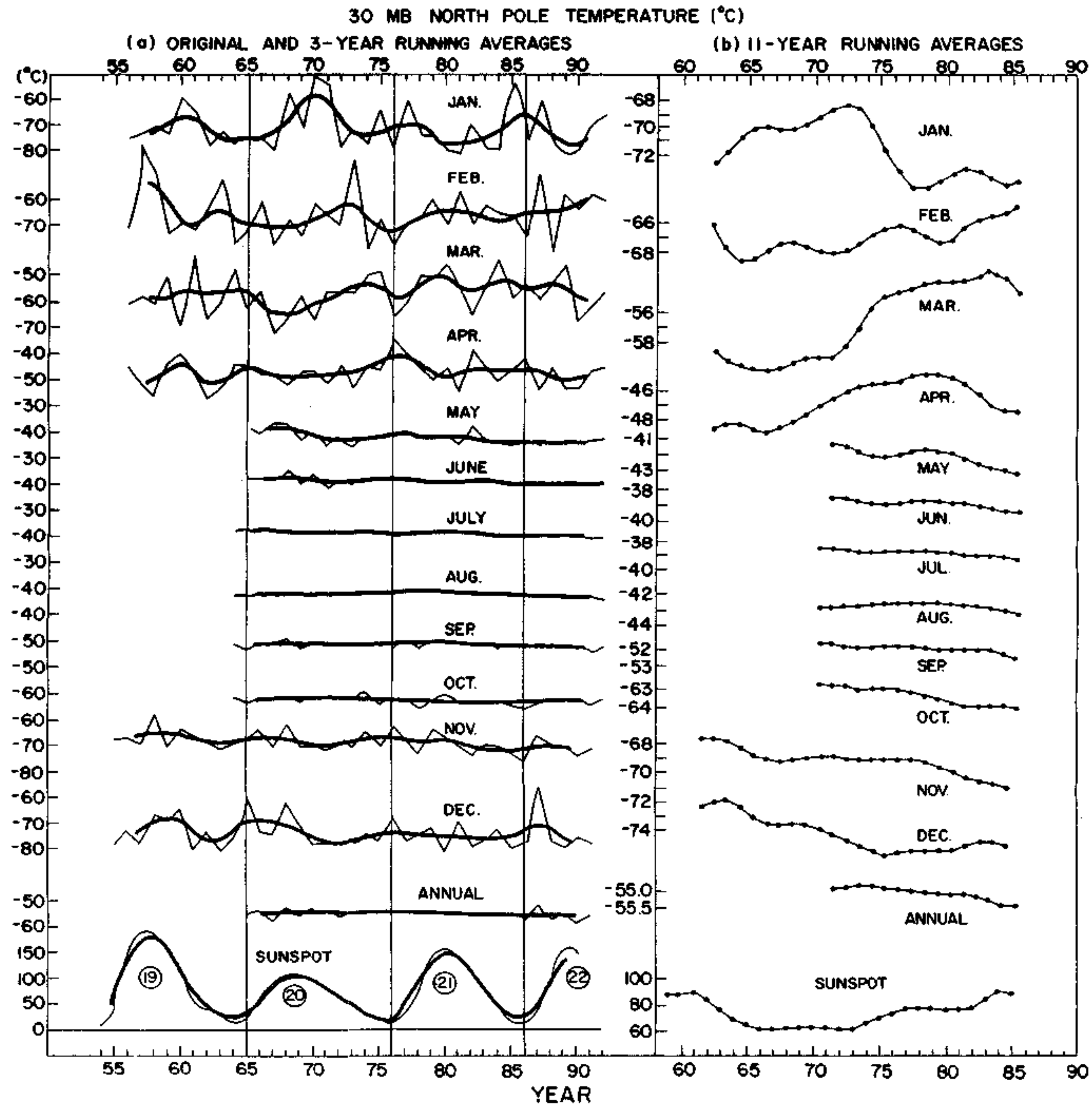

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Annual	− 0.33Δ ± 0.05	− 0.04Δ ± 0.04	− 0.23Δ ± 0.03

1967 to 1978 (11 years) and a drop of about 2° thereafter. December shows a drop of about 2° from 1963 to 1975 (12 years) and a steady level thereafter. Thus, the changes are very different for the different months. As a result, the annual means hardly show a 0.5° drop from 1974 to 1985 (11 years). If the variations in linearity are ignored and a straight line is fitted to the 11-year running averages, the decadal trends (°K per decade) are as given in Table 1. There is a significant difference between the trends in November, December, January (negative) and February, March, April (positive).

It must be remembered, however, that the monthly mean temperatures at the North Pole are greatly affected by major mid-winter warmings which occur during December to March. If these occurred more often in the earlier (or later) years, apparent down (or up) trends would result and may result in different trends for different winter months. The warming occurred in December of 1965, 1968, 1987, January of 1968, 1970, 1971, 1977, 1985, 1987, February of 1957, 1958, 1963, 1966, 1973, 1979, 1981, 1987, 1989, March of 1959, 1961, 1964, 1974, 1975, 1980, 1984, 1986, 1988 and April of 1976, 1982. Thus, these were well spread over earlier as well as later (recent) years and could not have affected very much the overall long-term trends. However, the differences in trends of different winter months (e.g. the abnormally high values for January during 1969–1973) may be due to such abnormal warmings.

4 Stratospheric temperature at other latitudes

Naujokat (1981) showed that trends may be different at different latitudes. Labitzke and van Loon (1991) reported results for the latitude belt 20°N–50°N but for October–November only. For a wider belt, (10°N–90°N), they reported results for all months. Figure 2 shows the trends for 30 mb temperatures for 2-month means (JF, . . ., ND).

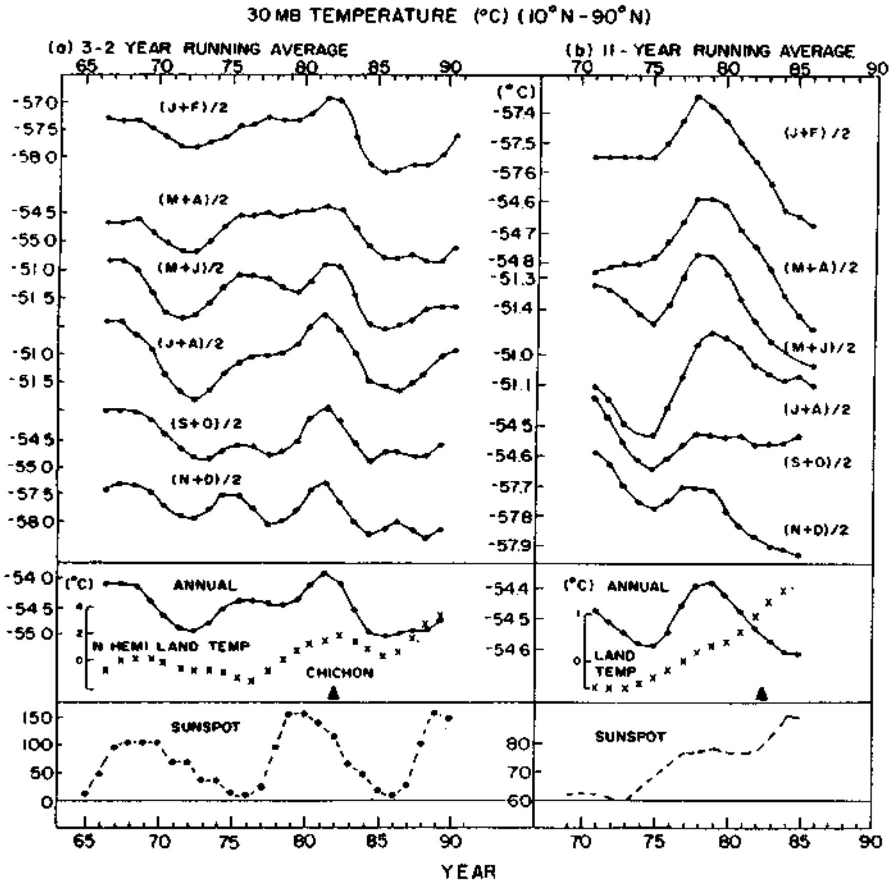

Fig. 2. a 3–2-year running averages of (10°–90°N) belt 30-mb 2-monthly mean temperatures as also for the whole year (annual), where the *crosses* show northern hemisphere land temperature; **b** 3–11-year running averages. *Bottom plots* are for sunspots

The left half (Fig. 2a) shows the 3–2-year running averages. When compared with the sunspots (bottom curve), the temperatures do indicate some resemblance with sunspots, with maxima near 1969, 1980 and probably near 1989–90. However, the temperature peak in 1982 (and not in 1980 sunspot maximum) may also be related to the El Chichon volcanic eruption. Also, the temperature plots show an additional peak near 1975 (sunspot minimum) in varying degrees for the various months, probably indicating a 5–6-year periodicity. The right half (Fig. 2b) shows the 11-year running averages. For almost all months, there was a negligible or downward trend from 1970 to 1975 (about 0.1° in 5 years), an uptrend from 1975 to 1978–79 (about 0.1°–0.2° in 3–4 years) and a sharp down trend from 1978 up to date except for September–October for which the change from 1978 up to date was negligible. As a result, a similar pattern is indicated for the annual means also (seventh plot). The crosses indicate the behaviour of northern hemisphere ground (land) temperatures (Jones *et al.*, 1986, updated). It appears that the recent (1979 onwards) drop in stratospheric temperatures in opposition to the rise in ground temperature. This is compatible with theoretical predictions (e.g. Ramanathan, 1988) that a tropospheric warming should be associated with stratospheric cooling. It is interesting to note, however, that the 11-year running averages of sunspots are not constant but show a rising trend from 1973 to date (Fig. 3b, bottom plot). Thus, the ground temperature rise and stratospheric temperature fall seem to vary in similar fashion to sunspot activity.

There is a quantitative difference between the changes at North Pole and changes in the 10°–90°N belt. In Fig. 1a, the year-to-year temperature variations in January–February were about 15 °C in the North Pole stratosphere. In contrast, Fig. 2a shows variations of only about 1 °C in the 10°–90°N belt. Correspondingly, the long-term changes also were several degrees at the North Pole stratosphere (Fig. 1b) but only fractions of a degree in the 10°–90°N belt stratosphere (Fig. 2b). Assuming linear fits, the decadal trends were as shown in Table 1.

Figure 3 is a plot of 50-mb temperatures in the 10°–90°N belt. The magnitudes of temperature variations are slightly smaller at 50 mb as compared to those at 30 mb (Fig. 2). Striking dissimilarities are: (i) For 1970–1975, the 50-mb plots of Fig. 3b show mostly downward trends while those of Fig. 2b show upward trends, no trends or downward trends depending on season; (ii) For September/October, Fig. 2b shows a steady level for 1978 onwards, while Fig. 3b shows a clear downtrend. The downward trend from 1978 onwards is in opposition to the upward trend of ground temperature in recent years, in agreement with theoretical predictions

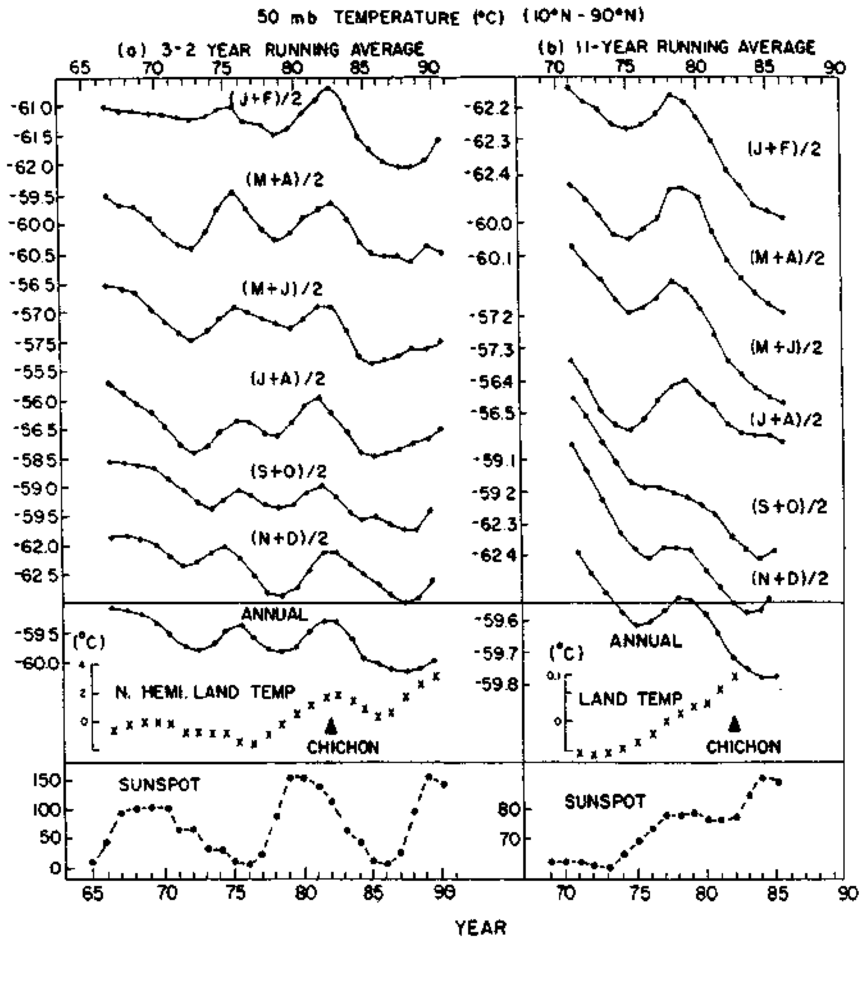

Fig. 3. **a** 3–2-year running averages of (10°–90°N) belt 50-mb 2-monthly mean and annual temperatures. The *crosses* show northern hemisphere land temperature; **b** 11-year running averages. *Bottom plots* are for sunspots

(Ramanathan, 1988). The linear gradients are given in Table 1.

5 Quasi-biennial oscillations

The zonal winds in the tropical stratosphere (16–40 km) exhibit a strong QBO. Several studies have tried to link this tropical QBO to interannual variations in the extra-tropical stratosphere. Holton and Tan (1980, 1982) showed that the equatorial QBO modulated the mean zonal wind and planetary wave components of the geopotential field in the northern hemispheric stratosphere in winter. Examining the polar stratospheric temperature data during the easterly and westerly phase years of the equatorial QBO separately, Labitzke (1982, 1987), van Loon and Labitzke (1987) (and many others) found that the polar vortex in northern winter was stronger and colder in the westerly phase. However, recently, Labitzke and van Loon (1992) have showed with an expanded data base that their earlier results are not statistically significant. In our earlier paper (Kane, 1992), it was shown that, whereas the winter month values showed large QBOs, these QBOs were intermittent, different for different months and not matching in phase with the equatorial 50-mb wind QBO. However, one value per year is not an ideal set to study QBO (2–3 years). Since we have now data for all months, 12-month running averages (to eliminate seasonal variation) centered a few months apart would be expected to reveal a better picture. Combining data for 4-monthly intervals (JFMA, MJJA, SOND, three values per year), running averages over three successive intervals were calculated, yielding 12-monthly means, centered 4 months apart (February end, June end, October end). Figure 4 shows the plots; the top plot for 30-mb North Pole temperature, the second plot for 30-mb (10°–90°N) belt temperature, the third plot for 50-mb (10°–90°N) belt temperature and the fourth plot for 50-mb equatorial wind (Venne and Dartt, 1990, upper half westerly, W; lower half easterly, E). The vertical lines mark the maxima of westerly (W) equatorial 50-mb wind. Whereas the equatorial wind QBO is fairly regular (in amplitude) and has peak separations in the range 22–34 months, the QBOs in the other parameters, though quite evident, are somewhat irregular with amplitudes sometimes large and sometimes small. For the North Pole temperatures (first plot), the peaks of largest (negative) temperatures (cold extremes) seem to match the QBO westerly-phase peaks within 4 months (in agreement with earlier results of Labitzke, 1982, 1987 who, incidentally, had used only one value per year, hence direct comparison is not possible) but not always in the same sense (lag or lead). For example, for the 1969 and 1970–71 peaks of North Pole negative temperature, the spacing was 32 months for the negative temperature peaks while it was 24 months for the wind QBO (westerly-phase) peaks. In 1989 end, the North Pole negative temperature shows a strong peak while wind QBO has no corresponding westerly-phase peak. For the 10°–90°N belt temperatures, the plots for 30 mb and 50 mb are similar except during 1977, 1978, 1979 and 1990. The peaks match between one another but do not always match with the North Pole temperature peaks or the 50-mb equatorial wind QBO peaks. This is understandable, because there is a phase shift of QBO

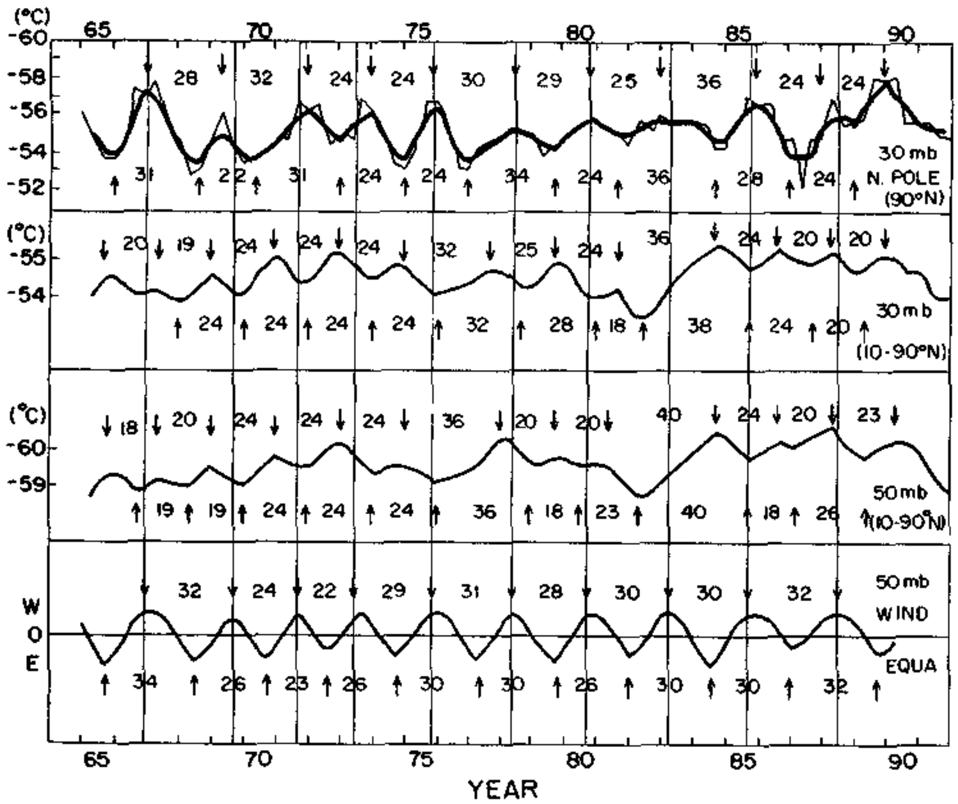

Fig. 4. 12-month running averages, centered 4 months apart, for North Pole 30-mb temperatures, (10°–90°N) belt 30-mb and 50-mb temperatures (watch negative scale) and 50-mb equatorial wind (westerly W and easterly E). The *arrows* indicate QBO peaks and the numbers indicate the spacings between successive QBO peaks (or troughs) in months. *Vertical lines* indicate westerly phase maxima of 50-mb wind QBO

from equatorial to subtropical and high latitudes. Hence, an average of such a wide belt as 10°–90°N would certainly have a complicated QBO. Dunkerton and Baldwin (1991, 1992) have studied the QBO modulation of planetary wave fluxes in the northern hemisphere winter and observed that whereas the stratosphere temperature and circulation varied interannually on time scales from 2–12 years, a substantial portion of the December–February interannual variance was due to QBO. According to them, additional variance could be due to a QDO (quasi-decadal oscillation) and QBO/low-frequency modulation.

6 Conclusions

The stratospheric temperatures show distinct trends. These are not always monotonically upward or downward.

1. At the North Pole, the trends are larger in winter months but different winter months (November, December, January, February) show very different trends, even qualitatively. Roughly, November and December show downward trends, January does not show a monotonic upward or downward trend, February, March and April show upward trends and other months have small downward trends. In winter, polar vortexes are formed which end up in final warmings and polar vortex breakdown which occurs in February–March in the North Pole region. It would thus seem that the North Pole vortex is getting colder in the last few years. This could be one of the causes for the ozone depletion there, reported by Bunn *et al.* (1991). In contrast, the temperatures after the North Pole vortex breakdown in March–April seem to have increased during the last few years, probably maintaining an overall heat balance. However, the temperatures in subsequent months (May–October) have a slightly decreasing tendency, indicating an overall cooling of the North Pole region. This needs further exploration.
2. For the 10°–90°N belt, there are slight differences in the trends of different months. During 1971–1975, the 30-mb temperatures show upward, downward or no trend, depending upon season, whilst 50-mb temperature trends are monotonically downward. During 1975–1978, the trend seems to have turned upwards at both 30 mb and 50 mb. For 1978 onwards, trends are predominantly downward at 50 mb for all months and at 30 mb for all months except September–October. This downward trend is in opposition to the recent upward trend showed by ground temperature in the northern hemisphere, thus it is in agreement with theoretical expectations (Ramanathan, 1988). The overall trend is slightly downward at 30 mb and considerably downward at 50 mb.
3. When seasonal variations are eliminated by calculating running averages over 12 consecutive months, the temperature plots show prominent QBO, though not as regular as that of 50-mb equatorial wind. For North Pole temperatures, 50-mb wind QBO west-phase maxima seem to be associated with colder polar temperatures, confirming earlier results of Labitzke (1982, 1987). For 10°–90°N belt, the 30-mb and 50-mb temperature variations are almost alike but their QBO phases do not match well with 50-mb wind QBO phases, probably because QBO phase shifts with latitude. Dunkerton and Baldwin (1992) have shown that the correlation between the equatorial QBO wind and the winter stratospheric temperature is positive in the 20°N–50°N belt and negative in the 50°–90°N belt. Thus, 10°–90°N is too wide a belt to show clear QBO features. A study with finer latitude belts is necessary and will be conducted as and when such data are available to us. However, since we are dealing with long-term temperature trends and have used running averages over several years, the differences due to different QBO effects are expected to have been wiped out.

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