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INFLUENCES OF SOLAR-TERRESTRIAL EVENTS ON ATMOSPHERIC ENVIRONMENT OVER SYOWA STATION, ANTARCTICA: A PRELIMINARY ANALYSIS OF RADIOSONDE OBSERVATIONS

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Abstract: Radiosonde observations at Syowa Station, Antarctica (69°S, 40°E), are analyzed to find the stratospheric and tropospheric influence of solar-terrestrial phenomena in 1967–1993. Although the level of statistical significance is generally low, mean temperature changes of 1–2°C are seen after solar proton events; these include transient warming in the lower stratosphere and cooling in the troposphere. The most significant temperature changes appeared during the East phase of quasi biennial oscillation (QBO$<$0). The presence of a weak correlation with the phase southern oscillation index (SOI) is also suggested. Only very low-level correlations are found for Forbush decreases of galactic cosmic rays and geomagnetic activities.

1. Introduction

The influence of transient solar-terrestrial activities (solar flares, solar proton events, geomagnetic storms, Forbush decreases of galactic cosmic rays, sector boundary passages, etc.) on the atmospheric environment has been a controversial subject for many years (*e.g.* HERMAN and GOLDBERG, 1978). Recently, the importance of high-energy particles (galactic cosmic rays and high-energy solar protons) on the terrestrial atmosphere has been pointed out by several authors. The presence of a causal relationship between the cosmic ray flux and intensification of the vorticity area index (VAI), which is an objective measure of the intensification of cyclonic storms and the deeping of low-pressure troughs, has been proposed by TINSLEY *et al.* (1989) and TINSLEY and DEEN (1991). They pointed out that decreases of the VAI at the 500 hPa pressure level started when Forbush decreases of the galactic cosmic rays were initiated. The decrease of the flux of galactic cosmic rays has been proposed to produce the decrease of the amount of latent heat released in supercooled clouds through an "electro-freezing process" (TINSLEY and DEEN, 1991).

SCHUURMANS (1991) has proposed that, on the other hand, the incidence of high-energy solar protons to the atmosphere will be the principal agent to produce transient change of upper-tropospheric temperature. He analyzed radiosonde data taken at De Bilt, Netherlands, and concluded that the incidence of solar protons produced notable decrease in the tropospheric temperature at the pressure level 200 hPa. He also pointed out that the influence of solar protons appears prominently in the periods of the east phase of the quasi-biennial oscillation (QBO$<$0).

KODAMA *et al.* (1992) analyzed radiosonde observations at Syowa to find the stratospheric temperature change after strong solar proton events in 1956–1990. They estimated the temperature difference between "before" the start of a solar proton event and "after" its peak, using temperatures obtained at the highest levels reached by relevant radiosondes (40–15 hPa pressure levels). A "normalization" of temperatures obtained at different pressure levels is performed by calculating the differential temperatures with respect to those at the 100 hPa pressure level. They concluded that, for 64% of 33 solar proton events, the amount of cooling of the lower stratosphere (20–30 km) was 2.4°C, on average. They suggested that direct chemical control by ozone destruction by solar-proton incidence will be important even in the lower stratosphere.

Since the analysis of KODAMA *et al.* (1992) did not depend on a machine-readable database which was not available when they conducted their analysis, further detailed statistical analysis using a comprehensive database is required to confirm the atmospheric influences of solar-terrestrial phenomena. The principal subject of the present work is to conduct detailed statistical analysis of the database of radiosonde observations at Syowa Station during 1957–1993 to find evidence of solar-induced stratospheric and tropospheric temperature changes. Important differences between the previous analysis by KODAMA *et al.* (1992) and ours are as follows.

(1) We introduce the superposed-epoch analysis. We estimate the difference between the mean temperatures (averages for the data of 5–10 days) before and after the key day. KODAMA *et al.* (1992) compared only two points; before and after the event.

(2) We remove the seasonal variation.

(3) We omit data obtained in the interval September–October because the lower stratosphere in this interval was highly disturbed almost every year. If we employed a theory of ozone depression caused by proton incidence, the chemical process involving the creation of NOy by proton incidence requires UV. From this point of view, the analysis should be done for the interval under sunlit condition. We tentatively select the interval November–April in the present analysis.

(4) KODAMA *et al.* (1992) employed normalized temperatures with respect to the temperatures at the 100 hPa pressure level. We simply compare the mean temperatures before and after the start of a particular solar-terrestrial phenomenon at each pressure level.

2. Data Sources

The data source of radiosonde observations at Syowa, Antarctica is a machine-readable database constructed by the Japan Meteorological Agency. This database includes radiosonde and ground-level observations since 1957. From 1974, routine observations have been conducted twice a day (at 0230 and 1430 in LT). In this database, temperature, humidity, dew point temperature, wind direction, and wind speed at each standard pressure level are listed. We use a part of the database, 1967–1993, in the present analysis because it provides good data coverage. The principal data source of solar flares (proton flares) and solar proton events is the Solar-Geophysical Data published by the US Department of Commerce, Boulder, CO 80303, U.S.A. We use an unpublished list prepared by S. YASUNO (private communication, 1995) for Forbush decreases of galactic cosmic rays. For geomagnetic activity data, we use geomagnetic K-index observations taken at Syowa in 1967–1993.

3. Method of Data Analysis

3.1. Removal of seasonal variation

In the present analysis, we estimate temperature changes before and after solar-terrestrial phenomena, with a time span of several days. Since the temperature at the 30 hPa pressure level, for example, shows a large seasonal variation with the characteristic

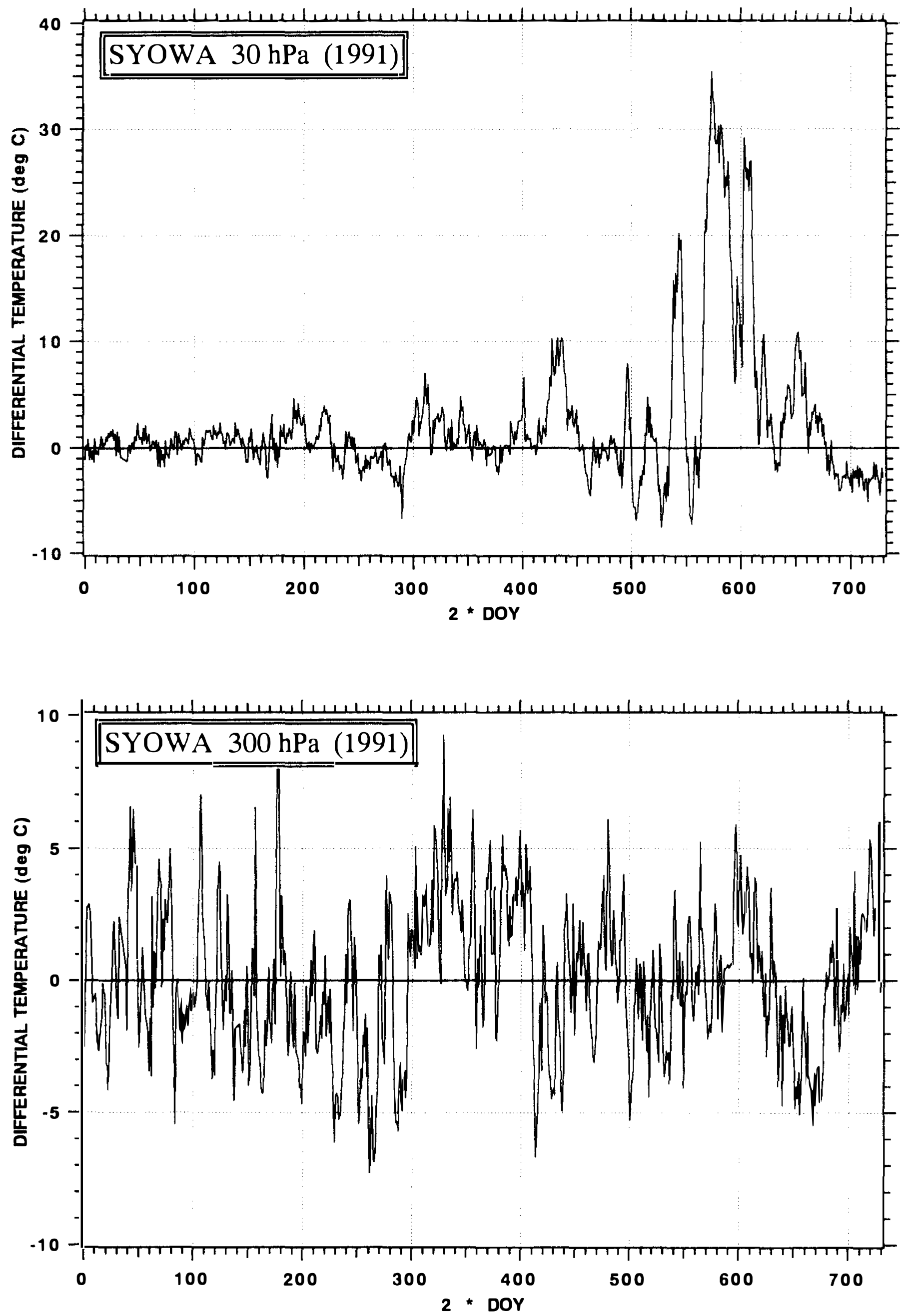

Fig. 1. "Flattened" temperature variations in 1991 at the 30 hPa (top) and the 300 hPa (bottom) pressure levels after removal of seasonal variations (see text). The horizontal axes are 2× of day-of-year (1 January = 0).

amplitude of 50°C, the maximum rate of temperature variation can be 0.3°C/day at this pressure level. According to the model developed by REID *et al.* (1991), predicted temperature changes induced by a solar proton event will be <3°C in the stratospheric ozone layer (40–50 km) and much smaller at lower levels. It is obvious that the seasonal variation must be removed before we calculate temperature variation before and after a specific solar-terrestrial event, because the time span can be several days. To remove the general trend of the seasonal variation, we use an averaged seasonal variation to be subtracted from daily observations. We determine the averaged seasonal variation using observations in 1967–1993, then we perform the running average to smooth the curve with the window of 30 days. Examples of "flattened" temperature variations at the 300 hPa and the 30 hPa pressure levels in 1991 are shown in Fig. 1. Although the seasonal variation appears to be successfully removed by the method mentioned above, it is still inappropriate to employ a long time span to estimate the temperature variations because the pattern of seasonal variation was considerably different from year to year. The maximum time span will be determined by a "false events test" which will be mentioned in Section 4 of this paper.

3.2. Superposed-epoch analysis

Since the purpose of our analysis is to confirm whether significant temperature changes are seen in the troposphere and the stratosphere before and after transient solar-terrestrial events, we perform a superposed-epoch analysis of radiosonde observations at Syowa, after removal of seasonal variations. We extracted the data in the interval of 20 days centered at the key day (time lag$=0$) which is the onset of each solar-terrestrial event. Since daily radiosonde observations at Syowa have been performed at 0230 and at 1430 (LT) respectively, the closest time to a given onset time is selected as the key day. Then we estimated mean temperatures before and after the key day at each pressure level, respectively, and the difference of the mean temperatures (after-before) is calculated as the final result. We average all observations without distinction between the two data sets which were taken at 0230 LT and at 1430 LT, respectively, because our purpose is to find relative changes in averaged temperatures, although this will partly contribute to increasing the amplitude of fluctuations of the data.

4. Results of Analysis

4.1. False events test

Before we apply the procedure mentioned in the previous section to actual solar-terrestrial events, we check the possibility of accidental correlation by assuming "false events" in such a way that the key days are tentatively shifted by $+10$ days from the day of occurrence of each solar proton event observed in 1967–1993. This time shift is selected to be about half of the solar rotation period because solar activities sometimes showed recurrent characteristics. The mean temperature difference (dT, horizontal axis) is plotted in Fig. 2 as a function of the pressure level in hPa (vertical axis). The bar added at each data point represents the level of fluctuations (variance). It is seen in this figure that all the points are distributed close to the line of $dT=0$°C. This means that no significant temperature change is obtained when we select events in a random manner. Based on a

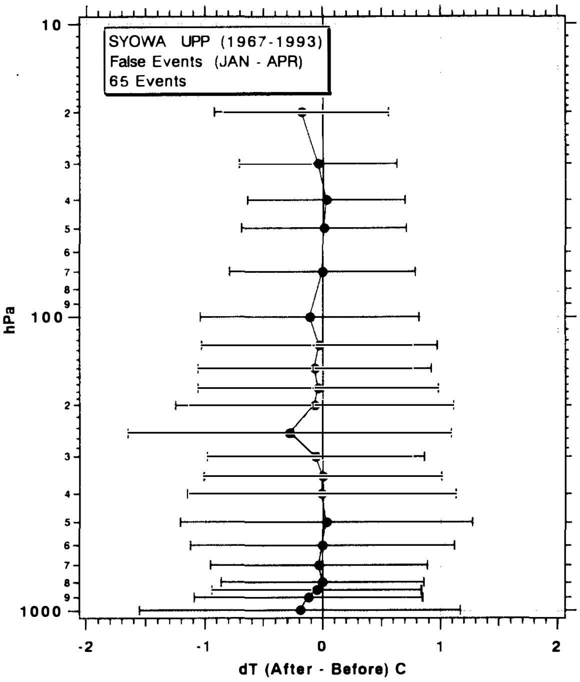

Fig. 2. Mean temperature differences at pressure levels over Syowa, Antarctica, before and after "false" events in 1967-1993 (65 events).

number of trial changes of the time shift, the temperature changes of $<0.5°C$ appear to be accidental.

The analysis for false events, mentioned above, was conducted for the interval of ± 5 days centered at key days. If we take longer intervals, *e.g.* ± 10 days, the results are considerably biased by seasonal variations which remain to be removed. In analyses given below, averages will be taken over the interval of 5 days before and after the key day, respectively.

4.2. Solar flares

We apply the superposed-epoch analysis to proton flares observed in November-April in 1976-1993, based on a list published in Solar-Geophysical Data. The result of the analysis is shown in Fig. 3 using the same format as that of Fig. 2. Instead of a low statistical significance level, we find an increasing tendency of stratospheric temperature with height. There exists a drop in temperature of about 1°C in the troposphere, at the levels around the 250 hPa pressure level. However, the present results are not be evidence of the direct influence of solar-flares on stratospheric and tropospheric atmosphere because many solar proton events were observed shortly after strong solar flares with time lags ranging from <1 hour to >24 hours.

4.3. Solar proton events

To see the atmospheric influence of solar proton events, we apply superposed-epoch analysis to proton events with pfu>10 for protons with energy larger than 10 MeV in a geosynchronous orbit. The result of the analysis for the interval November-April in 1967-1993 (65 events) is shown in Fig. 4. Although the level of statistical significance is not high, there exists a tendency for the temperature of the lower stratosphere to show an

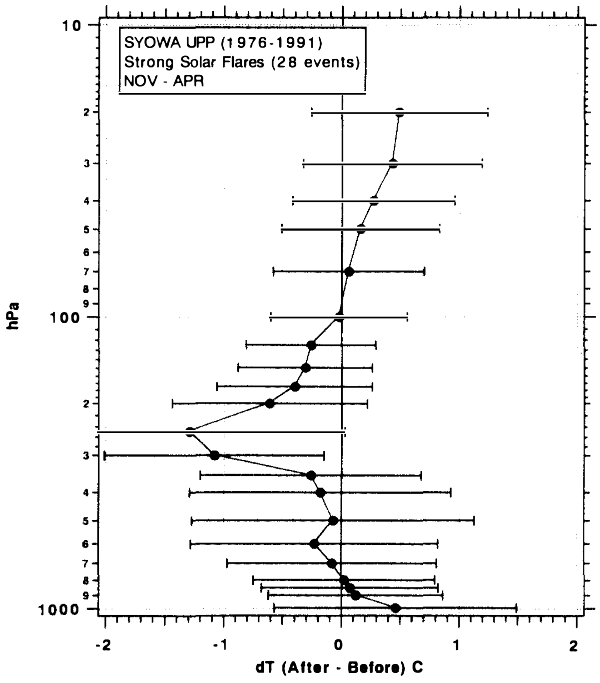

Fig. 3. Same as Fig. 2 but for proton flares in 1976-1991 (28 events).

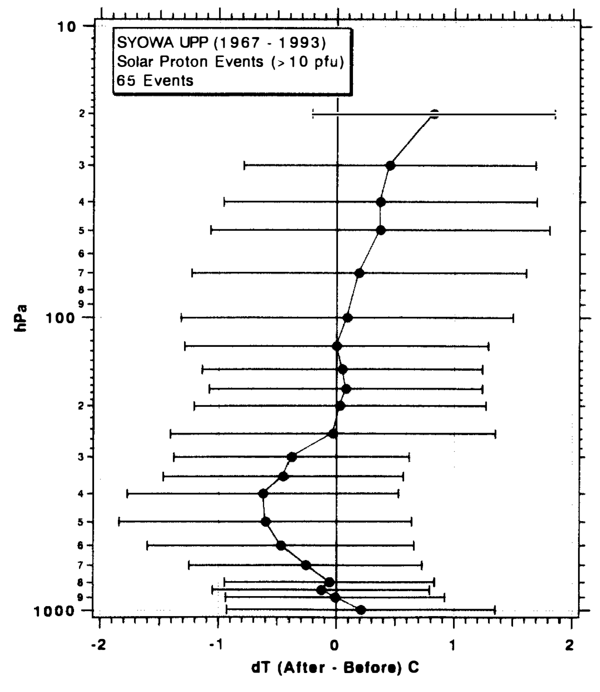

Fig. 4. Same as Fig. 2 but for solar proton events in 1967-1993 (65 events).

increase. In the troposphere, a temperature decrease is seen around the 500 hPa pressure level.

4.4 Forbush decrease of galactic cosmic rays

TINSLEY *et al.* (1989) and TINSLEY and DEEN (1991) proposed that the modulation of

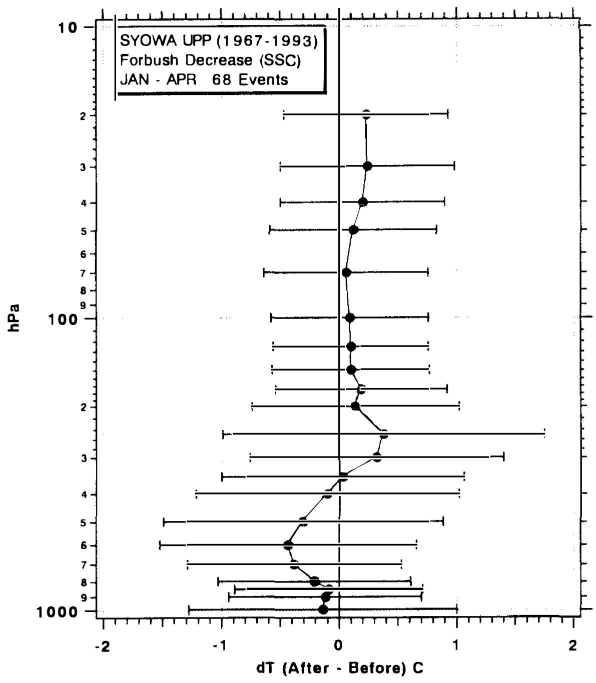

Fig. 5. Same as Fig. 2 but for Forbush decreases of galactic cosmic rays in 1967–1993 (68 events).

the flux of galactic cosmic rays is the principal cause of solar-induced variations of the global atmospheric circulation. The result of the analysis for 68 events in 1967–1993 is shown in Fig. 5. Although a very weak tendency of decreasing temperature in the troposphere is seen as suggested by TINSLEY *et al.* (1989) and TINSLEY and DEEN (1991), the level of statistical significance is low. Since many Forbush decreases were observed 1–2 days after strong solar flares which were frequently accompanied by solar proton events, it is suggested that the weak correlation seen in Fig. 5 is partly due to the effect of solar proton events.

4.5. Geomagnetic activity

The analyses performed in the previous three sections are for solar flares and their associated events. On the other hand, high geomagnetic activity is observed both in the intervals of high and low solar activities. When the solar activity is high, enhanced geomagnetic activities are observed in association with solar flares (or CMEs). In a period of low solar activity, high geomagnetic activity is induced by corotating high-speed streams of the solar wind. An analysis based on geomagnetic activity data will provide us with an opportunity to include non-flare associated events in our analysis. We use geomagnetic K-index observations at Syowa for this purpose. We selected "days of high geomagnetic activity" in such a way that the daily value of K indices, which is the daily sum of 3-hour K indices (ΣK index), is larger than 40. The result for 33 events observed in 1967–1993 is shown in Fig. 6. Although we may find decrease and increase of temperatures in the troposphere and the stratosphere, the significance level is not high enough to draw definite conclusions at present.

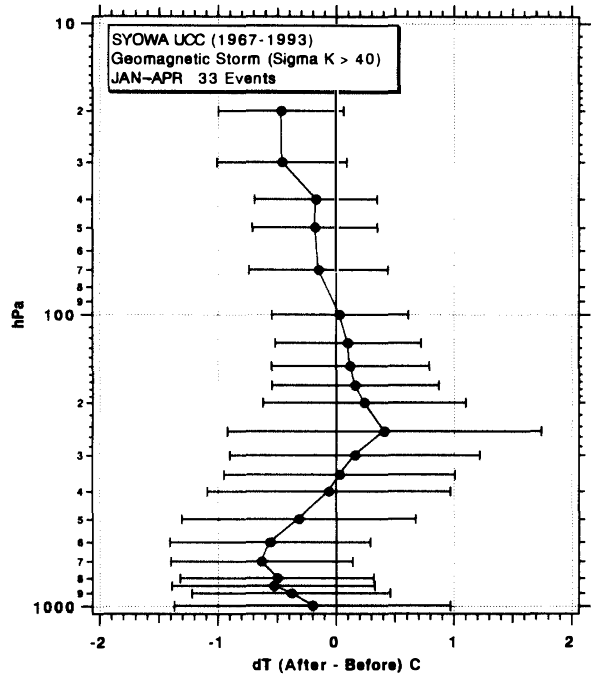

Fig. 6. Same as Fig. 2 but for high geomagnetic activities in 1967-1993 (sigma $K>40$, 33 events).

4.6. Discussion

If we compare the results of superposed-epoch analysis for solar-terrestrial phenomena with that for false events shown in Fig. 2, it is suggested that some changes took place both in the stratosphere and the troposphere, although the statistical significance levels are not high enough to draw definite conclusions. Hereinafter, we perform further analysis for solar proton events because the most significant correlation was obtained for solar proton events.

According to SHUURMANS (1991), the influence of solar proton events on the troposphere and the stratosphere will be high in the East phase of QBO. On the other hand, WATANABE and FUJITA (1994) suggested that the signs of tropospheric and stratospheric temperature changes will be reversed by switching of the SOI (Southern Oscillation Index). The low level of statistical significance obtained in the present analysis will be partly caused by a mixture of intervals of high and low response, even intervals with opposite sense of response. It is necessary to perform more detailed analysis taking account the phases of QBO and SOI. In next section, we perform superposed epoch analysis for solar proton events considering the phases of QBO and SOI.

5. Stratospheric and Tropospheric Response of Solar Proton Events and its Relationship to Global Atmospheric Circulation (QBO and SOI)

5.1. QBO dependence

The data source for QBO is the Meteorologisches Institut, Freie Universitat Berlin. The results of superposed-epoch analysis with respect to the QBO phase at the 30 hPa pressure level (>0 is the West phase, and <0 is the East phase) are shown in Fig. 7. It is seen that the QBO<0 (East) case gives significant decrease of the tropospheric tempera-

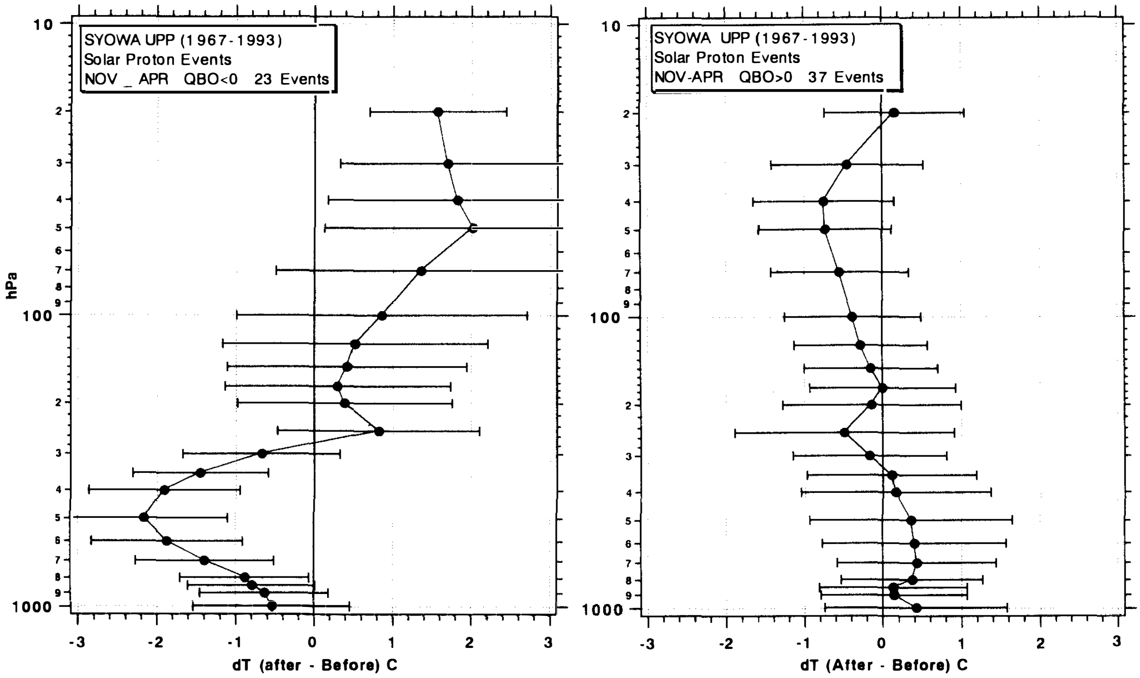

Fig. 7. *Same as Fig. 2 but for proton events in the QBO < 0 phase (left) and in the QBO > 0 phase (right).*

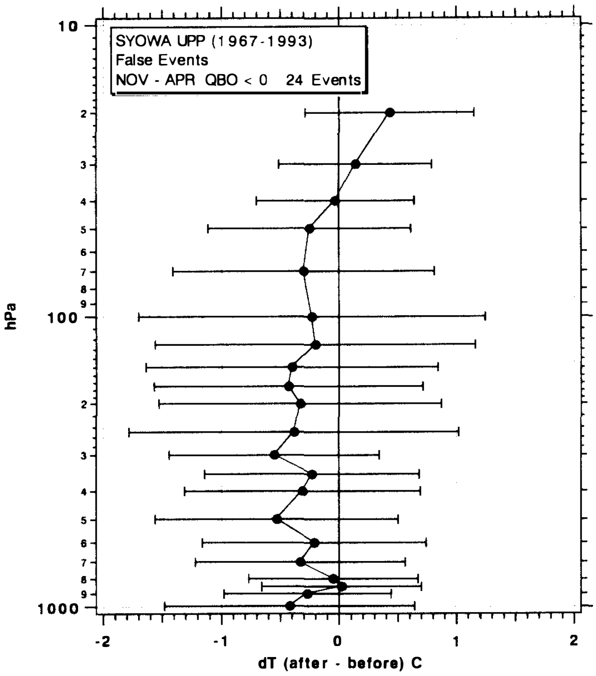

Fig. 8. *Same as Fig. 7 but for false events in the QBO < 0 phase. False events are created in such a way that each key-day (the occurrence of a proton event) is shifted by +20 days.*

ture of 2°C at 500 hPa level, and increase in the stratospheric temperature of similar magnitude. On the other hand, in the cases of QBO>0 (37 events), the tendency of temperature changes is opposite to that of QBO<0, although the temperature changes were small.

Since the number of examples is reduced by separating the QBO phases into two cases, the chance of accidental coincidence will be increased. To check this, we performed a false-event test for sets with reduced sample numbers. The result of the false-event test applied to the same data sets shown in Fig. 7, but the key-days are shifted by +20 days, is given in Fig. 8. It is seen that the temperature changes are considerably smaller than those seen in the case of East QBO (<0) phase in Fig. 7 but comparable to those in the cases of opposite QBO phase. This means that the atmospheric response to solar protons is more important during the East QBO phase than in West QBO cases.

5.2. SOI dependence

The data source of SOI is the CDF database of NSSDC. The results of superposed-epoch analysis with respect to the sign of the SOI are shown in Fig. 9. Since the positive phase appeared only occasionally, the number of events in the interval is small (26). Although the level of statistical significance is generally low, we find an increase in stratospheric temperature and decrease in the tropospheric temperature is during the positive SOI phase. The amplitude of atmospheric response during the negative SOI phases was considerably smaller than in the opposite cases.

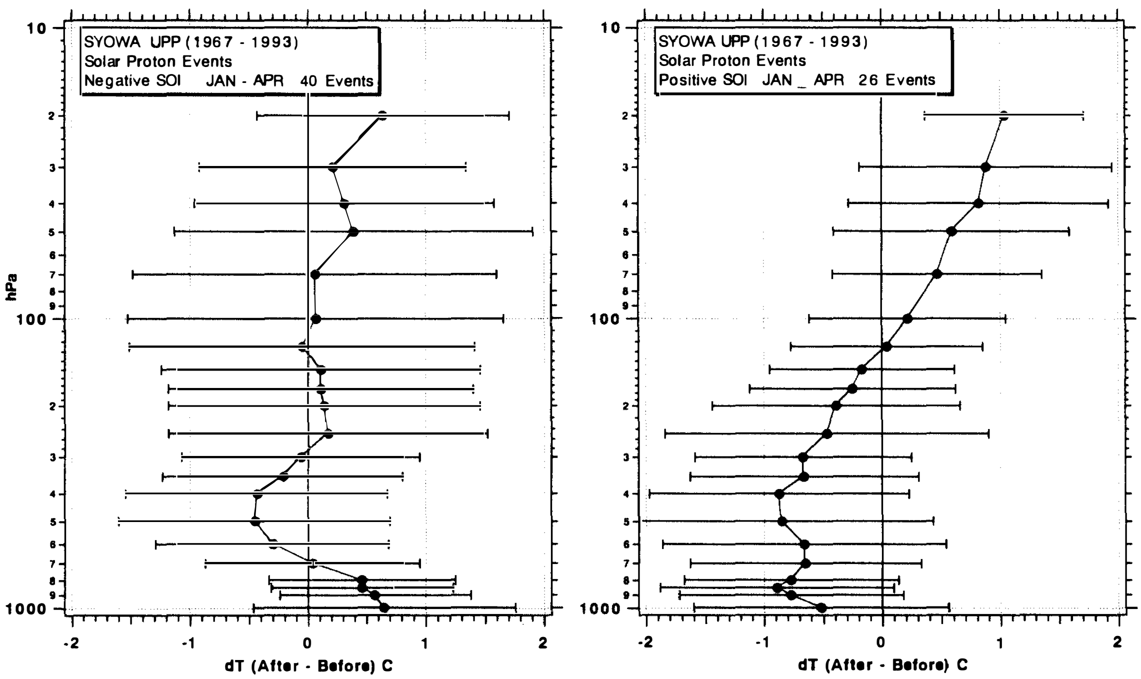

Fig. 9. Same as Fig. 2 but for proton events in the SOI<0 phase (left) and in the SOI>0 phase.

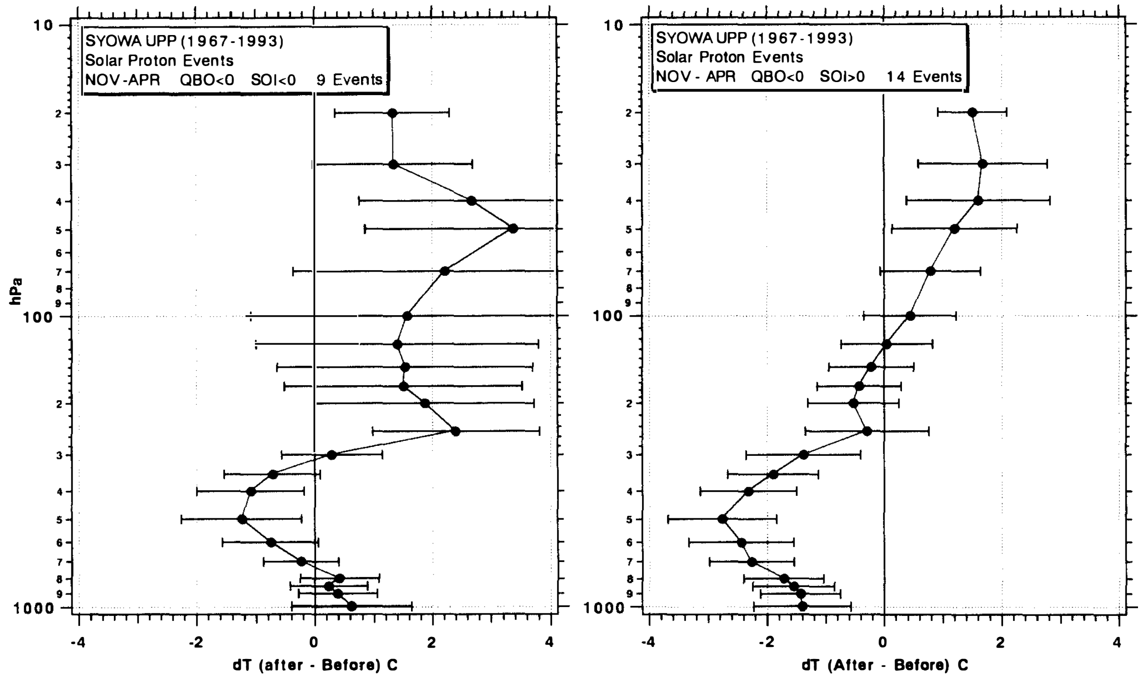

Fig. 10. *Same as Fig. 2 but for proton events in the (QBO < 0, SOI < 0) phase (left), and in the (QBO < 0, SOI > 0) phase (right).*

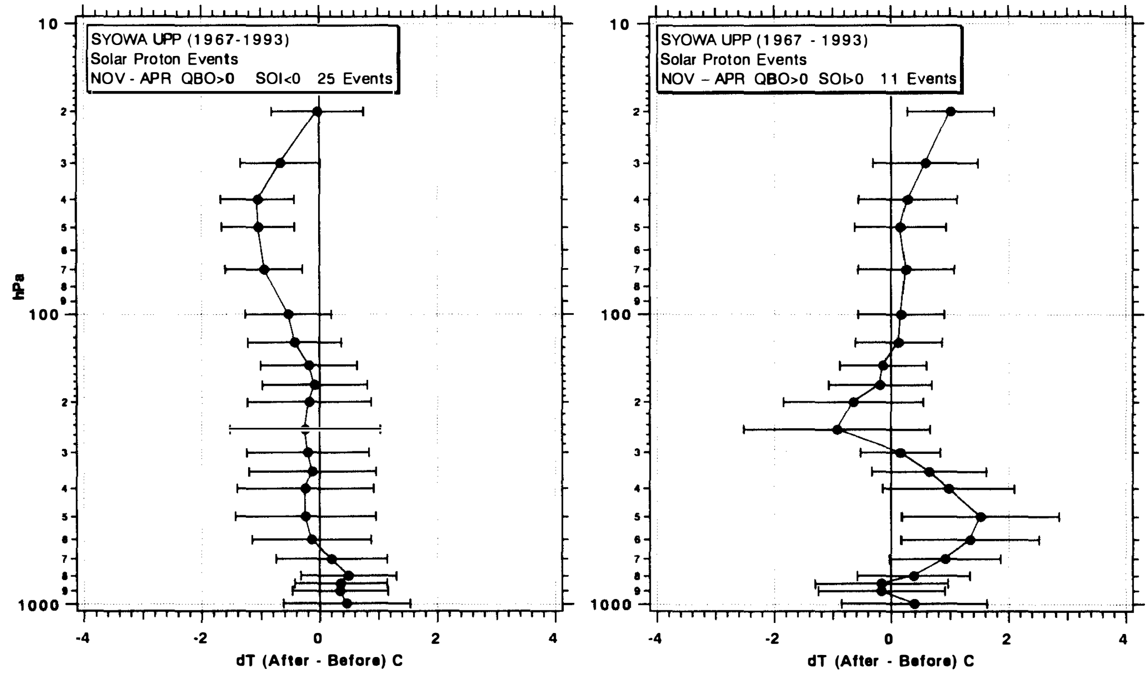

Fig. 11. *Same as Fig. 2 but for proton events in the (QBO > 0, SOI < 0) phase (left), and in the (QBO > 0, SOI > 0) phase (right).*

5.3. SOI-QBO dependence

It is suggested from analyses mentioned above that the atmospheric response to solar proton events depends on both the QBO and SOI phases. Detailed analysis for four combinations of QBO and SOI phases is performed in this section. Because of reduction of sample numbers, however, the chance of accidental coincidence will be increased considerably. The results shown below should be treated as of provisional.

5.3.1. QBO<0

The results for the cases SOI<0 (9 events) and SOI>0 (14 events) are shown in Fig. 10, respectively. In these cases, warming of the stratosphere and cooling of the troposphere are seen for both SOI phases.

5.3.2. QBO>0

The results for SOI<0 (25 events) and SOI>0 (11 events) are shown in Fig. 11. In the case SOI<0, no appreciable temperature changes are seen in the troposphere, and slight cooling is seen in the stratosphere. For SOI>0, the tropospheric temperatures showed increases, and warming of the stratosphere is also seen. It is suggested that the sign of temperature change was reversed by switching of the SOI (WATANABE and FUJITA, 1994).

6. Concluding Remarks

Although the level of statistical significance is not high enough to extract definite conclusions from the present provisional analysis, we have seen several interesting points.

(1) Considerable changes of tropospheric and stratospheric temperatures are seen for proton flares and solar proton events. Only very small changes are obtained for Forbush decreases of galactic cosmic rays and geomagnetic activities. The solar proton events are suggested to be the most important solar-terrestrial phenomena which can affect stratospheric and tropospheric conditions because the most significant, although still low, correlation is obtained for these events.

(2) Warming of the lower stratosphere and cooling of the troposphere were observed in association with solar proton events in many cases. On the other hand, our statistical result is opposite to that given by KODAMA *et al.* (1991) showing a decrease of stratospheric temperature of 3°C at 40–15 hPa after strong proton events in 1956–1990. They introduced a differential temperature with respect to that at the 100 hPa pressure level assuming that the level is "stable" to the dynamical motion of the atmosphere. According to the present work, the temperatures at the 100 hPa level also showed changes after proton events (see, for example, Fig. 8). When both the temperature at the 100 hPa level and that at the 30 hPa level (for example) increased after a key day and when the differential temperature after the key day is lower than that before the key day, we obtain an apparent temperature decrease as a result. It is suggested that the result of KODAMA *et al.* (1991) includes biased temperature changes caused by transient temperature changes at the 100 hPa level.

(3) The most significant correlation between solar proton events and stratospheric/tropospheric temperature changes was obtained during the East QBO phase (<0). This result is consistent with that given by SCHUURMANS (1991) using radiosonde data in the Netherlands. A weak dependence on the SOI phase is also suggested. According to KANZAWA and KAWAGUCHI (1990), both the total ozone and the stratospheric temperature increased during the East QBO phase. It is suggested from their study that the amplitudes

of responses to solar proton events are different for the different QBO phases.

(4) It is unlikely that the influence of solar protons in the stratosphere, or the stratospheric ozone layer, produced the tropospheric temperature change. It is also unlikely that solar protons directly affect the tropospheric atmosphere, because the ion production rate of solar protons in the troposphere is very low as compared with that in the stratosphere. We need a mechanism to produce a tropospheric temperature change triggered by stratospheric disturbance associated with incidence of solar protons. Although the mechanism remains unclear in this stage, atmospheric ionization by solar protons will trigger of subsequent atmospheric processes in the stratosphere and the troposphere. TINSLEY and DEEN (1991) proposed the electro-freezing mechanism to produce temperature changes in the northern hemisphere associated with Forbush decreases of MeV-GeV galactic cosmic rays. This mechanisms involves release of latent heat in midlevel clouds induced by nucleation of ice crystals in high-level clouds by enhancing the rate of freezing of thermodynamically unstable supercooled water droplets. The enhancement in atmospheric ionization rate caused by increase in the cosmic-ray (or solar proton) flux intensifies the atmospheric electric field, then ice-crystal nucleation is enhanced. It is uncertain whether this mechanism can be applied to solar-proton associated temperature changes over Antarctica or not. Direct measurements of atmospheric characteristics in the stratosphere and the troposphere during solar proton events will be important to find the "missing link" between solar proton events and associated temperature changes in the low-level atmosphere.

(5) Further detailed investigation using radiosonde observations performed at other stations in Antarctica is required to confirm the results obtained in the present work. In addition to statistical studies, *in situ* observations of atmospheric processes during solar-terrestrial events will be particularly important to find a physical connection between solar activity and terrestrial climate change.

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