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A Study on the Effects of Solar Protons on the NO_y by Magnetic Storm Events from 2003 to 2012: A Comparison between the Southern and Northern Hemispheres

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Abstract

In the study of solar-terrestrial relationships, magnetic storms and solar activity play important roles. In this paper, the intense magnetic storms in company with solar proton events occurred in October and November 2003, January 2005, December 2006, January and March 2012 have been considered. The variation of the odd nitrogen (NO_y) oxides and ozone in the stratospheric layer is investigated by the effects of energetic particle precipitation. Anomaly percentage of the odd nitrogen (NO_y) oxides and ozone are calculated separately for the Southern and the Northern hemispheres and geographic latitude from 60 to 80 degrees. The analyzed results of the observational data showed that the intense magnetic storms, which consist of more than 500 (particles/cm^2 s sr) solar energetic proton (E>10MeV), gave rise to the increase of the odd nitrogen (NO_y) oxides in the stratosphere, from level 1 mb to 200 mb. Also, the results showed that in November 2003, January 2005, December 2006, January and March 2012 the odd nitrogen (NO_y) oxides, which consist of over 500 (particles/cm^2 s sr) increased in the Northern hemisphere but decreased a little in the Southern hemisphere . Among the events of the magnetic storms in the autumn and winter seasons, the only event on the October 2003, showed that the odd nitrogen (NO_y) oxides increased in the Southern hemisphere. The results showed that the increase in the odd nitrogen (NO_y) oxides caused a decrease of ozone in the altitude below the odd nitrogen (NO_y) with a delay.

Keywords: Magnetic Storms, Solar Proton, Solar Activity, Odd Nitrogen Oxides, Energetic Particles.

1. Introduction

The magnetic storms are associated with coronal mass ejection and magnetic connection between the interplanetary magnetic field and that of the Earth. When these two events co-occur, we can experience a powerful magnetic storm. In this case, energetic charged particles easily enter the magnetosphere and precipitate into the Earth atmosphere and can influence variety of atmospheric processes. The energetic particle including electrons and protons can affect the atmosphere depending on their energy. Protons have more energy than electrons and have a greater influence on the atmosphere. Callis et al. (1998) investigated the effect of electrons on NO_y and ozone in the middle atmosphere.

The energetic particle precipitation into the middle atmosphere causes air ionization. On the other hand, in the recombination process, nitrogen oxides are generated. Porter et al. (1976) studied the efficiency of the production of atomic nitrogen and oxygen by energetic protons. They showed that each ion pair produces 1.25 nitrogen atoms and suggested that 1.27 N atoms produced per ion pair, of which 55% are in exited ($N(2D)$), and 45% are in-ground ($N(4S)$) states. The atomic nitrogen combines with oxygen to generate NO. The following equations indicate the generation of NO:

$$N(4S) + O_2 \rightarrow NO + O \tag{1}$$

$$N(2D) + O_2 \rightarrow NO + O \tag{2}$$

Also, the increased NO_y (N, NO, NO_2) is caused by energetic particles, participating in catalytic processes of ozone destruction (Callis et al., 1998; Baker, 2000). The odd NO_y lifetimes are enough for ozone destruction (in short and long terms). The NO_y - ozone loss cycle is as follows (Zossi de Artigas et al., 2016):

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{3}$$

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$$NO_2 + O \rightarrow NO + O_2 \quad (4)$$

And as a net result

$$O_3 + O \rightarrow O_2 + O_2 \quad (5)$$

As mentioned in the above equations, we expect that odd nitrogen oxides caused ozone destruction in the middle atmosphere during magnetic storm events. In the previous studies (before 2000), the variation of ozone in the middle atmosphere and for latitude above was detected but did not find the same pattern for its variety. For the first time, Jackman et al. (2001) investigated the effect of the energetic particle precipitation during magnetic storm events, on the odd nitrogen oxides and hydrogen oxide, and consequently on the ozone in the middle atmosphere. They studied the variation of atmospheric ozone in the northern hemisphere (for latitudes higher than 60 degrees) due to the July 2000 solar proton event. Effect of the same event on the southern hemisphere was investigated by Randall et al. (2001). Both studies reported an increase in the generation of odd nitrogen oxides and hydrogen oxides, and consequent destruction of 70% of middle atmospheric ozone by HO_y in the short term, and 9% destruction of stratospheric ozone by NO_y in the long term. Randall et al. (2005) studied the stratospheric effects of energetic particle precipitation in 2003–2004. Their results showed that the rate of NO_y generation was increased for the northerm hemisphere and was decreased for the southern hemisphere during magnetic storm events.

Lopez et al. (2005a) investigated the effect of the strong solar storm events observed on 2003 October//November by the ENVISAT satellite. They used MIPAS data to investigate nitrogen oxides and ozone. They focused on the Polar Regions (70 to 90 degrees of geomagnetic latitude) and considered the altitude range from 30 to 60 km for NOy, and 30 to 68 km for ozone. Their results showed a large asymmetry in the enhanced NOy abundances in the Northern and Southern Hemisphere (SH) polar caps (>70° geographic), with high and persistent values of NOy in the upper stratosphere and lower mesosphere in the NH polar winter region. Also, their results showed an increase in mean NOy abundance between 20 to 70 ppbv occurred in the NH polar cap, lasting for at least two weeks. They showed that ozone depletion correlated with NOy enhancement also exhibits a hemispheric asymmetry. Lopez et al. (2005b) have also reported the significant enhancements in HNO_3, N_2O_5, and $ClONO_2$ in the polar stratosphere produced after the intense solar proton events (SPEs), which occurred in October –November 2003.

Funke et al. (2011) have compared stratospheric and mesospheric composition (such as NO_2) changes after the “Halloween” solar proton event by high energy particle precipitation in the atmosphere model. The model responses to the proton perturbation so as to show a significant spread. However, the intercomparison has demonstrated that differences in the meteorology and/or initial state of the atmosphere in the simulations cause an important variability of the model results, even on a short timescale of only a few days. On the other hand, recent research has shown the existence of a connection between sudden stratospheric warming and extensive changes throughout Earth’s atmosphere, including affect atmospheric chemistry (Funke et al., 2010; Yamazaki et al., 2015). Also, the influences of the solar proton event that produced NO_y changed ozone somewhat differently in the two hemispheres (Jackman et al., 2014). A good review paper of energetic particle influence on the Earth atmosphere presented by Mironova et al. (2015). Zossi de Artigas (2016) investigated the effects of energetic particles precipitation on stratospheric ozone in the southern hemisphere. They suggested that variations between ozone value are related to the intensity of geomagnetic disturbances and the geomagnetic longitude. Also, their results showed a significant variation in NO_y concentration at altitudes from 30 to 50 km. Verma et al. (2019) presented a study of prediction of the next day of surface ozone by using multiple linear and nonlinear models.

In the present paper, we used the data from the Monitoring Atmospheric Composition and Climate (MACC) Reanalysis that is a global reanalysis data set of atmospheric composition (AC), made available by the Copernicus Atmosphere Monitoring Service (CAMS). Anomaly percentage of the odd nitrogen oxides (NO_y) and ozone are calculated separately for the Southern and the Northern hemispheres and geographic latitude from 60 to 80 degrees during the magnetic storms. We considered the altitude from 11 km to 48 km to investigation the anomalies. We consider the intense magnetic storms in company with solar proton events that occurred in October and November 2003, January 2005, December 2006, January, and March 2012. We investigated the variation of the odd nitrogen oxides (NO_y) and ozone in the stratospheric layer by the effects of energetic particle precipitation.

2. Data and Observations

We use daily and hourly data from National Aeronautics and Space Administration Goddard Space Flight Center (NASA/GSFC) OMNIWeb site (http://omniweb.gsfc.nasa.gov/) to obtain the most commonly used indices AE, Dst, Kp, Z component of the magnetic field (B_z) and energetic proton flux from 2003 to 2012 at greater than 10 MeV. To investigate the variations of the odd nitrogen oxides, we used the data from the Monitoring Atmospheric Composition and Climate (MACC) Reanalysis, made available by the CAMS. On the other hand, we used the daily average ozone data from ERA-Interim (from the European Centre for Medium-range Weather Forecasts (ECMWF) (on the website, https://apps.ecmwf.int/datasets/) with a horizontal resolution (Grid) of 0.75°×0.75°, on the 15 vertical levels from 1 to 200 mbar (11 to 48 km), for the Southern and the Northern hemispheres and geographic latitude from 60 to 80 degrees.

3. Analysis of Data and Discussion

To determine geomagnetic storms in company with solar proton events, we use the common geomagnetic indices (AE, Dst, Kp, B_z) and proton flux (Pf). Six events of the geomagnetic storm events with a proton flux more than 500 (particles/cm^2 s sr) were obtained from 2003 - 2012 (in October and November 2003, January 2005, December 2006, January and March 2012). Figures 1 and 2 show examples of geomagnetic indices (Kp, B_z , AE, Dst) and proton flux in October 2003, respectively. Figure 1a shows the daily variation of the Kp index. As it can be seen from the chart, the range of Kp index is between 4 and 5, from 14 to 22 October 2003; however, the value of this index is larger than 6 from 29 to 31 October. The maximum value of Kp index is 7.3 on October 29. According to Figure 1b, the sign of B_z change to the negative, from 1-2, 11-21 and 26-30 October 2003. Figure 1c shows the variations of the Auroral Electrojet index (AE). According to Figure 1c, the maximum values are from 13 to 22 and from 24 to 31. Figure 1d shows the decrease in the Dst (Disturbance storm time) index so that the Dst had dropped to $-221nT$ on October 30. Figure 2 shows the proton flux over the Earth's polar region for all events in October and November 2003. For example, as it can be seen from the graph of October, the proton flux is increased from 21 October. The average value of the proton flux is about 0.01 (particles/cm^2s sr) on the ordinary days, and it reaches to 3750 (particles/cm^2 s sr) (at approximately 10 MeV) whenever the magnetic storm occurred. Therefore we accept the increase in the ionization processes from 26 to 31 October 2003.

The common geomagnetic indexes (AE, Dst, Kp, B_z) and the proton flux (Pf) of six geomagnetic storm events at greater than 10 MeV, are summarized in Table 1. The table includes maximum values of Kp and AE, minimum values of Bz and Dst. Two last columns of the table show the maximum of proton flux (Pf) and related date.

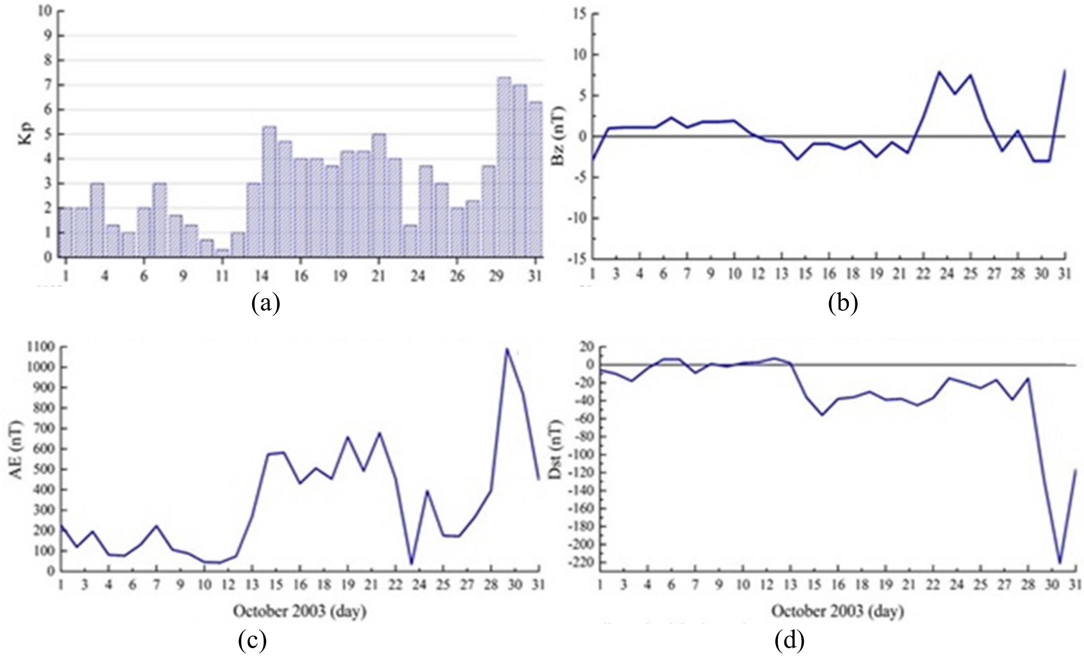


Figure 1. Variations of common geomagnetic indices for the period 1–31 October 2003: a) Kp, b) Z component of the interplanetary magnetic field, (B_z) in nT, c) Auroral Electrojet index (AE) in nT, d) Disturbance storm time index (Dst) in nT.

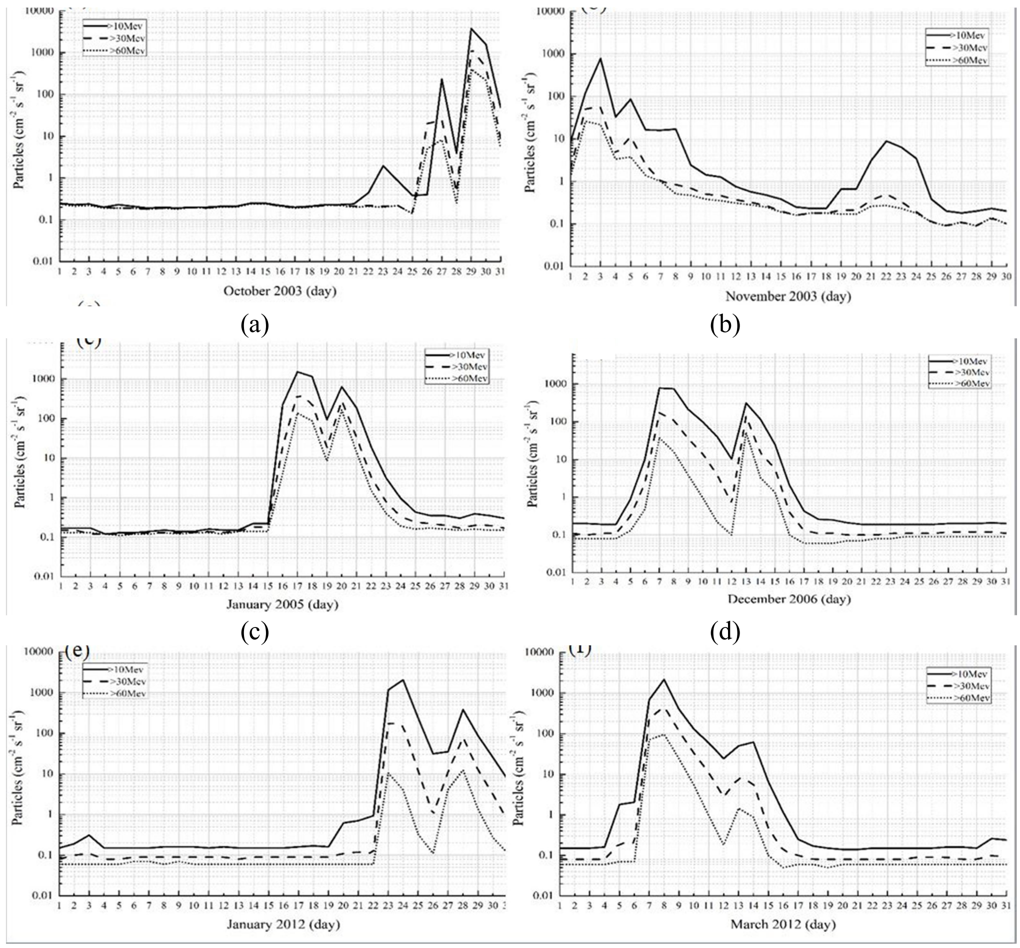


Figure 2. The daily proton fluxes with energies of tens of MeV(>10MeV (solid lines), >30MeV (dashed lines) and >60MeV (dot lines)) over the Earth's polar region in a) October 2003, b) November 2003, c) January 2005, d) December, e) January 2012, f) March, 2012.

Table 1. The characteristics of six magnetic storm events.

Date of event	Kp	Bz (nT)	AE(nT)	Dst(nT)	Proton Flux(PF) ($cm^{-2} s^{-1} sr^{-1}$)	Event day of Max. PF
Mar. 2012	5.7	-4.2	711	-98	2154.5	8
Jan. 2012	3.3	-2.4	333	-41	2051.0	24
Dec. 2006	5.7	-6.2	826	-116	777.0	7
Jan. 2005	6.0	-1.2	848	-65	1515.0	17
Nov. 2003	6.3	-16.1	829	-156	780.0	3
Oct. 2003	7.3	-3.0	1091	-221	3750.0	29

We consider six events mentioned in Table 1 to investigate anomalies of the odd nitrogen (NO_y) oxides and ozone in the north and south hemispheres. We calculate the anomaly percentage of the odd nitrogen (NO_y) oxides and ozone for the Southern and the Northern hemispheres and geographic latitude between 60 to 80 degrees.

To obtain the anomaly percentage of the odd nitrogen (NO_y) oxides and ozone, we used the following relations.

$$Anomaly\,percentage\,of\,NO_y = \left(\left(\frac{NO_{y,da} - NO_{y,ma}}{NO_{y,ma}}\right)\right)\times 100 \quad (6)$$

$$Anomaly\,percentage\,of\,O_3 = \left(\left(\frac{O_{3,da} - O_{3,ma}}{O_{3,ma}}\right)\right)\times 100 \quad (7)$$

where, $NO_{y,ma}$, $O_{3,da}$ and $O_{3,ma}$ are the daily average of NO_y, the monthly average of NO_y, the daily average of ozone and the monthly average of ozone, respectively. The average values are calculated over interval latitude from 60 to 80 degrees (-60 to -80 degrees for the Southern hemisphere) and over all longitudes. The results of the calculations are illustrated in Figures 3 to 8. In these Figures, the color range is used from negative values in blue color to positive values in red color. The details and discussions for each case are explained as follows.

Figure 3a shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via altitude that averaging over the northern latitudes (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in October 2003. Figure 3a shows no increase in the percentage of the stratospheric odd nitrogen oxides for all altitude on the days from 29 to 31. Since increasing in proton flux continues to November, it has been expected that NO_y increase in the early days of November. Figure 3b shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via altitude that are averaged over the southern latitudes (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in October 2003. Figure 3b shows an increase in the percentage (positive) of the stratospheric odd nitrogen oxides for all altitudes on the days from 26 to 31. At pressure level with 100 mb, two regions with an increase in percentage formed, as shown in Figure 3b. The first region shows an increase of 42% on 26 October, and the second region shows an increase of 55% on October 31. The increase in percentage for 10 mb level pressure on 27 and 31 October is 13% and 18%, respectively. Figure 3c shows the anomaly percentage of the stratospheric ozone via altitude that are averaged over the northern latitude from 60 to 80 degrees in October 2003. The Figure shows decreases of -6% and -1% at the 10 mb and the 1 mb pressure levels, respectively, on October 29-31. Figure 3d shows the anomaly percentage of the stratospheric ozone via altitude that are averaged over the southern latitude from 60 to 80 degrees in October 2003. It can be seen from Figure 3d that there was a decrease from 6% to 2% in the percentage of the stratospheric ozone. Below 100 mb, the decrease in the percentage of the stratospheric ozone reaches to -14% and -10% over the 26–29 and 31 October periods. It can be due to an increase of odd nitrogen (NO_y) oxides at the 10 mb and the 100 mb pressure levels.

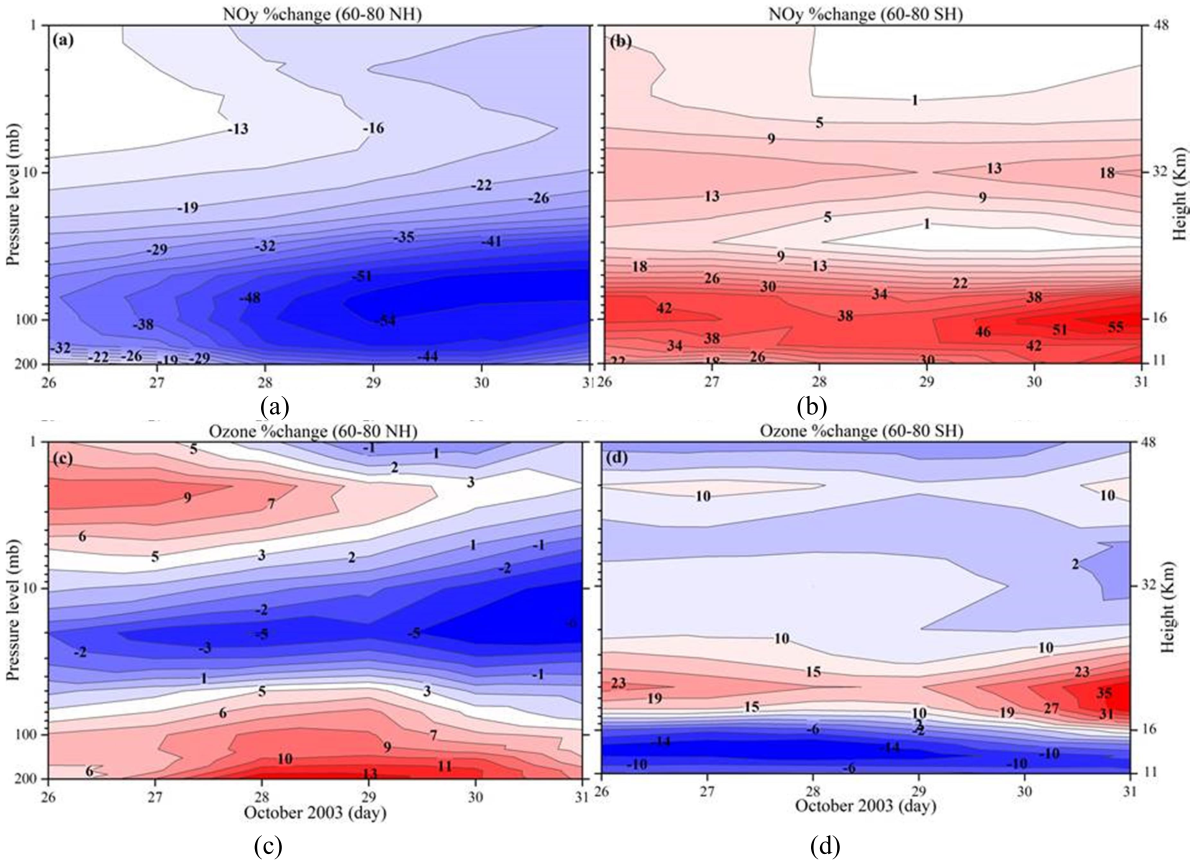


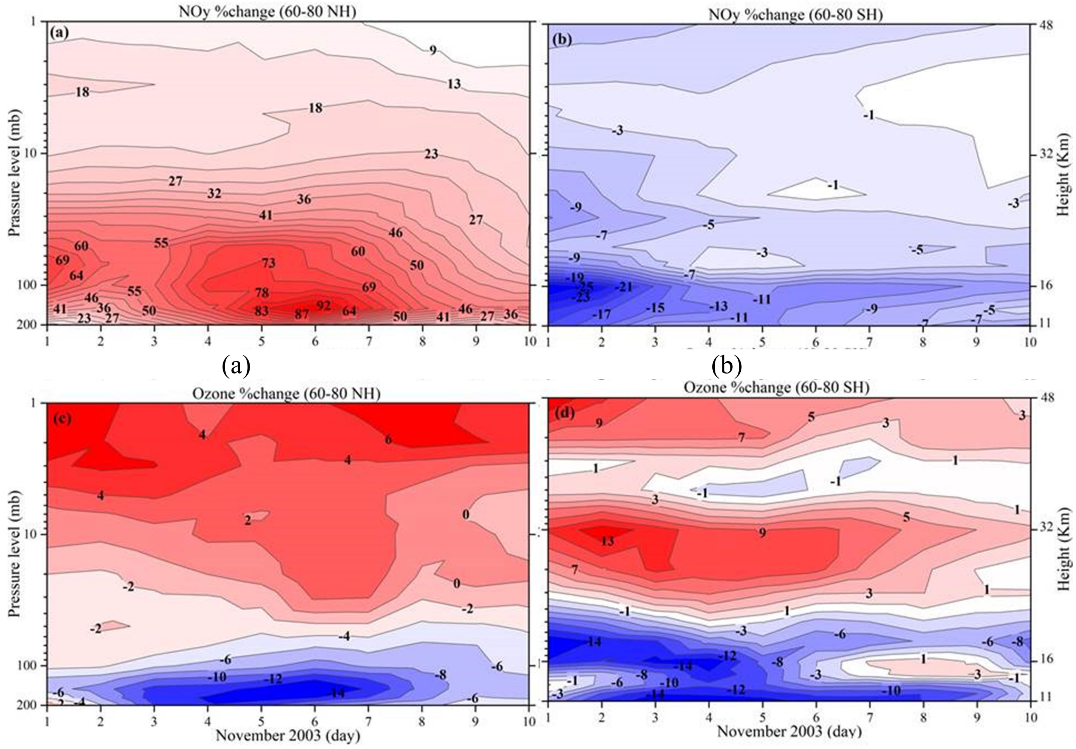
Figure 3. The anomaly percentages of NO_y via altitude in October 2003: a) in the Northern hemisphere, b) in the Southern hemisphere. The anomaly percentages of O_3 via altitude in October 2003: c) in the Northern hemisphere, d) in the Southern hemisphere.

Figure 4a shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the northern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in November 2003. It can be seen from Figure 4a that there was an increase in the percentage of the stratospheric odd nitrogen oxides for all altitudes on November 1 to November 10. The range of percentage increase is from 4% to 92% for the first ten days of November. Large increases are 69% and 92%, at 100 mb and 200 mb pressure levels on 1 and 6 November, respectively.

Figure 4b shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the southern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in November 2003. It can be seen from Figure 4b that there was a decrease (up to - 23%) in the percentage of the stratospheric odd nitrogen oxides. This is different from Figure 3b that showed an increase in the value. Attention should be paid that anomaly percentage for each month calculated based on monthly average in each level; therefore, the increase in percentage on the last days of October and the decrease in percentage on the beginning days of November can be due to the difference in the monthly average.

Figure 4c shows the anomaly percentage of the stratospheric ozone via the altitude that are averaged over the northern latitude from 60 to 80 degrees in November 2003. Figure 4c shows that the decrease in percentage for 100 mb pressure levels on November 2 and for 100-200 mb pressure levels on November 6 are - 4% and -14%, respectively.

Figure 4d shows the anomaly percentage of the stratospheric ozone via altitude that are averaged over the southern latitude from 60 to 80 degrees in November 2003. Below 100 mb, the decrease in the percentage of the stratospheric ozone reaches to -14% over the period of November 3 and 4. This can be due to an increase in (NO_y) in October.



(c) (d)

Figure 4. The anomaly percentages of NO_y via the altitude in November 2003: a) in the Northern hemisphere, b) in the Southern hemisphere. The anomaly percentages of O_3 via the altitude in November 2003: c) in the Northern hemisphere, d) in the Southern hemisphere.

The anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the northern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in January 2005 (see Figure 5a). Two regions with an increase in percentage formed, as shown in Figure 5a. The first region shows an increase of 58% below 100 mb on January 25 and the second region shows an increase of 46% below 10 mb on January 31. Although, the October and November 2003 events are a continuous event, but the calculations are monthly.

Figure 5b shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the southern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in January 2005. Figure 5b shows that there is an increase in the percentage of the stratospheric odd nitrogen (NO_y) oxides above 100 mb, from 15 January (starting of solar proton event) to 22 January, so that the maximum value is about 2% at 50 mb from January 18 to January 22. The percentage of NO_y is about 1% at 1 mb on 24 January. For the rest of the days, the percentage of NO_y is decreasing, so that there is a decrease of about -10% at 100 mb.

Figure 5c shows the anomaly percentage of the stratospheric ozone via the altitude that are averaged over the northern latitude from 60 to 80 degrees in January 2005. Figure 5c shows that there were some scattered regions with an increasing percentage of the stratospheric ozone in a different altitude. The maximum values of percentage decrease are -19% at below 100 mb on January 26 and -6% at 60 mb on January 31.

Figure 5d shows the anomaly percentage of the stratospheric ozone via the altitude that are averaged over the southern latitude from 60 to 80 degrees in January 2005. Figure 5d shows that the decreases in the percentage of the stratospheric ozone reach to -3% at 100 mb on 17 January and reach to -6% at 20 mb at the end of the month. These decreases are due to increases in NO_y over January 15 (starting of solar proton event) to January 22 periods. On the other hand, percentages fall (-9%) of NO_y in the last days of the month give rise to an increase in the percentage of the ozone up to 10% below 100 mb.

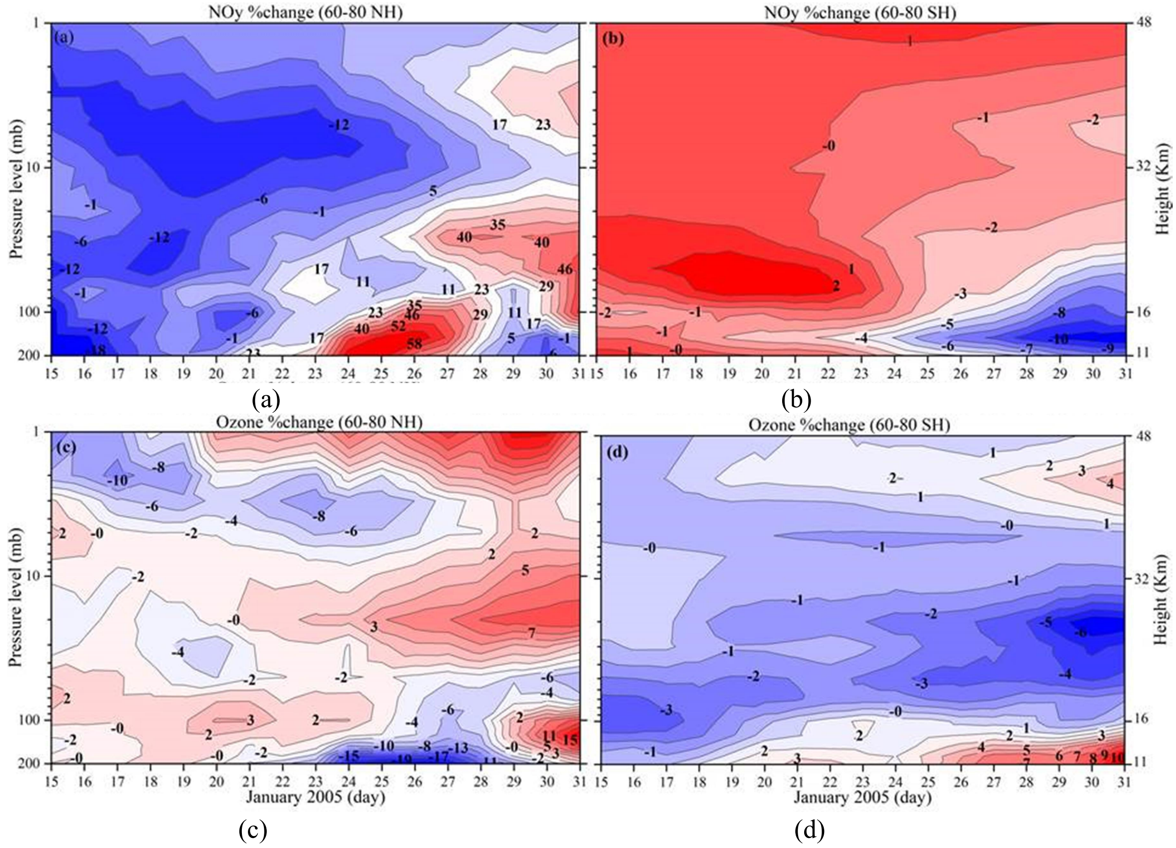


Figure 5. The anomaly percentages of NO_y via the altitude in January 2005: a) in the Northern hemisphere, b) in the Southern hemisphere. The anomaly percentages of O_3 via the altitude in January 2005: c) in the Northern hemisphere, d) in the Southern hemisphere.

Figure 6a shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the northern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in December 2006 when a geomagnetic storm occurred. Figure 6a shows that the increases in the percentage of the stratospheric NO_y that reach to 15% at 30 mb and 19% at 70 mb on 7 December and reach to 23% at 100 mb on 8 December. Also, Figure 6a shows that there are some regions with the increasing percentage up to 15% at 200 mb and up to 7% below 1 mb on 10 and 13 December, respectively. On the other hand, there are two regions with decreasing percentage up to -21% at 10 mb and up to -25% at 100 mb on 10 and 12 December, respectively.

Figure 6b shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the southern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in December 2006 when a geomagnetic storm occurred. It can be seen from Figure 6b that there is an increase in the percentage of the stratospheric odd nitrogen (NO_y) oxides from 20 mb to 200 mb all over the 5 December to 13 December periods, except two regions at 60 mb that show decreases in the percentage of NO_y up to -19% and -7% on 5 and 11 December, respectively.

Figure 6c shows the anomaly percentage of the stratospheric ozone via the altitude that are averaged over the northern latitude from 60 to 80 degrees in December 2006. Figure 6c shows a decrease in the percentage of the stratospheric ozone below 4 mb, from 5 December (starting of solar proton event) to 13 December. Two maximum decreases with -9% and -11% are occurred on 7 and 8 December, respectively.

Figure 6d shows that an increase in NO_y cause a decrease in the percentage of the stratospheric ozone up to -15% at 200 mb - 50 mb over the period of December 5 and 6. Also, there is a decreased area up to -14% on December 9.

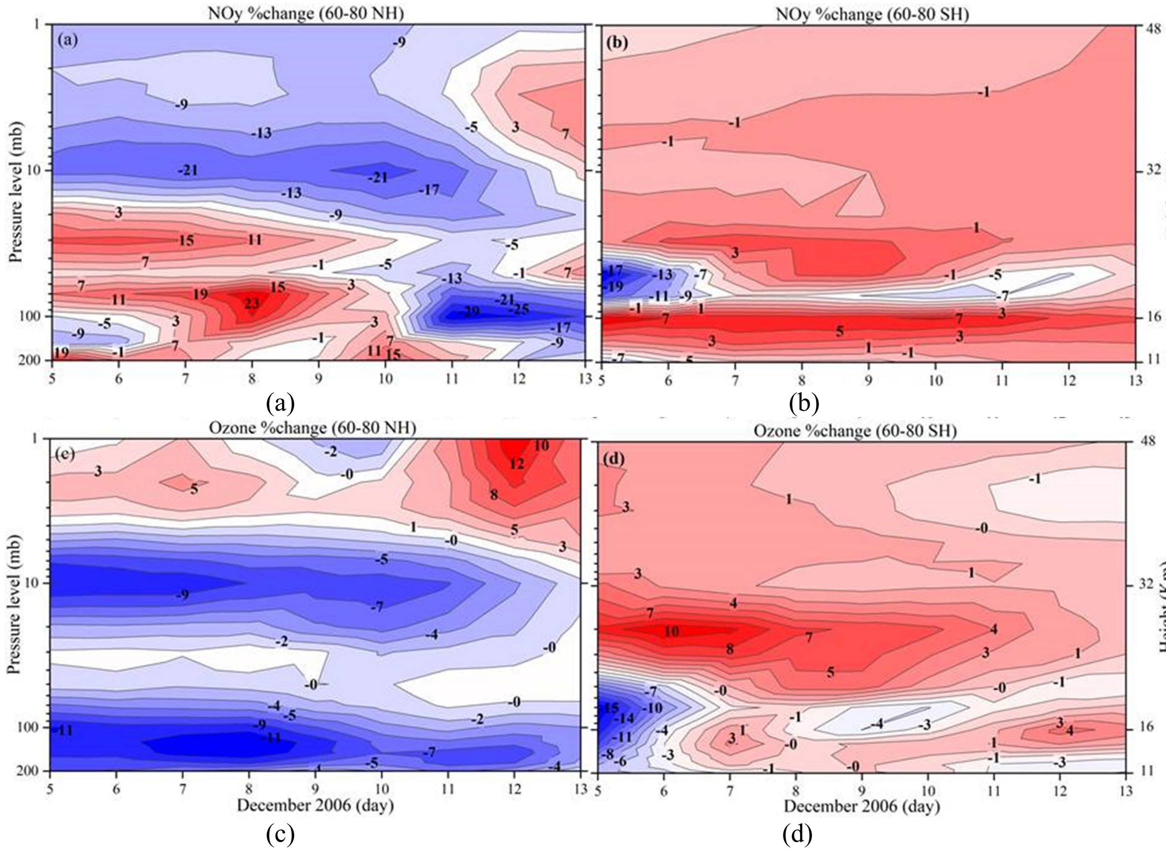


Figure 6. The anomaly percentages of NO_y via the altitude in December 2006: a) in the Northern hemisphere, b) in the Southern hemisphere. The anomaly percentages of O_3 via altitude in December 2006: c) in the Northern hemisphere, d) in the Southern hemisphere.

Figure 7a shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the northern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in 2012 January, when a geomagnetic storm occurred. The percentage of the stratospheric odd nitrogen (NO_y) oxides have increased at 50 mb since 24 January. This percentage increase observed in all latitudes from 24 to the end of January, so that the percentage increase reaches to 215% on January 31. With due attention to a large increase in NO_y, a large percentage decrease in ozone expected on the last days of January and early February 2012.

Figure 7b shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that averaging over the southern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in January 2012 when a geomagnetic storm occurred. Figure 7b shows that not only the percentage of the stratospheric odd nitrogen (NO_y) oxides were not increasing from January 22 when starting of solar proton event to the end of the month, but also it was decreasing up to -7% on the end of the month.

Figures 7c and 7d show the anomaly percentage of the stratospheric ozone via the altitude that are averaged over the northern latitude from 60 to 80 degrees in January and February 2012, respectively. In January, only on 31 January, there was a percentage decrease in the stratospheric ozone up to 2% at 100 mb as shown in Figure 7c, but in February, from 1st to 15th, there was a percentage increase in the stratospheric ozone as shown in Figure 7d. This percentage decrease in the stratospheric ozone (like a band) located at 200 mb. The maximum value of percentage decrease is about -18% on 10 February. This decrease in ozone with a delay suggested that the energetic proton flux influence the NOy with a delay (about in the 20 days).

Figures 7e and 7f show the anomaly percentage of the stratospheric ozone via the altitude that are averaged over the southern latitude from 60 to 80 degrees in January and February 2012, respectively. The increase in NO_y cause a decrease in the percentage of the stratospheric ozone up to -4% below 100 mb on 24 January and at 5 mb – 50 mb from 22 to the end of January, with a percentage fall about -5% on 28 January. The percentage decrease above 10 mb continues in a few of days in February, so that the percentage decrease reaches to -9% on 1 February.

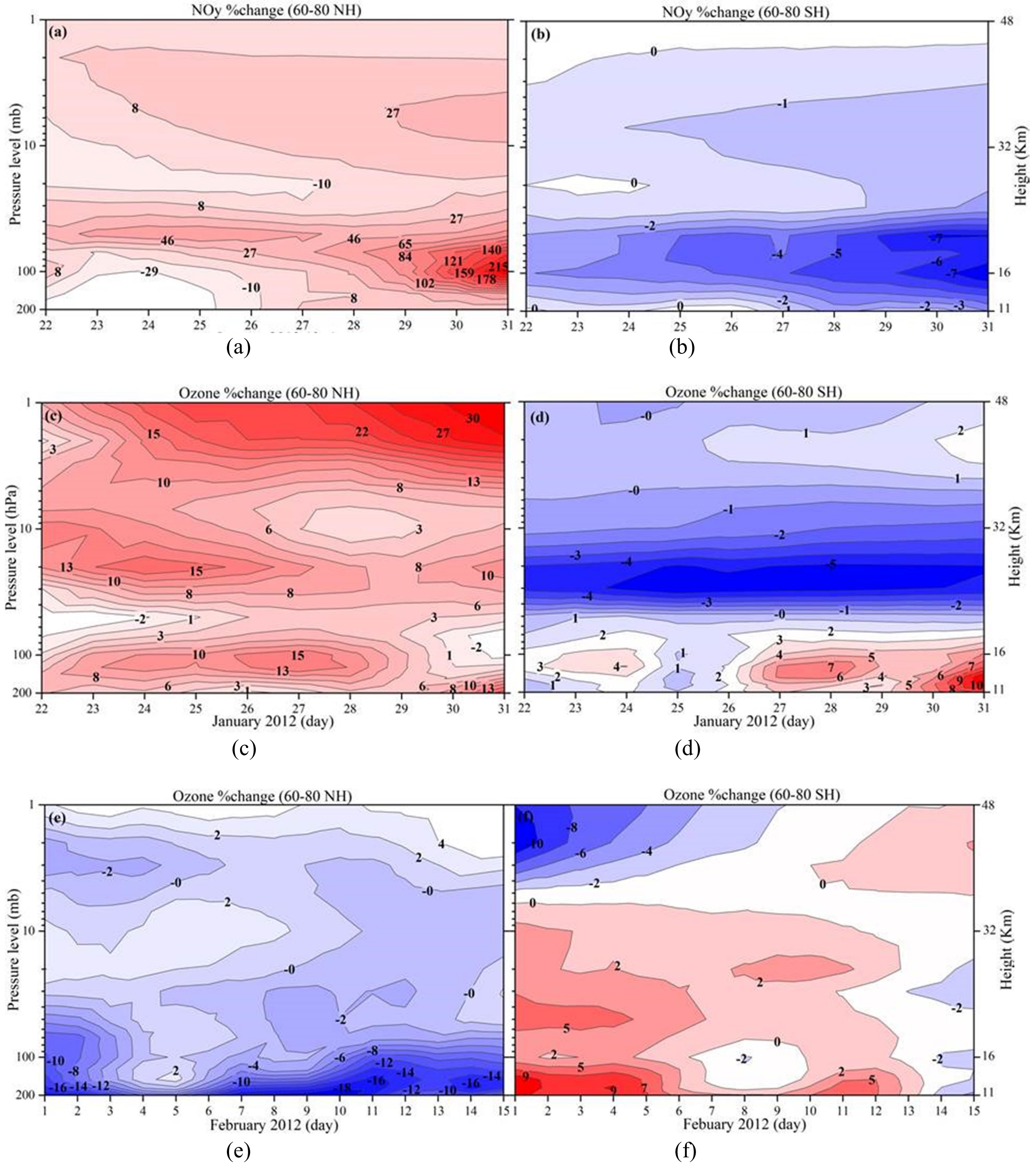


Figure 7. The anomaly percentages of NO_y via the altitude in January 2012: a) in the Northern hemisphere, b) in the Southern hemisphere. The anomaly percentages of O_3 via the altitude: c) in January 2012, in the Northern hemisphere, d) in January 2012, in the Southern hemisphere, e) in February 2012, in the Northern hemisphere, f) in February 2012, in the Southern hemisphere.

Figure 8a shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the northern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in March 2012, when a geomagnetic storm occurred. Figure 8a shows a gradual increase in odd nitrogen (NO_y) oxides, so that, the anomaly percentage change to plus, at above 100 mb from March 17. This increase in odd nitrogen oxides rise to 19% on March 22.

Figure 8b shows the anomaly percentage of the stratospheric odd nitrogen (NO_y) oxides via the altitude that are averaged over the southern latitude (pressure levels from 1 mb to 200 mb) from 60 to 80 degrees in March 2012, when a geomagnetic storm occurred. Figure 8b shows an increase in the percentage of the stratospheric odd nitrogen (NO_y) oxides, from March 6 to March 16, so that the maximum value is about 38% at 70 mb on March 6.

Figure 8c shows the anomaly percentage of the stratospheric ozone via the altitude that are averaged over the northern latitude from 60 to 80 degrees in March 2012. Figure 8c shows that there were some scattered regions with decreasing percentage of the stratospheric ozone in a different altitude, from March 14 to March 22. The decreases percentage are -8% (at 1 – 3 mb), -2% (at 80 mb) and -3% (at 200 mb) on 21, 17 and 20-22 March, respectively.

Figure 8d shows the anomaly percentage of the stratospheric ozone via the altitude that are averaged over the southern latitude from 60 to 80 degrees in March 2012. There was a decreasing percentage of the stratospheric ozone at 1 mb from March 6 to March 22. The maximum decrease is about -7% on March 18. It can be seen from Figure 8d that there were three scattered regions with decreasing percentage of the stratospheric ozone in a different altitude. The decreasing percentages are -7% (at 200 mb), -2% (at 10 mb) and -2%.

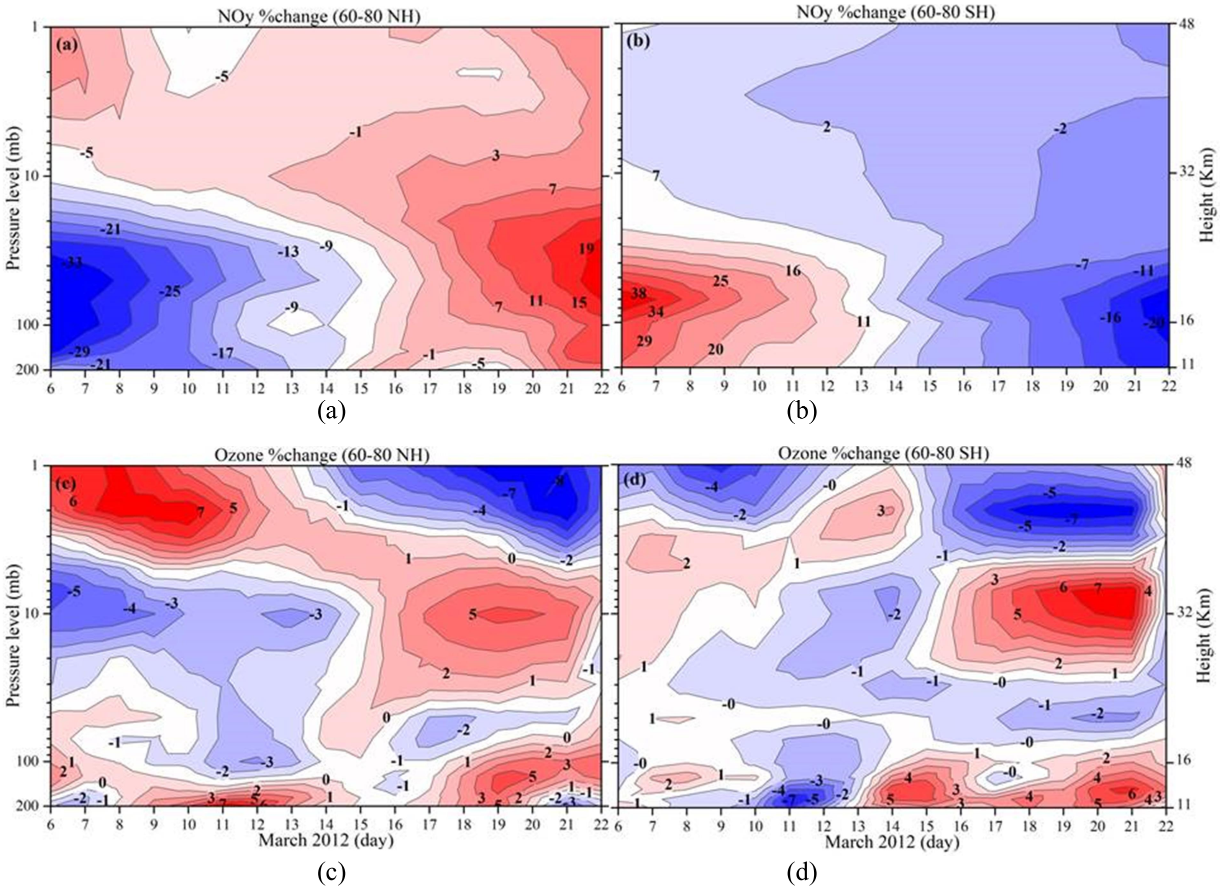


Figure 8. The anomaly percentages of NO_y via the altitude in March 2012: a) in the Northern hemisphere, b) in the Southern hemisphere. The anomaly percentages of O_3 via the altitude in March 2012: c) in the Northern hemisphere, d) in the Southern hemisphere.

Variations of the percentage of the stratospheric odd nitrogen (NO_y) oxides and the stratospheric ozone over southern and northern hemispheres are summarized in Table 2. It should be noted that the table summarizes the percentage of changes. In some months, there is a decrease in nitrogen oxides or an increase in ozone, which is not in this table. Table 2 includes the maximum value of the increasing percentage of the stratospheric odd nitrogen oxides and maximum value of decreased percentage of the stratospheric ozone.

4. Conclusions

The analyzed results of observation data suggest that the strong magnetic storms consist of a solar proton more than 500 (particles/cm^2 s sr) give rise to increasing the odd nitrogen oxides in the stratosphere, from level 1 mb to 200 mb. Since the solar zenith angle is dependent on the season, and also, it is very different in the Northern Hemisphere and Southern Hemisphere Polar Regions, the solar zenith angle impacts the background atmosphere. The analyzed results of observation data suggested that the influences of the solar proton event that produced NO_y changed ozone somewhat differently in the two hemispheres. Because of the difference between the solar zenith angle in fall and winter, we expected a different behavior of NO_y in the Northern Hemisphere and Southern Hemispheres. The main conclusions can be summarized as follows:

1) We observed a large increase in the anomaly percentage of NO_y over the Northern Hemisphere, on November 2003, January 2005, December 2006, January 2012 and March 2012; and only in October 2003, we observed a decrease.

2) For the Southern Hemisphere, we observed a small decrease in NO_y in the same dates, except for March 2012.

3) Increase in NO_y always cause a decrease in the stratospheric ozone (of short duration and with a delay of several days) at the low level.

4) The variation of the anomaly percentage of the stratospheric ozone directly related to the variation of NO_y, but the decrease in ozone cannot be considered as the exact model of increase in NO_y.

5) There is a delay (from few hours to several days) between starting time of the geomagnetic storm event and the time of the increase in NO_y and time of the decrease in ozone.

Table 2. A summary of changes in the anomalous percentage of NOy and ozone.

Date of event (magnetic storms in company with solar proton)	The maximum value of increase percentage of NO_y $60^\circ N - 80^\circ N$	The maximum value of increase percentage of NO_y $60^\circ S - 80^\circ S$	The maximum value of decrease percentage of O_3 $60^\circ N - 80^\circ N$	The maximum value of decrease percentage of O_3 $60^\circ S - 80^\circ S$
26-31 Oct. 2003	-13%	55%	-6%	-14%
1-10 Nov. 2003	87%	-1%	-14%	-14%
15-31 Jan. 2005	58%	2%	-19%	-6%
5-13 Dec. 2006	23%	7%	-11%	-15%
22-31 Jan. 2012	215%	0%	-18%	-10%
6-22 Mar. 2012	19%	38%	-8%	-7%

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