The Possible Responses of Polar Ozone to Solar Proton Events in March 2012 by FengYun-3 Satellite Observations

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Abstract In this work, we use observations by the Solar Backscatter Ultraviolet Sounder and Space Environment Monitor on FengYun-3 to analyze the polar ozone depletion during the solar proton events (SPEs), which occurred in early March 2012. The ozone distributions changed evidently with the increasing energetic proton flux (the particle energy is over 100 MeV) at the approximate altitude of 30 km. From the ozone profile relative changes, the short-term impacts of SPEs can be distinguished from the long-term effects of ozone season variations after the SPEs take place and cause about 4–17% of the short-term polar ozone decreases at the different levels in the upper stratosphere of both hemispheres. In the upper stratosphere, the SPE-related polar ozone depletion is more significant and continuous in the Northern Hemisphere but shows the short-term effects in the Southern Hemisphere during the March SPEs. The ozone depletion responses to the first SPE on 7 March are more pronounced in this altitude region than the second one on 13 March in both hemispheres due to the “harder” particle energy spectrum.

1. Introduction

It is known that severe solar activities, such as solar flares or coronal mass ejections (CMEs), will erupt an intense flux of charged energetic particles (protons, ions, and so on) (Reames, 1999) and cause solar proton events (SPEs) with particle energies over 10 MeV. When these charged particles are ejected toward the Earth, they are guided by the geomagnetic field and precipitate into the polar atmosphere (Patterson et al., 2001). Energetic particles generate odd hydrogen and odd nitrogen, such as HOx and NOx, which participate in the catalytic chemical process of polar ozone loss in the middle atmosphere. As shown in Figure 1, the particles penetrating into the atmosphere generate ions, such as N2+, O2+, N+, O+, and NO+, which react with O2 and water clusters to form NOx and HOx that are well known to cause ozone loss by the NOx and HOx cycles [Swider & Keneshea, 1973; Crutzen et al., 1975; Frederick, 1976; Rusch et al., 1981; Solomon et al., 1981; Solomon et al., 1983; Jackman & McPeters, 1985; Jackman & McPeters, 2004]. Many investigations about the polar ozone depletion during SPEs show that severe SPEs may cause significant polar ozone changes in the middle atmosphere (Weeks et al., 1972; Heath et al., 1977; McPeters et al., 1981; Reid et al., 1991; Zadorozhny et al., 1992; Jackman et al., 2001; Seppälä et al., 2004; Jackman et al., 2005a; Jackman et al., 2005b; Degenstein et al., 2005; López-Puertas et al., 2005; Rohan et al., 2005; von Clarismatico et al., 2013; Jackman et al., 2014).

The SPEs that occurred in early March 2012 are the twelfth largest SPEs in the satellite era since 1963 based on the study in (Jackman et al., 2008; von Clarismatico et al., 2013) and caused significant impact on the polar middle atmosphere (von Clarismatico et al., 2013; Jackman et al., 2014). In this study, for the first time, we apply the measurements of Solar Backscatter Ultraviolet Sounder (SBUS) and Space Environment Monitor (SEM) on board the FengYun-3 meteorological satellites to investigate how the March SPEs of 2012 affected the polar ozone density in the upper stratosphere of both hemispheres, and we provide the simultaneous observations of proton fluxes and stratospheric ozone depletion during the SPEs at different latitudes. This study focuses on the middle to upper stratosphere, while the previous publications were more focused on the mesosphere.
2. SBUS and SEM

The SEM and the SBUS are two of the payloads on board the FengYun-3 satellites, which are Chinese Sun-synchronous polar orbit operational meteorological satellites at the altitude of 830 km. The FengYun-3 series of satellites are developed in three groups: FY-3A and FY-3B in the first group were launched on 7 May 2008 and 5 November 2010, respectively; the second group consists of FY-3C and FY-3D, which were launched on 23 September 2013 and 15 November 2017; the third group containing FY-3E (dawn-dusk orbit), FY3F, FY-3G, and FY-Rainfall (instruments focus on the origins of rainfall) will be launched in the future (after 2020). FY-3A has been stopped after March 2018, but FY-3B/C/D are still running. SEM has the capability to detect proton flux with an energy range from 3 to 300 MeV (six bands: 3–5, 5–10, 10–26, 26–40, 40–100, and 100–300 MeV) and electron flux with energy range from 0.15 to 5.7 MeV (five bands: 0.15–0.35, 0.35–0.65, 0.65–1.2, 1.2–2.00, and 2.00–5.70 MeV). From the 1960s, many missions launched to detect the radiation belts [Northrop & Teller, 1960; Mcllwain, 1961; Hess, 1968; Heckman & Nakano, 1969] and major satellite series, which are POES (Polar Orbiting Environmental Satellites) and FengYun-3, provide operational particle products presently. POES have been running for more than 40 years from 1979, and now, NOAA-15/18/19/20 satellites are still in operation. SBUS applies Solar Ultraviolet Backscattered technique, which has been developed for 40 years from the 1970s (Bhartia et al., 1996; Flynn et al., 2009; World Meteorological Organization [WMO], 2010) to derive ozone profile from the troposphere (several kilometers high) to the mesosphere (about 70 km). According to the in-orbit cross calibration with the ozone vertical profiles from National Oceanic and Atmospheric Administration Solar Backscatter Ultraviolet (NOAA SBUV), the uncertainty of the SBUS measurements is approximately 6–7% (F. X. Huang et al., 2012). SBUS has 21 layer detections from 1,013 hPa to the top of atmosphere like SBUV on board POES, and each layer’s value is the average value over this layer. It should be noted that the detections above 70 km are unreliable. Due to the reflection impacts of the aerosols in the troposphere and the rare ozone density in the mesosphere, we consider that the ozone profiles retrieved by SBUS are more reliable in the stratosphere (about 10–55 km) (F. X. Huang et al., 2012). So in this work, we used the ozone profiles measured by SBUS from 30 to 50 km (Layers 11 to 16, from 10.13 to 1.013 hPa) to investigate the March SPEs’ impacts on the ozone in the upper stratosphere. The relationships between the layers (11 to 16) and the altitudes in polar region are shown in Table 1. Previous studies about ozone profile measured by SBUS can be found in (Huang et al., 2010; Liu et al., 2011). The SBUS data are provided in Dobson units (DU). The number density or volume mixing ratio might be more suitable for this work; however, the SBUS on board FY-3 satellite is designed to monitor the
Table 1

| Layer number | Pressure range         | Approximate altitude |
|--------------|------------------------|----------------------|
| Layer-11     | 10.13–6.393 hPa        | 30 km                |
| Layer-12     | 6.393–4.034 hPa        | 35 km                |
| Layer-13     | 4.034–2.545 hPa        | 38 km                |
| Layer-14     | 2.545–1.606 hPa        | 41 km                |
| Layer-15     | 1.606–1.013 hPa        | 46 km                |
| Layer-16     | 1.013–0.630 hPa        | 50 km                |

ozone in the low to middle stratosphere. More details of SEM and SBUS instruments, data retrievals, calibrations, and validations can be found in (C. Huang et al., 2012) and (F. X. Huang et al., 2012). In this work, we applied the particle detections by SEM on board two satellites (FY-3A and FY-3B) and the ozone measurements by SBUS on board one satellite (FY-3B) because the SBUS on board FY-3A suffered a mechanical failure during the SPE days. It should be noted that SEM works both day and night but SBUS only works at daytime. So, to one satellite, the available particle detections are about twice as much as the ozone detections.

We also applied the proton measurements from the SEM on board FengYun-2D (FY-2D, launched on 8 December 2006 and located at 86.5° E) geosynchronous meteorological satellite, which has the ability to detect the proton flux in three bands (P1: 10–30 MeV; P2: 30–100 MeV; and P3: 100–300 MeV) and the electron flux in two bands (≥ 350 keV and ≥ 2 MeV), to derive the situation of the proton flux during the March SPEs (Figure 2, P1, P2, and P3 are combined to derive the proton flux in the bands of 10–300 and 30–300 MeV).

3. The SPE-Induced Ozone Depletion

3.1. The March SPEs of 2012

SPEs caused by intense solar flares or CMEs are always accompanied by high-energy protons that appear at high latitudes. The SPEs that occurred on 7 (Day 67) and 13 (Day 73) March were caused by the solar active region of AR1429. In Figure 2, the proton flux measured by FengYun-2D Chinese geosynchronous meteorological satellite shows that the proton flux with particle energy over 100 MeV reached over 100 pfus (proton flux units) during the SPE on 7 March when the proton (10–100 MeV) fluxes increased 3–4 orders of magnitude. From Figure 2, it is found that the first SPE on 7 March (Day 67) has much higher flux (about an order of magnitude) and “harder” particle energy spectrum with the flux of energetic proton (particle energy is over 100 MeV) than the second SPE on 13 March (Day 73). More “harder” particles may bring more significant impacts on lower atmosphere at about 20 hPa (von Clarmann et al., 2013) because higher energy particles have the ability to penetrate deeper into the atmosphere and produce the ozone destruction materials at lower altitudes. The proton flux measured by FY-2D is slightly different from GOES-13 measurements in Figure 2 of Jackman et al. [2014] due to the different locations of the two geostationary satellites.

3.2. The North Hemisphere Responses

Figure 3 shows the ozone distribution at 10 hPa (Layer 11, about 30 km high) measured by SBUS and the proton flux with particle energy over 100 MeV detected by SEM in the March SPEs. The ozone distribution plot is made by the bilinear interpolation method. SBUS data were gridded onto a 5° grid map, and we used bilinear interpolation to derive every latitudinal gridding’s value. Then, we generated the ozone distribution

Figure 2. The proton flux measured by FY-2D geostationary satellite during the March SPEs. The dashed line denotes the threshold value of solar proton event (10 counts/(cm² s sr)). When the proton flux is over this value, this event is called solar proton event.
Figure 3. The proton flux (first and third columns) detected by SEM (in situ) and the ozone distributions (second and fourth columns, by the bilinear interpolation) covering 45°N to 90°N at 10 hPa measured by SBUS in the Northern Hemisphere during the March SPEs. DU is Dobson units of ozone thickness.
Figure 4. The same as Figure 3, but for the proton at 40–100 MeV and the ozone at 2.51 hPa (approximately 41 km).
Figure 5. (top panel) The changes of mean ozone profile that the observations cover at 60°N to 82°N due to the satellite inclination considering the latitude weight of data points. The changes refer to the profile of 6 March (Day 66). The black dashed lines mark the onset days of SPEs. The black dash-dotted lines denote the 0 level of ozone changes. (bottom panel) The same as top panel, but in the Southern Hemisphere.

map. The particles with energy over 100 MeV have the ability to reach the level of 10 hPa and induce ozone variations there (Hargreaves, 1992). In early March 2012, the north polar ozone distribution at 10 hPa shows very significant depletion responses and distribution changes to the SPEs on 7/8/9 March (the area of very low ozone actually agrees well with the area of highest proton fluxes) and no obvious feedback to the SPE on 13 March. Figure 4 shows the proton flux in 40–100 MeV (the protons in this energy band have the ability to reach approximately 40 km) and the ozone distribution at 2.51 hPa level (about 41 km). The protons in this energy band have the ability to reach approximately 40 km. The ozone distribution at 2.51 hPa changed significantly from 7 to 10 March with the high proton flux that the ozone depleted in the regions of high particle flux, but there still exists the ozone increasing somewhere. It should be noted that the significant ozone depletion at 2.51 hPa occurred on 10 March, which is different from that at 10 hPa. The direct impact of the particles lasts longer (about 5 days) at 2.51 hPa than that at 10 hPa (about 3 days), which might be due to the longer duration of the energetic particle flux. The top panel of Figure 5 shows the relative changes of the ozone profile from the altitude of 30 to 50 km during the March SPEs, which are relative to the ozone profile on 6 March (Day 66). It is found that there exists about 10–17% ozone reduction in the upper stratosphere around the height of 40 km simultaneously after the SPE on 7 March (Day 67). The ozone depletion from 35 to 50 km lasts several days, but the SPE on 13 March (Day 73) only makes some ozone reduction overlapping the effects of the SPE on 7 March around the height of 40 km. The upper stratospheric ozone begins to be reduced from mid-March to the end of this month. The ozone depletion might be the result of the downward ozone destruction propagation from the mesosphere, which is due to the great SPEs in late January 2012. Päivärinta et al. (2016) studied the early SPEs in 2012 by the model-measurement comparison. Their results show the January 2012 SPEs might have significant indirect impacts on the stratosphere and cause the long-term ozone depletion in March in the Northern Hemisphere by the downward transport of NO\textsubscript{x}. In general, the north polar ozone depletion responses to the first SPE on 7 March (Day 67) are more significant than the second SPE on 13 March (Day 73) because the first March SPE has more “harder” particle energy spectrum, which may affect the lower level of stratosphere.

3.3. The South Hemisphere Responses

Figure 6 presents the ozone distribution at 10 hPa and the proton flux over 100 MeV from FY-3 observations in the Southern Hemisphere. From Figure 6, the significant ozone destruction in the region of high proton flux at 10 hPa level are observed after the SPE of 7 March, but the SPE of 13 March does not cause any ozone depletion at 10 hPa level. Similarly to Figure 4, Figure 7 shows the ozone distribution responses to the
Figure 6. The same as Figure 3, but in the Southern Hemisphere. It should be noted that the particle detections near the left upper border are the particles in SAA (South Atlantic Anomaly) region, which are irrelevant to the SPEs.
Figure 7. The same as Figure 4, but in the Southern Hemisphere.
proton flux at about 41 km in the Southern Hemisphere, where there are obvious responses to the proton flux in the ozone distribution map during 7 to 10 March but slight ozone depletion due to the 13 March SPE. As in the Northern Hemisphere, on 8 March, the ozone depletions at 2.51 hPa occurred in most regions, but there were also some increases as shown by the red regions in the ozone plot for 20120308. There are significant ozone destructions on 8 and 10 March (Days 68 and 70). Similar to the Northern Hemisphere, the direct impacts of the energetic particles last longer (about 4 days) at 2.51 hPa than that at 10 hPa (about 2 days). From the figure of ozone profile change (the bottom panel in Figure 5), two ozone depletion events caused by March SPEs are clear from the height of 40 to 50 km. The SPE of 7 March induces over 14% ozone depletion in the upper stratosphere, and the SPE of 13 March brings about 9% ozone reduction at the height of 40 km, respectively. The March SPEs cause 2–5% ozone loss around the altitude of 30 km continuing several days. The ozone recovered from middle March. It is interesting that in the bottom panel there exist the positive ozone anomaly at the time of the first SPE and the negative anomaly toward the end of March at low altitudes. Considering first the positive ozone anomaly, we compared it with Figure 2 in (von Clarmann et al., 2013). According to this figure, ozone levels are increasing from January to March in the upper stratosphere in the Southern Hemisphere, which may be a seasonal effect. In addition, Figure 2c in (von Clarmann et al., 2013) and Figure 6 in (Jackman et al., 2014) show that there is a peak of ozone just before the time of 7 March SPE at 42–43 km in the Southern Hemisphere (Figures 2c and 6, top right). So we tend to consider that this positive ozone anomaly might be part of the natural ozone variation. Now considering the negative anomaly, we compare it with Figure 2 in (von Clarmann et al., 2013). This shows ozone levels decreasing at low latitudes from February to March in the Southern Hemisphere. So we think the negative anomaly around 30 km may also be a seasonal effect. Similar to the Northern Hemisphere, the SPE-related ozone depletion on 7 March (Day 67) is significant, lasting more than a week but much shorter than the depletion in the Northern Hemisphere.

4. Conclusion and Discussion

The SPEs which occurred in early March 2012 brought significant impacts on both hemispheres’ polar middle atmosphere. From FY-3 satellite observations, there exist short-term but obvious ozone changes in the upper stratosphere, and the direct impacts of the energetic particles last longer at higher altitude than that at lower altitude in both hemispheres. Due to the “harder” particle energy spectrum, the responses of SPE-related ozone depletion at 10 hPa are more pronounced on 7 March (Day 67) than that on 13 March (Day 73). Seppälä et al. (2008) reported the impacts of hard-spectra SPEs, the 2005 January SPEs, on the middle atmosphere, and the model results showed that the 2005 January SPEs caused insignificant impacts on the ozone in the stratosphere even if the SPEs lasted 24 hr. In our work, the hard-spectra SPE that occurred on 7 March brought significant impacts on the ozone in the upper and middle stratosphere. We think the cause of the differences between the March 2012 SPEs and the January 2005 SPEs may the long duration of the high flux of energetic protons (about 48 hr), the more “harder” particle spectrum in the March 2012 SPEs. In our work, the short-term ozone depletion after the March SPEs is more evident in the northern polar upper stratosphere, and there exists continuous ozone reduction in the north polar upper stratosphere, which may be due to the downward motion of odd nitrogen caused by the Arctic vortex from the upper level (Funke et al., 2005). The NOx downward transport inside the polar vortex is common (Funke et al., 2011; Funke, López-Puertas, Stillier, et al., 2014; Funke, López-Puertas, Holt, et al., 2014; Fytherer et al., 2015). In the work of von Clarmann et al. (2013), they reported that the March SPEs made the continuous ozone depletion in March (see Figure 11 in their paper) around the altitude of 40 km in the Northern Hemisphere, but only a short-term negative response of ozone was found after the March SPEs in the Southern Hemisphere (see Figure 2c in their paper) by the MIPAS observations. Our results are in agreement with those findings in von Clarmann et al. (2013). Jackman et al. (2014) calculated the ionization rate during the March SPEs (see it in the bottom panel of Figure 2 in their paper) and presented the ozone changes in the Southern Hemisphere observed by MLS (see it in the top panel of Figure 6 in their paper). According to the results in Jackman et al. (2014), the peaks of the ionization rate and the ozone depletion during the March SPEs occurred on 8 March. In our work, we also find that the significant peak of ozone destruction is on 8 March in the Southern Hemisphere (see it in Figure 6), which may be because the ionization rate reaches a maximum on 8 March and coincides with the MLS observations. The process of energetic particle precipitation effects on ozone deserves to be studied so that we can better understand how space weather events influence middle atmosphere and also the mechanism between solar activities and climate changes of the Earth.
Appendix A: The SBUS Ozone Map Generating

We use the SBUS on board FY-3B (one satellite) to detect ozone, and the ozone detections have limitations. There exist temporal differences between the detections of each orbit (it is not a simultaneous observation; the satellites on polar orbit do the observations at the fixed local time). We assume the ozone distributions change little during a quiet day, so that we can do data gridding and interpolation to all the detections in 1 day and plot the contour map. From Figures 3, 4, 6, and 7, it is found that the ozone distribution map changed little (day to day) during the quiet days but changed much during the disturbed days. So, we think this assumption is reasonable. Using the interpolation method will inevitably create some artifacts. We think the main artifacts made by the interpolation might exist in the zonal structure of the ozone plot rather than in the radial structure of the ozone plot because the sampling interval is short in the radial direction, but there is about 102 min between each orbit. In addition, with the satellite going from high latitudes to low latitudes, the distances between the zonal observation positions are increasing, which might cause the zonal sampling points to become sparse at low latitudes. So the data interpolation between the different orbits might cause the unsmooth transition in the zonal structure of the ozone plot. However, our purpose is to see the differences between quiet days and disturbed days on the ozone map. We think, for this purpose, this solution is acceptable.

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References

Bhartia, P. K., McPeters, R. D., Mateer, C. L., Flynn, L. E., & Wellemeyer, C. (1996). Algorithm for the estimation of estimation of vertical ozone profiles from the backscattered ultraviolet technique. Journal of Geophysical Research, 101(D13), 18,793–18,806.

Crutzen, P. J., Iakovenko, I. S. A., & Reid, G. C. (1975). Solar proton events: Stratospheric sources of nitric oxide. Science, 189, 457–458.

Degenstein, D. A., Lloyd, N. D., Bourassa, A. E., Gattinger, R. L., & Llewellyn, E. J. (2005). Observations of mesospheric ozone depletion during the October 28, 2003 solar proton event by OSIRIS. Geophysical Research Letters, 32, L03S11. https://doi.org/10.1029/2004GL02152

Flynn, L. E., McNamara, D., Beck, C. T., Petropavlovskikh, I., Beach, E., Pachepsky, Y., et al. (2009). Measurements and products from the solar backscatter ultraviolet (SBUV/2) and ozone mapping and profiler suite (OMPS) instruments. International Journal of Remote Sensing, 30(15/16), 4259–4272.

Frederick, J. E. (1976). Solar corpuscular emission and neutral chemistry in the Earth's middle atmosphere. Journal of Geophysical Research, 81, 3179–3186.

Funke, B., Baumgaertner, A., Calisto, M., et al. (2011). Composition changes after the “Halloween” solar proton event: The High Energy Particle Precipitation in the Atmosphere (HEPPA) model versus MIPAS data intercomparison study. Atmospheric Chemistry and Physics, 11, 9089–9139.

Funke, B., López-Puertas, M., Gil-López, S., von Clarmann, T., Fischer, G. P. S. H., & Kellmann, S. (2005). Downward transport of upper atmospheric NO into the polar stratosphere and lower mesosphere during the Antarctic 2003 and Arctic 2002/2003 winters. Journal of Geophysical Research, 110, D24308. https://doi.org/10.1029/2005JD006643

Funke, B., López-Puertas, M., Holt, L., Randall, C. E., Stiller, G. P., von Clarmann, T. (2014). Hemispheric distributions and interannual variability of NO₃ produced by energetic particle precipitation in 2002–2012. Journal of Geophysical Research – Atmospheres, 119, 13,565–13,582.

Funke, B., López-Puertas, M., Stiller, G. P., & von Clarmann, T. (2014). Mesospheric and stratospheric NO₃ produced by energetic particle precipitation during 2002–2013. Journal of Geophysical Research – Atmospheres, 119, 4429–4446.

Fytterer, T., Mlynář, M., Gries, M., Nieder, H., et al. (2015). Energetic particle induced inter-annual variability of ozone inside the Antarctic polar vortex observed in satellite data. Atmospheric Chemistry and Physics, 15(6), 3327–3338.

Hargreaves, J. K. (1992). The solar-terrestrial environment. In Cambridge Atmospheric and Space Science Series (Chap. 5, pp. 132–207). Cambridge, UK: Cambridge University Press.

Heath, D. F., Krueger, A. J., & Crutzen, P. J. (1977). Solar proton event: Influence on stratospheric ozone. Science, 197, 886–889.

Heckman, H. H., & Nakano, G. H. (1986). Low-altitude trapped protons during solar minimum period. Journal of Geophysical Research, 74(14), 3575–3590.

Hess, W. N. (1968). The radiation belt and the magnetosphere. New York: Blaisdell.

Huang, C., Li, J. W., Yu, T., et al. (2012). The capabilities and applications of FY-3A/B SEM on monitoring space weather events. IEEE Transactions on Geoscience and Remote Sensing, 50(12), 4975–4985.

Huang, F. X., Huang, Y., Flynn, L. E., et al. (2012). Radiometric calibration of the solar backscatter ultraviolet sounder and validation of ozone profile retrievals. IEEE Transactions on Geoscience and Remote Sensing, 50(12), 4956–4964.

Huang, F. X., Liu, N. Q., Zhao, M. X., Wang, S., & Huang, Y. (2010). Vertical ozone profiles deduced from measurements of SBUS on FY-3 satellite. Chinese Science Bulletin, 55(10), 943–948.

Jackman, C. H., DeLand, M. T., Labow, G. J., Fleming, E. L., Weisenstein, D. K., & Ko, M. K. W., et al. (2005b). The influence of the several very large solar proton events in years 2000–2003 on the neutral middle atmosphere. Advances in Space Research, 35, 445–450.

Jackman, C. H., DeLand, M. T., Labow, G. J., Fleming, E. L., Weisenstein, D. K., & Ko, M. K. W., et al. (2005a). Neutral atmospheric influences of the solar proton events in October–November 2003. Journal of Geophysical Research, 110, A09S27.

Jackman, C. H., Marsh, D. R., Pfitzner, R., et al. (2008). Short- and medium-term atmospheric effects of very large solar proton events. Atmospheric Chemistry and Physics, 8, 765–785.

Jackman, C. H., & McPeters, R. D. (1985). The response of ozone to solar proton events during solar cycle 21: A theoretical interpretation. Journal of Geophysical Research, 90(D5), 7955–7966.

Jackman, C. H., & McPeters, R. D. (2004). The effect of solar proton events on ozone and other constituents. In Solar variability and its effects on climate (Vol. 141, pp. 305–319). Washington, DC: Geophys. Monograph.
Jackman, C. H., McPeters, R. D., Labow, G. J., Fleming, E. L., Pradas, C. J., & Russel, J. M. (2001). Northern Hemisphere atmospheric effects due to the July 2000 solar proton events. *Geophysical Research Letters*, 28, 2883–2886.

Jackman, C. H., Randall, C. E., Harvey, V. L., et al. (2014). Middle atmospheric changes caused by the January and March 2012 solar proton events. *Atmospheric Chemistry and Physics*, 14(2), 1025–1038.

Liu, N.-Q., Huang, F. X., & Wang, W. H. (2011). Monitoring of the 2011 spring low ozone events in the Arctic region. *Chinese Science Bulletin*, 56(27), 2893–2896.

López-Puertas, M., Funke, B., Gil-López, S., von Clarmann, T., Stiller, G. P., Höpfner, M., et al. (2005). Observation of NOx enhancement and ozone depletion in the Northern and Southern Hemispheres after the October–November 2003 solar proton events. *Journal of Geophysical Research*, 110, A09S43.

Mellinwa, C. E. (1961). Coordinates for mapping the distribution of magnetically trapped particles. *Journal of Geophysical Research*, 66(11), 3681–3691.

McPeters, R. D., Jackman, C. H., & Stassinopoulos, E. G. (1981). Observations of ozone depletion associated with solar proton events. *Journal of Geophysical Research*, 86, 12071–12081.

Northrop, T. G., & Teller, E. (1960). Stability of the adiabatic motion of charged particles in Earth’s field. *Physics Review*, 117(1), 215–225.

Päivärinta, S. M., Verronen, P. T., Funke, B., et al. (2016). Transport versus energetic particle precipitation: Northern polar stratospheric NOx and ozone in January–March 2012. *Journal of Geophysical Research – Atmospheres*, 121, 6085–6100.

Patterson, J. D., Armstrong, T. P., Laird, C. M., Detrick, D. L., & Weatherwax, A. T. (2001). Correlation of solar energetic protons and polar cap absorption. *Journal of Geophysical Research*, 106, 149–163.

Reed, G. C., Solomon, S., & Garcia, R. R. (1991). Response of the middle atmosphere to the solar proton events of August–December, 1989. *Geophysical Research Letters*, 18, 1019–1022.

Rosen, G., von Savigny, C., Sinnhuber, M., et al. (2005). Ozone depletion during the solar proton events of October/November 2003 as seen by SCIAMACHY. *Journal of Geophysical Research*, 110.

Rusch, D. W., Gerard, J.-C., Solomon, S., Crutzen, P. J., & Reid, G. C. (1981). The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere. 1. Odd nitrogen. *Planetary and Space Science*, 29, 767–774.

Seppälä, A., Clilverd, M. A., Rodger, C. J., Verronen, P. T., & Turunen, E. (2008). The effects of hard-spectra solar proton events on the middle atmosphere. *Journal of Geophysical Research*, 113, A11131. https://doi.org/10.1029/2008JA013517

Seppälä, A., Verronen, P. T., Kyrölä, E., Hassinen, S., & Backman, L. (2004). Solar proton events of October–November 2003: Ozone depletion in the Northern Hemisphere polar winter as seen by GOMOS/Envisat. *Geophysical Research Letters*, 31, L19107.

Solomon, S., Reid, G. C., Rusch, D. W., & Thomas, R. J. (1983). Mesospheric ozone depletion during the solar proton event of July 13, 1982, 2. Comparison between theory and measurements. *Geophysical Research Letters*, 10, 257–260.

Solomon, S., Rusch, D. W., Gerard, J.-C., Reid, G. C., & Crutzen, P. J. (1981). The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere. 2. Odd hydrogen. *Planetary and Space Science*, 29, 885–892.

Swider, W., & Keneshea, T. J. (1973). Decrease of ozone and atomic oxygen in the lower mesosphere during a PCA event. *Planetary and Space Science*, 21, 1969–1973.

Turunen, E., Verronen, P. T., Seppälä, A., et al. (2009). Impact of different energies of precipitating particles on NOx generation in the middle and upper atmosphere during geomagnetic storms. *Journal of Atmospheric and Terrestrial Physics*, 71(10-11), 1176–1189.

von Clarmann, T., Funke, B., López-Puertas, M., et al. (2013). The solar proton events in 2012 as observed by MIPAS. *Geophysical Research Letters*, 40, 464–469.

Weeks, L. H., CuiKay, R. S., & Corbin, J. R. (1972). Ozone measurements in the mesosphere during the solar proton event of 2 November 1969. *Journal of the Atmospheric Sciences*, 29, 1138–1142.

World Meteorological Organization (WMO) (2010). *Scientific assessment of ozone depletion: 2010. Executive summary, the Scientific Assessment Panel of the Montreal Protocol on Substances that Deplete the Ozone Layer Report*. Silver Spring, MD: NOAA Research.

Zadorozhny, A. M., Tuchkov, G. A., Kikhtenko, V. N., Lastovicka, J., Boska, J., & Novak, A. (1992). Nitric oxide and lower ionosphere quantities during solar particle events of October 1989 after rocket and ground-based measurements. *Journal of Atmospheric and Terrestrial Physics*, 54, 183–192.