ELSEVIER

Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 2042–2052

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Southern ozone variations induced by solar particle events during 15 January–5 February 2005

A. Damiani[a,b,*], M. Storini[b], M. Laurenza[b], C. Rafanelli[a],
E. Piervitali[a], E.G. Cordaro[c]

[a]*Istituto di Scienze dell'Atmosfera e del Clima—CNR—Area di Ricerca Roma-Tor Vergata, Via del Fosso del Cavaliere, 100–00133 Roma, Italy*
[b]*Istituto di Fisica dello Spazio Interplanetario—INAF—Area di Ricerca Roma-Tor Vergata, Via del Fosso del Cavaliere, 100–00133 Roma, Italy*
[c]*Department of Physics/FCFM, University of Chile, P.O. Box 487-3, Santiago, Chile*

Abstract

A preliminary analysis of effects induced on the high-latitude Southern ozone layer by the enhanced Space Weather storms of January 2005 is presented. Data from Earth Probe TOMS V.8, SAGE II and POAM III suggest short (hours) ozone depletions induced by the outstanding solar activity. Such ozone variabilities are investigated at the edge of the so-called polar cap region.

Keywords: Space weather; Ozone layer variability; Solar energetic particles; Antarctic environment

---

1. Introduction

Sun's activity is in its declining phase and few sunspots can be observed on the solar disk. The spots related to the NOAA 10720 Active Region (AR) deserve special attention, as they are connected with an intense space storm period.

A series of highly energetic solar eruptions were the origin of huge perturbations propagating in the interplanetary medium since the middle of January 2005. They caused an enhanced cosmic ray modulation (a Forbush decrease in cosmic ray detectors) and the arrival to the terrestrial environment of solar energetic particles (SEPs). In particular, the worldwide network of neutron monitors registered short-time increases in their intensity records (GLEs: ground level enhancements), related to the presence of solar relativistic particles.

This work discusses the ozone layer variability during 15 January–5 February 2005, to single out possible effects induced by the solar activity. Data from Earth Probe TOMS V.8 and SAGE II/POAM III profiles were used together with data of some interplanetary/terrestrial instruments. A short overview of the Space Weather conditions during the investigated period is given in Section 2. Section 3 describes the variability of the TOC (columnar Total Ozone Content) at five Southern geographic

---

*Corresponding author. Istituto di Scienze dell'Atmosfera e del Clima—CNR—Area di Ricerca Roma-Tor Vergata, Via del Fosso del Cavaliere, 100–00133 Roma, Italy. Tel.: +39 06 49934268; fax: +39 06 20660291.

E-mail address: a.damiani@isac.cnr.it (A. Damiani).

1364-6826/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2006.03.010

sites (King George, Marambio, General Belgrano, Scott Base and South Pole). SAGE II and POAM III data are used in Section 4 to illustrate possible effects induced by the solar particle arrival in the terrestrial environment on 20 January 2005 and 17 January 2005, respectively. Section 5 reports a short discussion on the reliability of our findings and gives the conclusion.

2. Space weather overview

The beginning of the 2005 was characterized by a low/moderate solar activity between 1 and 13 January and 23 January–5 February, while for 14–22 January, the NOAA AR 10720 displayed an interesting evolving dynamics, going from a simple beta magnetic sunspot group during its East limb apparition to a magnetically complex sunspot region, when crossed the West limb. More than 80 X-ray flares were observed during its solar disk transit (http://www.sel.noaa.gov/weekly/pdf2005/prf1533.pdf to 1536.pdf). Among them, five flares were classified as X1.2 (DD-MM/START: 15-01/0039 UTC), X2.6 (15-01/2154 UTC), X3.8 (17-01/0659 UTC), X1.3 (19-01/0803 UTC) and X7.1 (20-01/0641 UTC).

In the first panel (from the top) of Fig. 1, the GOES 10 (W135 location) data for the analysed period is shown. They are 5-min averaged X-ray fluxes in two wavelength bands: 0.05–0.30 nm (XS) and 0.10–0.80 nm (XL), as obtained from http://goes.ngdc.noaa.gov/data/avg/. Enhanced solar proton events were observed by GOES 10 (second panel of Fig. 1) and GOES 12 in the same period. In particular, the 17 January showed a big injection of solar particles peaking at 5040 particles/cm^2 s sr at the >10 MeV channel and 20 January exhibited the hardest and most energetic particle event of the on going solar activity cycle.

The peak for the >100 MeV channel (here not reported) was 652 particles/cm^2 s sr at 20-01/0710 UT, while the 10 MeV one was 1860 particles/cm^2 s sr at 20-01/0810 UT (see http://umbra.nascom.nasa.gov/SEP/seps.html). Moreover, the 17 January event seems to be characterized by near-relativistic solar particles while the 20 January one probably contained up to about 10 GeV particles. The latter event was worldwide observed in neutron monitor records (GLE event, shown in the third panel by plotting the neutron monitor intensity of the Antarctic Laboratory for Cosmic Rays located on King George Island–Fildes Bay: http://www.dfi.uchile.cl/ec_web/htm/datosrco.htm).

The third panel of Fig. 1 shows that during 17–24 January, the cosmic ray (CRs) flux is depressed; the fourth and sixth panels illustrate the variability of the geomagnetic K_p and D_{st} indices (see http://www.swdc.kugi.kyoto-u.ac.jp/index.html), while the fifth panel shows the Y component (in the GSE coordinate system) of the interplanetary electric field E (http://omniweb.gsfc.nasa.gov). Data gaps, created by the storms of solar particles on the in-situ instruments, prevent to fill the E_y trend. Nevertheless, we can notice enhanced field values at least during 17 and 21 January. They could have had a role in the dynamics of the terrestrial atmospheric environment.

Fig. 2 reports the OMNI 2 hourly interplanetary parameters at the near-Earth space (http://omniweb.gsfc.nasa.gov) from 15 January to 5 February 2005 (V: solar wind speed, T: solar wind temperature, D: solar wind proton density, B: magnetic field intensity, Theta: latitude of B-angle, Phi: Longitude of B-angle). Gaps in B intensity were filled with the corresponding ACE (Advanced Composition Explorer) data (http://www.srl.caltech.edu/ACE). As we can observe in Fig. 2, high-speed ($V_{\max} > 900$ km/s) interplanetary macrostructures engulfed the Earth from 17 January till about January 23, explaining not only the associated cosmic ray modulation but also the different levels of geomagnetic activity reported in Fig. 1.

Possible linkages between solar activity and the variability of the terrestrial environment were extensively investigated in the past; this is particularly true for the solar-induced effects on the ozone layer dynamics (e.g. Laštovička and Križan, 2005; Krivolutsky et al., 2005; Jackman and McPeters, 2004; Laštovička et al., 2003; Krivolutsky, 2003; Storini, 2001 and references therein). The natural ozone layer variability induced by solar activity has its origin in:

(i) the electromagnetic solar radiation;
(ii) the solar wind, the electron precipitations and auroral activity;
(iii) the changing galactic cosmic ray incoming;
(iv) the transient effects induced by the arrival of energetic solar particles.

We will not discuss such phenomena but we recall that energetic solar particles supply additional external energy to the terrestrial environment, being

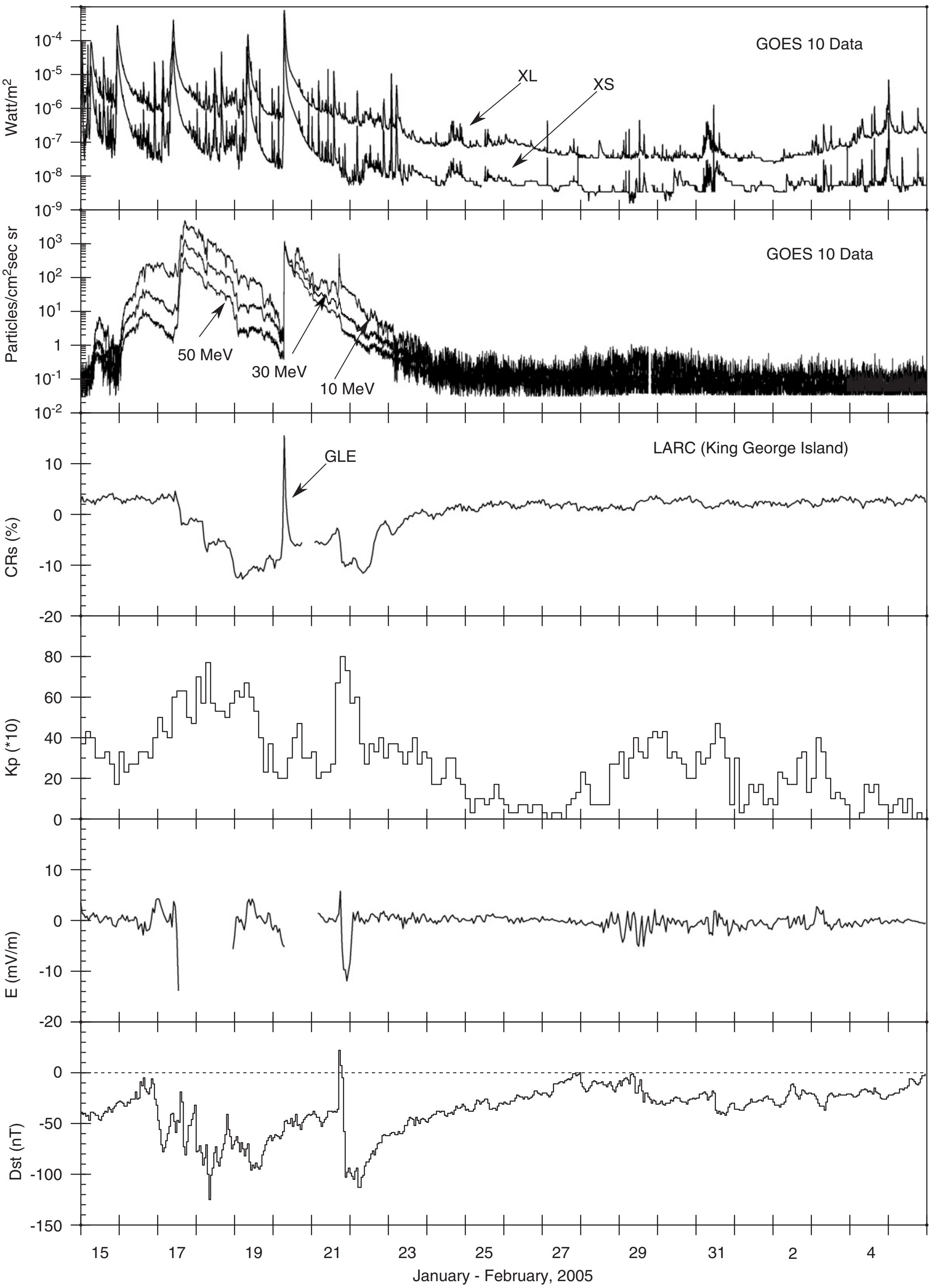

Fig. 1. Variability of some parameters of the Earth environment. From top to bottom: X-ray flux (XS: 0.5–3.0 Å and XL: 1–8 Å), proton flux, cosmic ray intensity (at LARC), K_p geomagnetic index, Electric Field and D_{st} geomagnetic index from 15 January to 5 February, 2005.

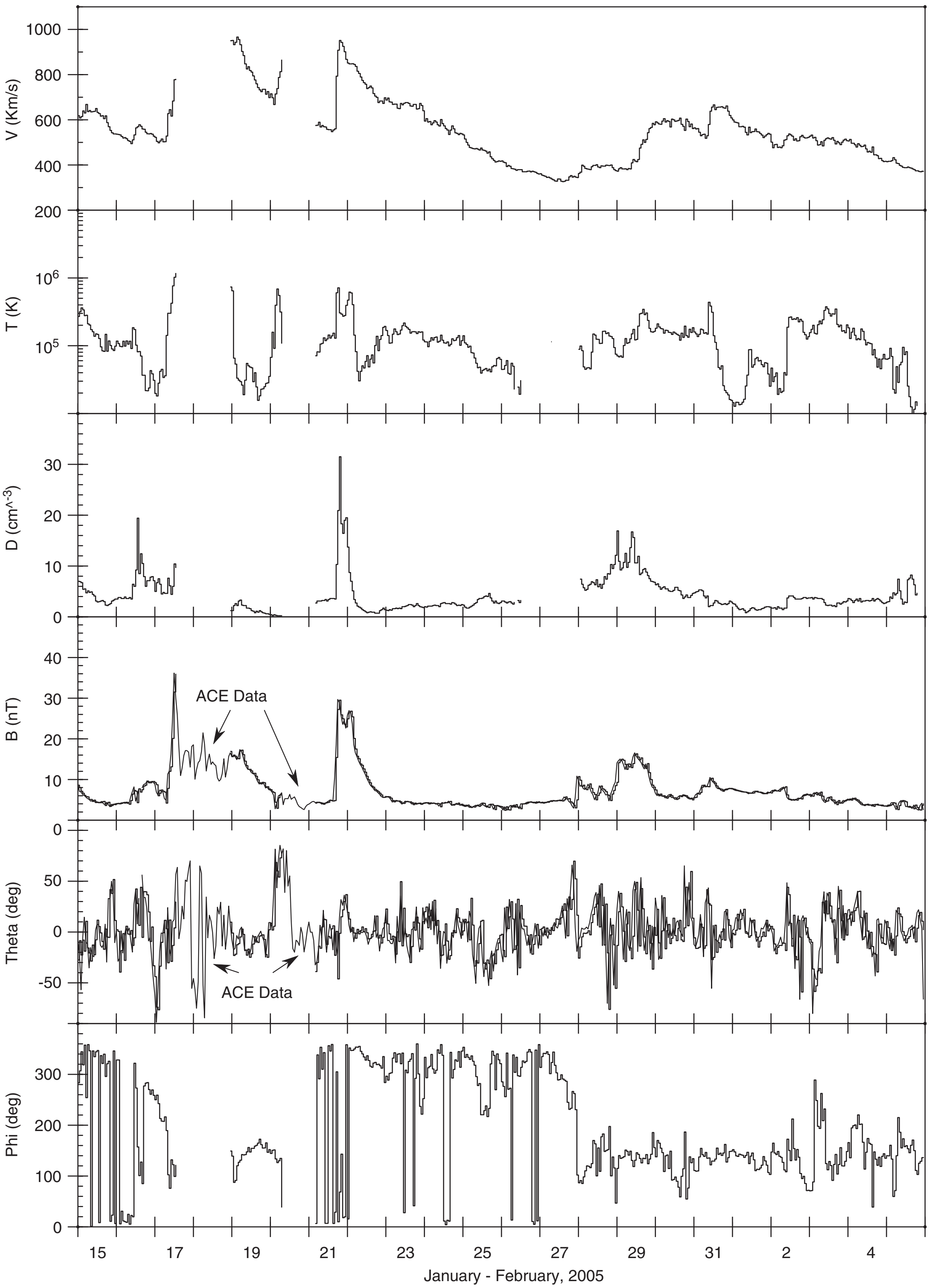

Fig. 2. Interplanetary medium parameters near the Earth's from OMNI2 data set. From top to bottom: solar wind velocity (*V*), temperature (*T*), density (*D*), magnetic field intensity (*B*; completed with ACE data), *B*-latitude (Theta in GSE system, completed with ACE data), *B*-longitude (Phi in GSE system) from 15 January to 5 February, 2005.

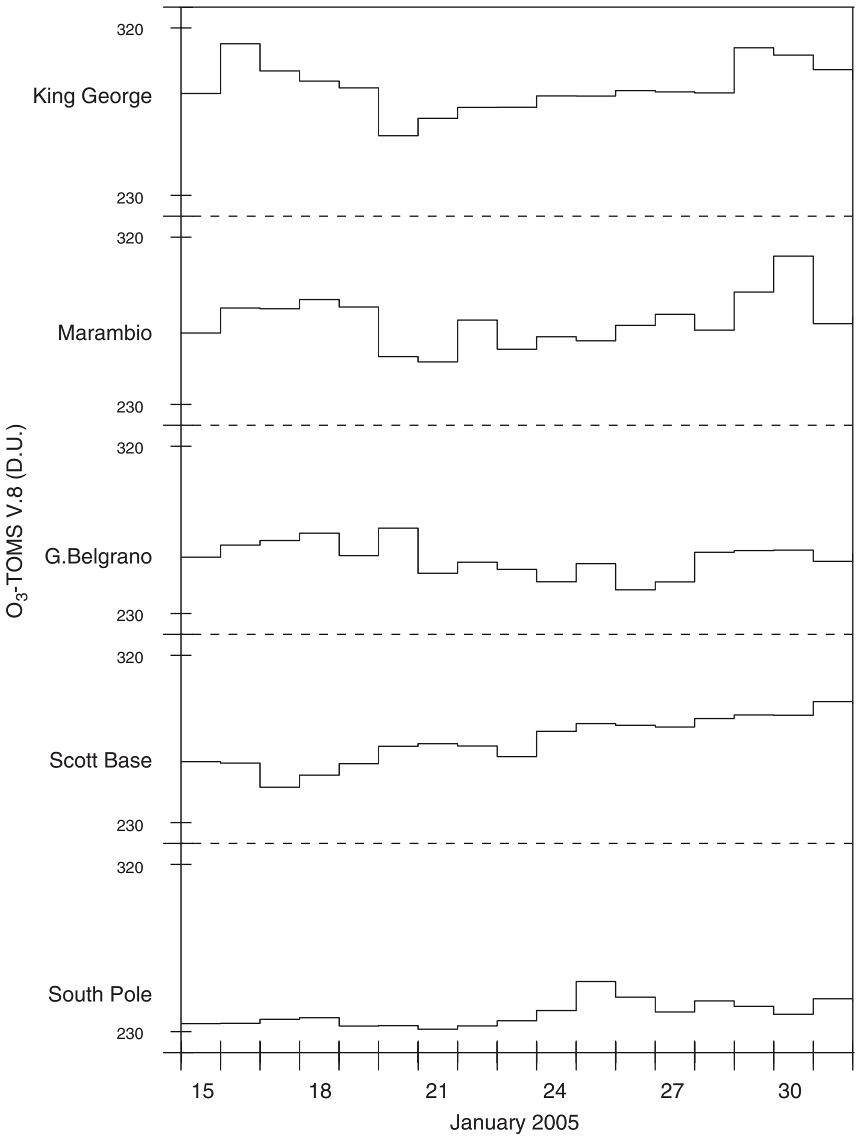

Fig. 3. TOC (TOMS) variability at five different geographic sites of the high-latitude Southern hemisphere from 15 January to 5 February 2005.

able to interact with the constituents of the atmospheric layer and produce ionizations, dissociations, dissociative ionizations and excitations. The layer level to be considered depends on the particle energy. MeV particles can reach the mesosphere and upper stratosphere, while relativistic particles mainly impact in the middle stratosphere (at the so-called Pfotzer Maximum); the daughter particles can be detected on the ground as GLEs.

The additional ionisation, induced by energetic solar particles, increases the production of HO_x (H, OH, HO_2) and NO_x (NO, NO_2). The HO_x and NO_x chemical constituents can destroy ozone molecules by the well-known catalytic cycles (Crutzen, 1971).

3. TOC variability at the southern high latitudes

As a first step of our research, we looked for the TOC variability at five Southern geographic sites during 15–31 January 2005. They are: King George Island (62°10′S–58°54′W), Marambio (64°13′S–56°43′W), General Belgrano (77°52′S–34°–40′W),

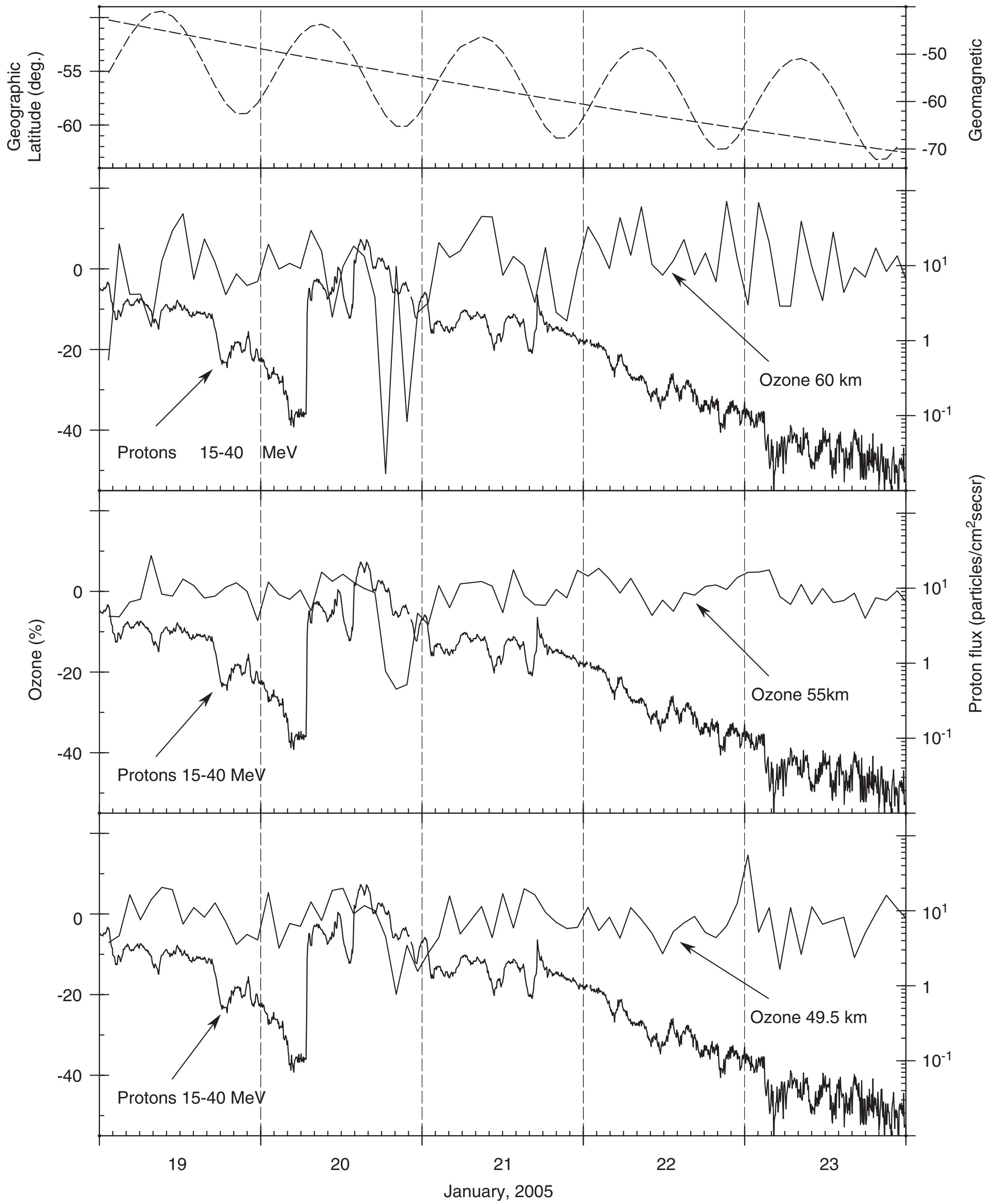

Fig. 4. SAGE II O_3 (% of the average between 19-01/01.21 UT to 20-01/17.00 UT) at altitudes of 60, 55 and 49.5 km (thick line) and the 15–40 MeV proton flux from GOES 10 (thin line). The SAGE II geographic (straighter line) and geomagnetic (sinusoidal line) latitudes are shown in the top panel.

Scott Base (77°48′S–165°36′E) and South Pole (89°58′S–24°47′W).

Data from the Earth Probe—Total Ozone Mapping Spectrometer (EP-TOMS), available at http://toms.gsfc.nasa.gov/index_v8.html, are displayed in Fig. 3 for the five geographic sites. We notice clear O_3 depletions at King George (maximum: 8%), Marambio (5%) and General Belgrano (3%) for the 20–21 January. A modulated O_3-trend of several days can be seen in Fig. 3 at least for three of the five sites.

Can the effects mentioned above be related to the space storm period? A good quantitative evaluation of the TOC variation at a fixed geographic position cannot be directly linked with the Space Weather of the investigated period, because such variations can be affected by the air intrusion coming from low latitudes (depleted ozone regions) towards the pole. We recall that in January (the austral summertime), the air on polar region is usually not isolated by the polar vortex. Moreover, several sources of ozone variability (e.g. the ones listed in Section 2) can create contemporary effects on the ozone layer. Disentangling such effects is a difficult task. Hence, we decided to look for at least the induced effects of the solar particle events. SAGE II data are available (data between January 15 and January 18 are missing for the Southern hemisphere) for the GLE event, while POAM III is available for the SEP of January 17.

4. Solar particle events and SAGE II/POAM III profiles

The influence of the solar energetic particles on the ozone concentration should be better estimated at high altitudes of the atmosphere. The NASA Langley Atmospheric Sciences Data Center provided us with the SAGE2_V6.20_AEROSOL_O3_NO2_H2O_BINARY data set obtained by SAGE (Stratospheric Aerosol and Gas Experiment) II sensor on ERBS (Earth Radiation Budget Satellite); it uses the solar occultation technique to measure the attenuated solar radiation. This data set, covering the latitude range from ~80°N to 80°S and with a 0.5-km vertical resolution (http://eosweb.larc.nasa.gov/), includes number density profiles of ozone and nitrogen dioxide, plus molecular density and mixing ratio profiles of water vapour together with aerosol extinction profiles at 1020, 525, 453, and 385 nm. Concerning the investigated period, the data set covers 19 January–2 February 2005 and we retrieved these data from about 50–72°S.

Fig. 4 shows the period from 19 to 23 January 2005 in order to emphasize the relation between the proton flux in a selected MeV range (15–40 MeV, GOES 10 data) and the ozone content at different atmospheric heights. The ozone values, as obtained by SAGE II (see the upper panel for the involved geographic and geomagnetic latitudes), at three atmospheric levels (60, 55 and 49.5 km) are reported as percent variation from the average values (computed between 19-01/01.21 UT and 20-01/17.00 UT). Although data are referred only to the satellite orbit (i.e. without any interpolation or average procedure), we notice that after several hours of the SEP peak the ozone trends suggest O_3 depletion during the second half of 20 January. At 60 (55, 49.5) km, we found an O_3 decrease of about 50% (25%, 20%) at 18.35 (20.10) UT, delayed by about 12 h from the proton flux rise in the 15–40 MeV range; at that time, the satellite was at about 54°S, 142°E (55°S, 118°E) geographic coordinates (at the edge of the geomagnetic polar cap region). No relevant O_3 decreases are seen during 21–22–23 January.

We searched for the induced effects on the SAGE II ozone profiles. Fig. 5 reports them from ~45 to 70 km. The profiles are similar for 19, 21 and 22 January, while during 20 January, there exists a displacement of the profile towards reduced ozone values. In particular, we notice the start of the ozone depletion at about 65 km in the 18.35 UT profile

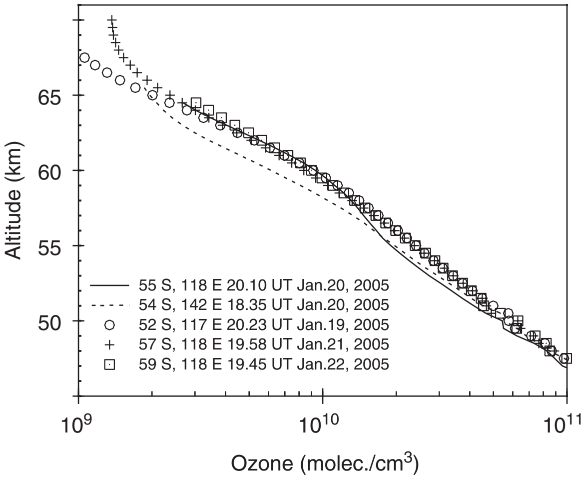

Fig. 5. O_3 profile between 45 and 70 km, as obtained by SAGE II in its passage at ~118°E and ~55°S during 19, 21 and 22 January compared with the one of 20-01/20.10 UT (thick line) together with the profile for 20-01/18.35 UT (dotted line).

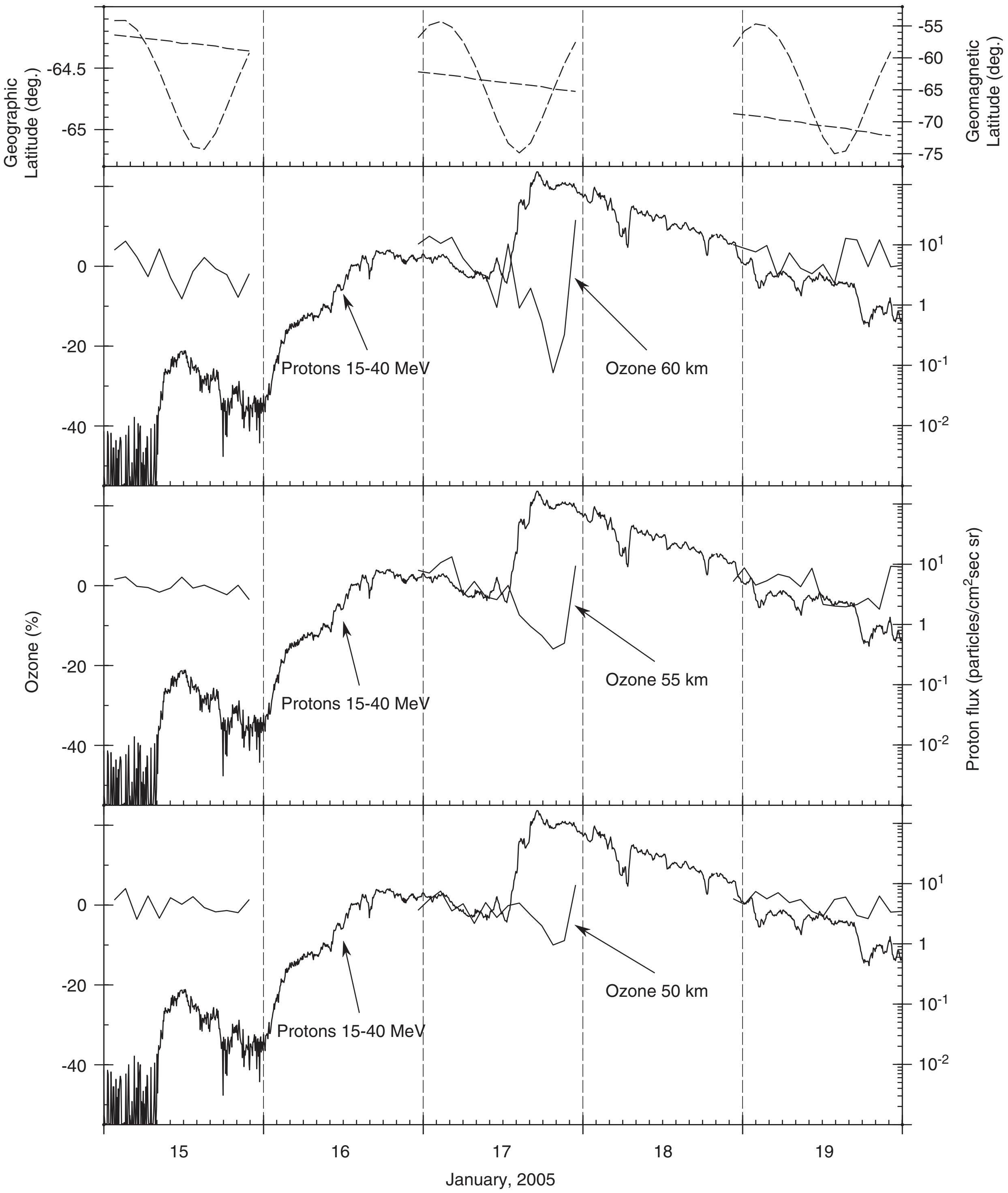

Fig. 6. POAM III O_3 (% of the 15-01 average) at altitudes of 60, 55 and 50 km (thick line) and the 15–40 MeV proton flux from GOES 10 (thin line). The POAM III geographic (straighter line) and geomagnetic (sinusoidal line) latitudes are shown in the top panel.

(54S, 142E, dotted line in Fig. 6) and at about 56 km at 20.10 UT (55S, 118E, thick line). The evaluation of the O_3 depletion between 64.5 and 38.5 km at 20.10 UT resulted to be ~2.25%. This rough evaluation is in agreement with what expected from the findings of Jackman et al. (2001, 2005) and

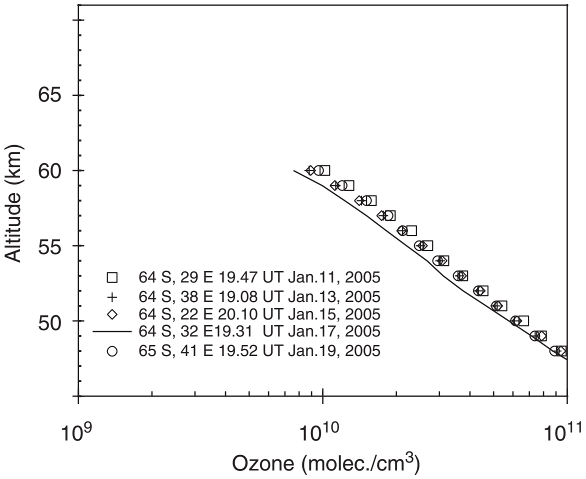

Fig. 7. O_3 profile between 45 and 70 km, as obtained by POAM III in its passage at ~22°/41°E and ~64°S during 11, 13, 15 and 19 January compared with the one of 15-01/19.31 UT (thick line).

Rohen et al. (2005); they indicate that only small variations (few %) associated with SEPs can be observed in the total ozone column. We have considered SAGE II profiles at about the same time for consecutive days. We believe that the short O_3 depletion, lasting about half a day in Fig. 5, can arise from an increase of HO_x molecules, being very reactive with each other and having a short lifetime.

In order to confirm this finding, we looked for POAM III data (http://eosweb.larc.nasa.gov/PRODOCS/poam3/table_poam3.html) during the GLE events. However, POAM III made measurements in one hemisphere at a time, on alternating days. Hence, we only obtained data for 15, 17 and 19 January 2005 in the southern hemisphere (but not for 20 January). Fig. 6, analogous to Fig. 4, shows POAM III data together with the proton flux in the range 15–40 MeV. It is interesting to observe that after the proton rise of 17 January 2005 a short-term depletion in the O_3 trend can be identified; it is similar to the one for 20 January. Moreover, Fig. 7 confirms for 17 January the depleted O_3 values in the 45–60 km range.

We are also interested in the NO_x contribution to the ozone dynamics, being able to influence the middle stratospheric ozone with long-lasting effects after a solar particle event (Jackman et al., 2001; Randall et al., 2005). Even if NO_2 molecules are not the best representatives of NO_x amount during the austral summertime (daylight; see Seppälä et al., 2004 for a discussion on the topic), we looked for the NO_2 variability from SAGE II data at altitudes between 50 and 40 km where the chain effectiveness of the NO_x catalytic cycle reaches its peak (Lary, 1997).

We plotted January NO_2 data from 1990 to 2000 and compared them with the ones for January 2005 (Fig. 8). Data refer to 40 km (January 1990–2000: 3317 points, January 2005: 190 points), 45 km (January 1990–2000: 3006 points, January 2005: 183 points), 47 km (January 1990–2000: 2462 points, January 2005: 183 points) and 49 km (January 1990–2000: 1784 points, January 2005: 176 points) and are plotted as function of the geographic latitude of SAGE II. The results of the linear data regression for the 1990–2000 (solid line) and 2005 (dashed line) are reported also in Fig. 8. We notice that NO_2 number density for January 2005 is lower than 1990–2000 at 40 km, similar at 45 km, and higher at the other two levels (47 and 49 km). In order to check if such moderate increase in a NO_x proxy pertains to the investigated Space Weather storm, we analysed the SAGE II data also during January 1995, 1996 and 1997 (i.e. during the solar minimum phase characterized by the lack of SEPs). We found that during the storm period of January 2005, the NO_2 number density at ~50 km indeed maintains a level of 2×10^7 higher than the average one for 1995–1997 in the $-50°/-70°$ geographic latitudinal belt. This suggests that possibly limited (as NO_x is depleted faster in the summer hemisphere) mid-term effects on the stratospheric ozone could be found with an ad hoc analysis.

5. Discussion and conclusion

During the current solar activity cycle (n. 23), several periods of intense Space Weather storms occurred. One of them was the space storm period that occurred in 2003 (late October–early November), when several flying instruments on satellites were able to acquire useful data to investigate the contemporary ozone layer variability. Works by using GOMOS/Envisat (Seppälä et al., 2004), NOAA 16 SUBV/2 and HALOE (Jackman et al., 2005), SCIAMACHY (Rohen et al., 2005), MIPAS (López-Puertas et al., 2005a, b) revealed clear solar-induced effects on the ozone layer, particularly inside the polar cap regions.

Here, we present some clues for solar-induced effects on the ozone layer during the intense Space

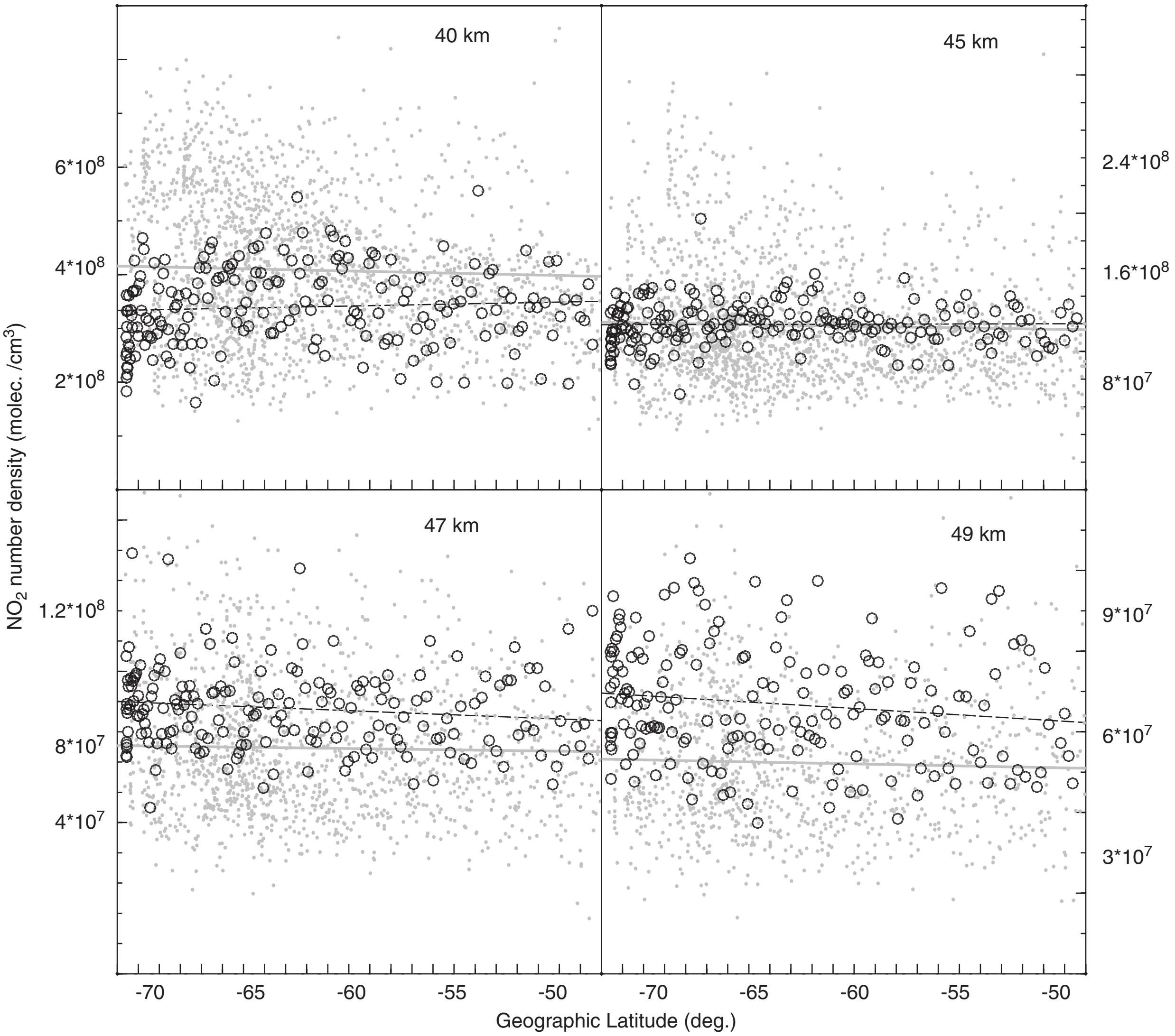

Fig. 8. January NO_2 data from 1990 to 2000 (dots) and the average trend (solid line) compared with the 2005 NO_2 data (circles) and average trend (dashed line). Data refer to 40, 45, 47 and 49 km and are plotted as function of the geographic latitude of SAGE II.

Weather storm of January 2005 (see Figs. 1 and 2). They are

(i) the O_3 modulation at five high-latitude Southern sites for several days (Fig. 3);
(ii) a short-term (<12 h) O_3 depletion (Fig. 4) in the lower mesosphere and upper stratosphere during 20 January at ~54°S–142°/118°E (Fig. 5), following the peak of the solar particle flux;
(iii) a short-term (<12 h) O_3 depletion (Fig. 6) in the lower mesosphere and upper stratosphere during 17 January at ~64°S–22°/41°E (Fig. 7), following the peak of the solar particle flux;
(iv) a moderate increase in the NO_2 density at ~50 km in the geographic latitudinal range −50°/−70° (Fig. 8) after the GLE event.

We believe that these preliminary results, integrated by the analysis of data from other satellites, will bring us to a better comprehension of ozone variability induced by outstanding solar activity periods. We conclude for this Space Weather storm period that the ozone layer at the edge of the polar cap was also affected at least by the solar particle arrival in the terrestrial environment.

Acknowledgements

Work partly supported by the PNRA (National Antarctic Research Program) of Italy in the frame of Science for Solar-Terrestrial Relations. Thanks are due to the PIs of the different experiments from which we have taken the data and the corresponding international Data Centers and Services. Particular thanks are due to the NASA Langley Research Center (NASA-LaRC) and Langley Radiation and Aerosols Branch. The Chile/Italy Collaboration via INACH and PNRA supports LARC neutron monitor. Work also performed inside COST 724 Action.

References

Crutzen, P.J., 1971. Ozone production rates in an oxygen-hydrogen-nitrogen oxide atmosphere. Journal of Geophysical Research 76 (30), 7311–7327.

Jackman, C.H., McPeters, R.D., 2004. The effect of solar proton events on ozone and other constituents. In: Pap, J.M., Fox, P. (Eds.), Solar Variability and its Effects on Climate. AGU, Washington DC, Geophysical Monograph Series, vol. 141, pp. 305–319.

Jackman, C.H., McPeters, R.D., Labow, G.J., Fleming, E.L., Praderas, C.J., Russell, J.M., 2001. Northern Hemisphere atmospheric effects due to the July 2000 solar proton event. Geophysical Research Letters 28 (15), 2883–2886.

Jackman, C.H., DeLand, M.T., Labow, G.J., Fleming, E.L., Weisenstein, D.K., Ko, M.K.W., Sinnhuber, M., Anderson, J., Russell, J.M., 2005. Neutral atmospheric influences of the solar proton events in October–November 2005. Journal of Geophysical Research 110, A09S27.

Krivolutsky, A.A., 2003. History of cosmic ray influence on ozone layer-key steps. Advances in Space Research 31 (9), 2127–2138.

Krivolutsky, A.A., Kuminov, A., Vyushkova, T., 2005. Ionization of the atmosphere caused by solar protons and its influence on ozonosphere of the Earth during 1994–2003. Journal of Atmospheric and Solar-Terrestrial Physics 67, 105–117.

Lary, D.J., 1997. Catalytic destruction of stratospheric ozone. Journal of Geophysical Research 102 (D17), 21515–21526.

Laštovička, J., Križan, P., 2005. Geomagnetic storms, Forbush decreases of cosmic rays and total ozone at northern higher middle latitudes. Journal of Atmospheric and Solar-Terrestrial Physics 67, 119–124.

Laštovička, J., Krizan, P., Kudela, K., 2003. Cosmic rays and total ozone at higher middle latitudes. Advances in Space Research 31 (9), 2139–2144.

López-Puertas, M., Funke, B., Gil-López, S., von Clarmann, T., Stiller, G.P., Höpfner, M., Kellmann, S., Fischer, H., Jackman, C.H., 2005a. Observation of NO_x enhancement and ozone depletion in the Northern and Southern Hemispheres after the October–November 2003 solar proton events. Journal of Geophysical Research 110, A09S43.

López-Puertas, M., Funke, B., Gil-López, S., von Clarmann, T., Stiller, G.P., Höpfner, M., Kellmann, S., Mengistu Tsidu, G., Fischer, H., Jackman, C.H., 2005b. HNO_3, N_2O_5, and $ClONO_2$ enhancements after the October–November 2003 solar proton events. Journal of Geophysical Research 110, A09S44.

Randall, C.E., Harvey, V.L., Manney, G.L., Orsolini, Y., Codrescu, M., Sioris, C., Brohede, S., Haley, C.S., Gordley, L.L., Zawodny, J.M., Russel III., J.M., 2005. Stratopheric effects of energetic particle precipitation in 2003–2004. Geophysical Research Letters 32, L05802.

Rohen, G., von Savigny, C., Sinnhuber, M., Llewellyn, E.J., Kaiser, J.W., Jackman, C.H., Kallenrode, M.-B., Schröter, J., Eichmann, K.-U., Bovensmann, H., Burrows, J.P., 2005. Ozone depletion during the solar proton events of October/November 2003 as seen by SCIAMACHY. Journal of Geophysical Research 110, A09S39.

Seppälä, A., Verronen, P.T., Kyrölä, E., Hassinen, S., Backman, L., Hauchecorne, A., Bertaux, J.L., Fussen, D., 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.

Storini, M., 2001. Geomagnetic storm effects on the Earth's ozone layer. Advances in Space Research 27 (12), 1965–1974.