Variations in cutoff latitude during the January 2012 solar proton event and implication for the distribution of particle energy deposition

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[1] Protons in the energy range 1–20 MeV deposit most of their energy in the middle atmosphere (60–100 km). Knowledge of their magnetic latitudinal and local time distribution is crucial for determining their effect on the chemistry and dynamics in the atmosphere. Using POES 16–19 and METOP02 satellites, we investigate the latitudinal cutoff boundaries and the energy deposition during the January 2012 solar proton event. The dayside cutoff latitudes show high correlation with the *Dst* index even when *Dst* turns positive, leading to an abrupt poleward movement of more than 5°. In the same time interval, the nightside cutoff latitudes move equatorward resulting in vastly asymmetric energy deposition into the atmosphere on the dayside and nightside. The differences are sustained for almost a day in the middle atmosphere at 65° corrected geomagnetic latitude. These features cannot be taken into account by applying the frequently used GOES particle data.
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1. Introduction

[2] Today, it is well established that energetic particle precipitation (EPP) can influence the middle atmospheric chemistry and dynamics at high latitudes and midlatitudes. In particular, solar protons events (SPEs) has been found to produce large amounts of chemically reactive nitrogen and hydrogen species, which reduce the ozone concentration and alter the radiative balance [e.g., *Sinnhuber et al*., 2012, and references therein]. This alters the latitudinal temperature gradients and perturbs the dynamics of the middle and upper atmosphere and may change the vertical energy transfer throughout the lower atmosphere [e.g., *Gray et al*., 2010].

[3] The access of solar protons into the Earth's magnetosphere is mainly controlled by the magnetospheric magnetic field [e.g., *Størmer*, 1955; *Smart and Shea*, 2001] and is limited in latitude by the particle cutoff energy. The geomagnetic field is influenced by the solar wind and the interplanetary magnetic field (IMF), being compressed at the dayside and stretched toward the magnetotail on the nightside. Hence, there is an asymmetry in the cutoff latitudes (CL) depending on magnetic local time (MLT). During geomagnetic storms, current systems such as the ring current also modify the geomagnetic field [e.g., *Leske et al*., 2001].

[4] The variation of CL has been the subject of both theoretical and experimental studies where the majority focuses on particle energies of tens of MeV [*Leske et al*., 2001, *Birch et al*., 2005]. However, protons with lower energies (< 20 MeV) reveal a more complicated dynamics with stronger day-night asymmetry, as well as stronger dawn-dusk asymmetries of CL [*Fanselow and Stone*, 1972; *Dmitriev et al*., 2010]. These protons will deposit most of their energy in the middle atmosphere (60–100 km altitude), and knowledge of their latitudinal and local time distribution is crucial for determining their potential effect on the middle atmospheric chemistry and dynamics.

[5] During an SPE event at 23–25 January 2012, POES 15–19, as well as METOP 02 were orbiting the Earth in polar, sun-synchronous orbits at around 850 km altitude with a period of approximately 100 min. The different spacecraft all carry the same particle detectors with the same nominal energy ranges. Combining measurements sorted into 1° latitude bins from the Medium Energy Proton and Electron Detector (MEPED), we cover the proton energy range: 30 keV–70 MeV. MEPED includes two proton solid-state telescopes that monitor the intensity of protons in six energy bands over the range 30–6900 keV and ≥6900 keV pointing 9° and 89° to the local vertical and will be referred to as the vertical and horizontal detector, respectively. Additionally, MEPED includes an omnidirectional detector system, which cover a wide range of angles: 0°–60° from the vertical, for protons with energies 16–70 MeV. At high latitudes, both the vertical detector and the omnidetector measure protons in the loss cone. Under the assumption of isotropic fluxes, we combine the two detector systems and obtain integral spectra by fitting monotonic piecewise cubic Hermite interpolating polynomials (PCHIP) [*Fritsch and Carlson*, 1980] to the measurements. The differential energy spectra were determined from the integral spectra. We define the cutoff location to be that invariant latitude where the count rate is half of its mean value above 70° CGM (Corrected GeoMagnetic) latitude in agreement with, e.g., *Leske et al.* [2001]. We investigate the cutoff dependence on the *Dst* (Disturbance storm time) index, solar wind pressure (P_{dyn}), and IMF orientation. The NOAA/POES satellites cover different MLT sectors and measure the energetic proton precipitation at all latitudes from equator to about 80°. This enables us to study how the geomagnetic cutoff energy varies with latitude in different local time sectors. Finally, we show for the first time how the cutoff variation affects

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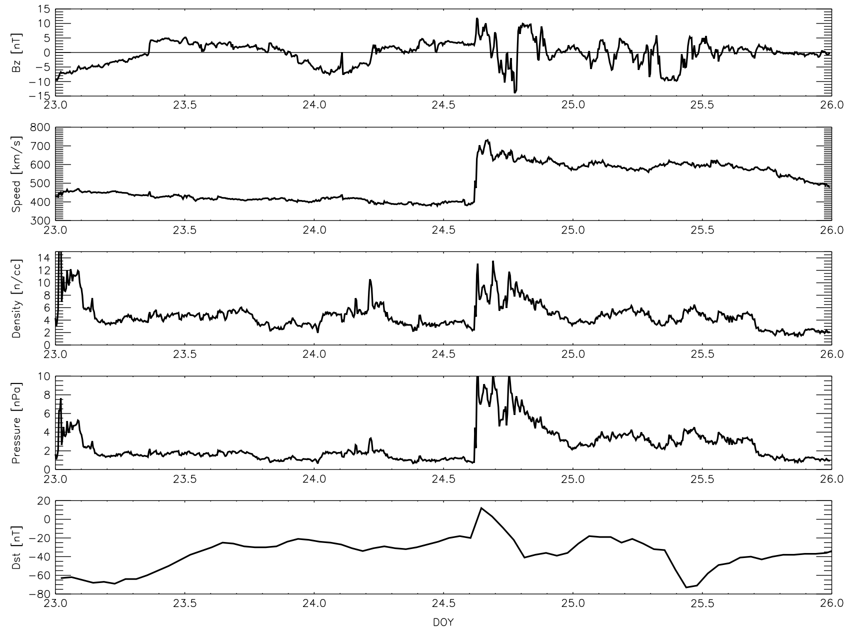

Figure 1. SPE event of 23–25 January 2012: The Bz component (GSM) of the interplanetary magnetic field solar wind velocity, density, and pressure based on measurement by the WIND satellite time shifted to the front of the magnetosphere (http://omniweb.gsfc.nasa.gov/) and *Dst* index (http://wdc.kugi.kyoto-u.ac.jp).

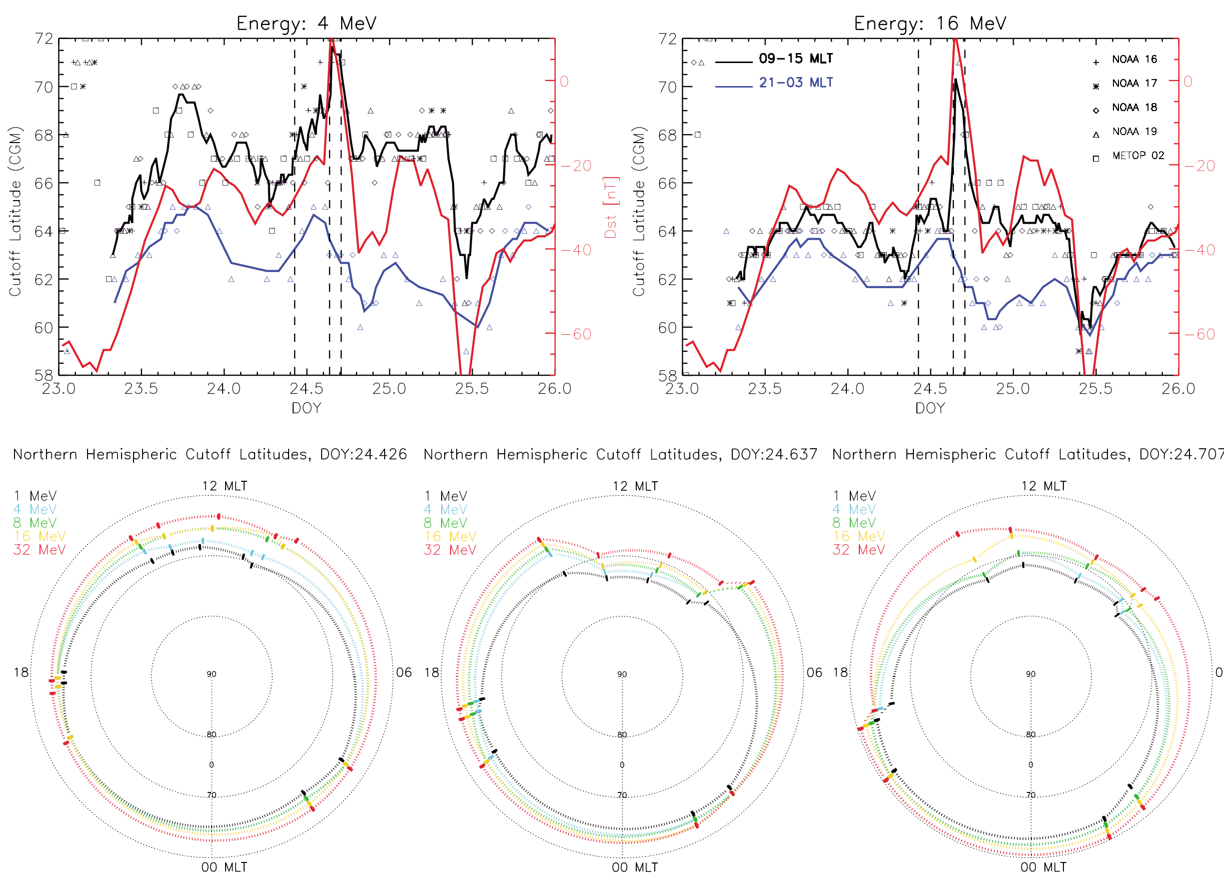

Figure 2. (top panels) Calculated cutoff latitudes on the dayside (09–15 MLT) (black symbols) and nightside (21–03 MLT) (blue symbols) for proton energies of 4 and 16 MeV as function of time on the 23–25 January 2012 based on particle measurement on NOAA/POES 16–19 and METOP02. The black and blue lines are based on a running average between the cutoff latitude points. The *Dst* variation are shown as a red solid line. (bottom panels) Maps of the cutoff latitude at selected times (marked as vertical dashed lines in the top panels) at the Northern Hemisphere for five different energies (1, 2, 8, 16, and 32 MeV) based on particle measurement on POES 16–19 and METOP02.

Table 1. Summary of *Dst*/Cutoff Correlation Based on the Data Shown in Figure 2 for the MLT Intervals 09–15 and 21–03

MLT	Regression Line 4 MeV	Sigma	Correlation Coefficient	Regression Line 16 MeV	Sigma	Correlation Coefficient
Day: 09–15	0.098 *Dst* + 70.1	±1.29	0.73	0.088 *Dst* + 66.6	±1.12	0.75
Night: 21–03	0.049 *Dst* + 64.4	±1.42	0.49	0.041 *Dst* + 63.1	±1.12	0.49

the EPP energy deposition in the middle atmosphere. We compare the result with the energy deposition derived from measurement by the geostationary satellites NOAA/GOES and discuss the implication it will have for studies concerned with EPP effects on the middle atmosphere chemistry and dynamics.

2. Cutoff Latitude Variations With Geomagnetic Activity and Local Time

[6] On 23 January 2012, a proton flare (type M8/long duration) occurred on the Sun (28°N, 36°W), peaking at 03:59 UT. A coronal mass ejection (CME) was observed at 04:00 UT. Within the terrestrial magnetosphere, the flux of energetic protons began to increase at 04:50 UT on 23 January (day of year (DOY) 23.2) and peaked at 15:30 UT on 24 January (DOY 24.6). This was only a moderate geomagnetic storm ($Dst \geq -73$ nT) possibly due to the CME delivering only a glancing blow to the Earth. The interplanetary magnetic field *Bz* component, solar wind velocity, density, and pressure are shown in Figure 1 along with the *Dst* index.

[7] The *Dst* index is also shown in the upper panel in Figure 2 together with the measured CL on the dayside (09–15 MLT) and nightside (21–03 MLT) for proton energies of 4 and 16 MeV during the January 2012 SPE event. In general, there is a clear difference between the dayside and nightside CL. The difference is, as expected, more pronounced for the 4 MeV protons compared to the 16 MeV protons, which have their maximum ionization at ~75 and ~60 km, respectively. Variations of the cutoff location clearly show similarity with variation in *Dst*. The correlation between *Dst* and CL is 0.73 and 0.75 for 4 and 16 MeV, respectively, on the dayside (see Table 1). This is consistent with the correlation factors found by *Leske et al.* [2001] and somewhat less than the correlation found by *Birch et al.* [2005]. However, the nightside CL shows a correlation with the *Dst* of ~0.5 for both 4 and 16 MeV. In particular, the correlation is poor when the *Dst* turns positive. The dayside cutoff follows the increase of the *Dst* and moves to higher latitudes while the nightside cutoff moves to lower latitudes.

[8] The day-night asymmetry is also evident in the lower panel in Figure 2 showing maps of the CL at selected times (marked as vertical lines in the upper panel in Figure 2). The left map is representative for the general cutoff distribution in the Northern Hemisphere throughout the storm. The dayside cutoff for particles of 1–16 MeV is located at higher latitudes compared to the nightside. The nightside CL for the different energies also show smaller latitude variation compared to the dayside consistent with, e.g., *Dmitriev et al.* [2010].

[9] In Figure 2, the middle map coincides with the time interval when *Dst* turns from negative to positive values as shown in the upper panel. The dayside cutoffs are abruptly pushed poleward at all energies (1–30 MeV) in the late morning to noon sector. Even at the highest energies, the cutoff is moved northward by approximately ~5°. A short time later this sector has been widened to include both the afternoon and the early morning sector (06–18 MLT) shown in the right upper map. On the evening-nightside, we have the opposite effect. The CL are pushed to lower latitudes at all energies. However, the latitude shift is smaller compared to the dayside with only a couple of degrees latitude, from about 64° to 61° CGM latitude for 4 MeV protons.

[10] In summary, there are periods in time where the *Dst* index alone is not a sufficient indicator of the cutoff variation. The opposite day-night response indicates that the ring current is not the dominating cause for the dayside cutoff latitude variation. Figure 1 shows an increase in P_{dyn} and *Bz* getting abruptly more positive coinciding with the poleward push of the dayside CL. However, the response of geomagnetic shielding to changes in solar wind conditions is not fully understood. P_{dyn} is found to cause both an increase and a decrease in cutoff, with an increase more likely near noon local time [*Kress et al.*, 2010, and references therein]. *Birch et al.* [2005] found a similar period of strong day-night asymmetry and a poleward push of the dayside CL during the September 2001 SPE. The dayside CL followed the increase of the *Dst*, while the CL at local times 0300 and 1800 attained their lowest value. Also, this period in time coincided with both a strong increase in $P_{dyn}$and *Bz* here oscillating between positive and negative values. Although, *Birch et al.* [2005]

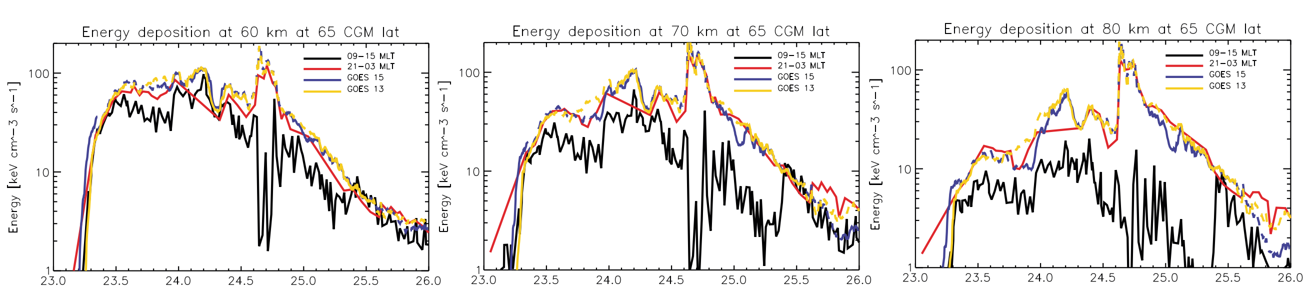

Figure 3. Estimated energy deposition at three different altitudes (60, 70, and 80 km) based on POES satellites (16–19) and METOP02 for two MLT sectors (09–15 MLT and 21–03 MLT) at 65° CGM latitude in the Northern Hemisphere, as well as estimated energy deposition based on GOES 13 and 15. (The dashed parts of the GOES 13 and 15 lines mark the satellites located in the nightside MLT region).

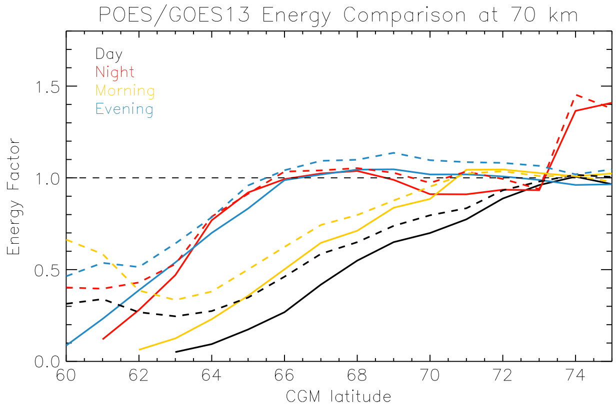

Figure 4. The estimated energy deposition ratio between the POES satellites (16–19) and METOP02 and GOES 13 for four MLT sectors at 60°–75° CGM latitude in the Northern Hemisphere. The solid lines are based on the vertical detector and the dashed lines are based on the horizontal detector.

did not speculate on the cause of this behavior, the orientation of the *Bz* field together with the arrival of CME appears to be common features coinciding with the strong poleward push of the dayside CL.

3. Asymmetric Energy Deposition

[11] The storm time variation of CL and the associated asymmetries will have consequences for the distribution of the particle energy deposition and its subsequent effects on the chemistry and dynamics in the middle atmosphere. Figure 3 shows the estimated energy deposition based on POES satellites (16–19) and METOP02 measurements for two MLT sectors (09–15 and 21–03 MLT) at 65° CGM latitude in the Northern Hemisphere, as well as the energy deposition based on the GOES 13 and 15 measurements. The energy deposition height profile for protons is calculated based on range energy of protons in air given by *Cook et al.* [1953] for $E < 300$ keV and by *Bethe and Ashkin* [1953] for 300 keV $< E <$ 500 MeV. The atmospheric densities are retrieved from the MSIS-E-90 model Hedin [1991]. The same procedure is used for the geostationary satellites GOES 13 (75°W) and GOES 15 (135°W) using proton PCHIP-fitted integral spectra based on measured proton fluxes in the energy range 1–100 MeV. We have assumed that the proton fluxes are isotropic over the downward hemisphere.

[12] In the beginning of the event, there is little difference between day and night considering the energy deposition at and above 60 km at 65° CGM latitudes. However, at DOY 24.6, the nightside experiences maximum energy deposition, while the dayside energy deposition drops by a factor of more than 10 at and above 60 km. The discrepancy between day and night is substantial for almost a whole day after the arrival of the CME. In other words, when the flux of energetic protons peaks during the storm in the terrestrial magnetosphere, dayside latitudes of 65° CGM experience little or no particle energy deposition throughout the whole mesosphere.

[13] Comparing the energy deposition derived from POES measurements and GOES measurements, there is a better agreement on the nightside than on the dayside. GOES 13 and 15 fail to observe the particle reduction associated with the poleward push of dayside CL and provide a large overestimation of the particle energy deposition at 65° CGM latitudes. This is interesting since several models aiming to estimate EPP effects on the atmosphere use GOES satellite measurements assuming uniform energy deposition above a fixed nominal boundary [e.g., *Jackman et al.*, 2005; *Krivolutsky et al.*, 2005; *Verronen et al.*, 2002]. This assumption does not hold for SPEs, in particular events where we have an increase in the dayside cutoff. The relative differences between the estimated energy deposition at 70 km from the POES and GOES 13 measurements for a period of 24 h starting at noon on the 24 January are shown in Figure 4. We have given the ratio for both the vertical and horizontal detector as the assumption of isotropy fails below ~68° CGM latitude. Although the fluxes measured by the horizontal detector are mirroring particles which will not precipitate in the atmosphere, it can be an estimate of the maximum energy deposition possible assuming isotropy at this flux level. The vertical detector gives the minimum energy deposition possible based on POES measurements. The true value of the energy deposition ratio is somewhere in between the solid (vertical detector) and dashed (horizontal detector) line. On the dayside, at and below 67° CGM latitude, the assumption of uniform energy deposition will give an overestimate of the particle energy deposition by 50–100% in the main phase of the January 2012 event. The total energy input over the hemispheres at 70 km will be overestimated by ~20–30% for ≥ 60° CGM latitude. Considering that the components studied by the models, such as ozone depletion, are subject to nonlinear processes triggered by the particle energy input, the error in the model products may be significantly larger than the error in the energy input. Also, the ionization rates from the AIMOS (Atmospheric Ionization Module Osnabrück) model [*Wissing and Kallenrode*, 2009] frequently used in different atmospheric models [e.g., *Funke et al.*, 2011] may introduce errors in respect to the varying CL. Often, only two satellites, POES 15 and 16, are used to determine an empirical polar cap from 9 MeV protons estimated from the scanning electron microscope detectors in geographical latitude-longitude grid. These satellites will not cover the dayside and will therefore overlook the day-night asymmetry of the cutoff boundaries. Within the polar cap, proton measurement from only one of the geostationary GOES satellites is used to estimate the fluxes.

[14] The errors caused by using geostationary satellites to monitor the particle input are also critical for ground based (GB) studies or in combination with satellites measuring atmospheric components such as HO_X and NO_X gases. Depending on the MLT difference between GOES and the GB station or the other satellite below 70° CGM latitude, the actual ionization caused by energetic particles could be only a fraction of what is predicted from GOES measurement, or the other way around. Above 70° CGM latitude, Figure 4 also reveals that there can be a large variation in the particle precipitation within the polar caps.

4. Conclusion

[15] In many models and experimental studies of effects of energetic solar particles on the middle atmosphere, one uses only particle measurements from GOES spacecraft. However, the highly variable CL during geomagnetic activity is a potential source of errors. Particularly critical are periods in time

when the magnetic shielding is dominated by different processes on the dayside and on the nightside, which appears to be the case with the arrival of CME together with northward turning of the IMF. A good parameterization of the particle ionization impact requires a global view of particle precipitation to cover temporal and spatial variation. Combining the different POES and METOP satellites provides a much more realistic picture of the actual energy deposition into the middle atmosphere throughout a SPE. The POES and METOP satellites also give information of particle flux variations within the polar cap.

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