**Thermosphere variation at different altitudes over the northern polar cap during
magnetic storms**

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Abstract

In this study, we report observations and simulation results of heated neutrals at various altitudes inside the polar cap during two magnetic storms in January 2005. The Poynting flux measurements from the Defense Meteorological Satellite Program (DMSP) satellites show enhanced energy input in the polar cap during the storm main phase, which is underestimated in the TIE-GCM simulation. Neutral temperature measurements at 250 km from the ground-based Fabry-Perot Interferometer (FPI) at Resolute Bay are presented, along with the neutral density observations at 360 km and 470 km from Challenging Minisatellite Payload (CHAMP) and the Gravity Recovery and Climate Experiment (GRACE) satellites, respectively. These data have been analyzed to demonstrate the altitudinal dependence of neutral response to the storm energy input. By comparing the TIE-GCM simulation results and the observations, we demonstrate that Poynting fluxes as well as the thermosphere response were underestimated in the model. The simulated neutral temperature at Resolute Bay increases by approximately 260° and 280° K for the two events, respectively, much lower than the observed temperature enhancements of 750° and 900° K. Neutral density enhancements with more than 30% increase over the background density were also observed at polar latitudes, with no clear distinction between the auroral zone and polar cap. All measurements indicate enhancements at high latitudes poleward of 80° magnetic latitude (MLAT) implying that substantial heating can occur within the polar cap during storms.

1. Introduction

The geomagnetic field lines in the polar cap are directly connected to the interplanetary magnetic field (IMF); therefore, the momentum and energy of the solar wind have direct access to Earth's upper atmosphere in this region. The solar wind interacts with Earth's magnetic fields and deposits its energy into the coupled magnetosphere-ionosphere-thermosphere (MIT) system via Poynting flux and particle precipitation. Previous studies of magnetic storms have shown clear enhancement of ionization due to low-energy precipitating electrons at F-region altitudes throughout the open field line region with a peak enhancement in the cusp [Huang et al., 2014b]. Additionally, a significant amount of energy input in the form of Poynting flux was found to occur at polar latitudes [Crowley et al., 2010; Knipp et al., 2011]. Huang et al. [2015] reported that dynamic and intense Poynting fluxes larger than 20 mW/m^2 enter the polar cap at all local times during magnetic storms based on measurements obtained from Defense Meteorological Satellite Program (DMSP) satellites.

The geomagnetic energy deposited into the MIT system has substantial impact on the plasma and neutral heating of the upper atmosphere, for example, the majority of Poynting flux is dissipated as Joule heating of ions and neutrals. Huang et al. [2014a] investigated the energy budget of the thermosphere for the storm which occurred on 5-6 August 2011, and concluded that the majority of energy required to heat the thermosphere must enter the system at polar latitudes. Similar conclusions were made by an independent study of solar wind energy dissipation in the ionosphere [Hajra et al., 2014]. The thermospheric density enhancement in the cusp has been observed by the

CHALLENGING Mini-Satellite Payload (CHAMP) satellite [Lühr et al., 2004; Rentz and Lühr, 2008; Lühr and Marker, 2013], which is typically 20% above the background density at 400 km. By examining simulation results particularly in the cusp region, various studies [Zhang et al., 2012; Deng et al., 2013; Sheng et al., 2015] have reported significant contributions of Poynting flux and particle precipitation on the neutral density in the cusp.

Strong neutral enhancements at latitudes poleward of the auroral zone are not expected to occur due to little energetic particle precipitation as well as small conductivity in this region [Cowley, 1993; Baumjohann and Treumann, 2012]. Moreover, no clear density enhancement poleward of the dayside cusp was demonstrated from previous TIE-GCM simulations [Kwak et al., 2010; Zhang et al., 2012]. However, by analyzing all storms occurring between 2002 and 2005 with the D_{st} index below -100 nT, spikes of anomalous high neutral densities were measured by the CHAMP satellite at latitudes poleward of 78° MLAT [Liu et al., 2010]. These density enhancements distributed across the polar cap do not correlate with the IMF conditions and show little relation to the field-aligned currents (FACs). Therefore, they are distinct from the cusp events reported by Lühr et al. [2004].

Because the heating within the polar cap can have a profound impact on the thermospheric circulation and ionospheric response to the geomagnetic storm, it is important to understand how the thermosphere reacts to the solar wind energy input. Past observations were based on spaceborne instruments on CHAMP or Gravity Recovery and

Climate Experiment (GRACE) satellites, which sampled at relatively high altitudes of about 400 to 500 km. In this paper, we combine the satellite observations with neutral measurements at 250 km by the ground-based Fabry-Perot interferometer (FPI) at Resolute, Canada [Wu et al., 2004; Won et al. 2003], which provides neutral measurements at 250 km altitude. These combined observations better characterize the spatial and temporal variation of the polar thermosphere during storms, and are used to evaluate the GCM performance.

In this paper, we will illustrate the spatial and temporal distribution of magnetospheric energy input over the polar region based on DMSP Poynting fluxes, and analyze independent measurements of neutral temperature and density over the polar cap to demonstrate a fast response of neutrals during two magnetic storms that occurred in January 2005. The neutral temperature and wind data at 250 km were obtained from the ground-based FPI at Resolute Bay. The neutral densities measured by the CHAMP and GRACE satellites were normalized to 360 and 470 km altitude (see details in Section 5), respectively, using the NRLMSISE2000 model (MSISE00) [Picone et al., 2002]. Observations at different altitudes make it possible to demonstrate the altitudinal dependence of neutral response at polar latitudes. The paper is organized as follows. The data and model are described in Section 2. Then the observations are discussed in connection with the solar and geomagnetic conditions in Section 3. Finally, we summarize our findings in Section 4.

2. Data and model description

The instrumentation and the simulation are described in this section with a detailed methodology of data analysis for each dataset.

2.1 Poynting flux observed by DMSP satellites

DMSP carries a suite of particle and field sensors that make comprehensive measurements of the ionospheric state. We utilize the observations from DMSP F13, 15 and 16 in this study. They fly in circular, sun-synchronous polar orbits at approximately 840 km. Each of these spacecraft carries: (1) a magnetometer which obtains magnetic field perturbations $\delta\mathbf{B}$ as the difference between measured and International Geomagnetic Reference Field (IGRF) vectors, (2) an ion drift meter (IDM) that provides cross-track velocities in the horizontal (V_z in spacecraft-centered coordinates) and vertical directions (V_x), (3) a retarding potential analyzer (RPA) that provides plasma densities, ion and electron temperatures and the fractions of heavy/light ions, and (4) energetic particle spectrometers that measure fluxes of precipitating ions and electrons. In this study, only the drift velocities considered of good quality (IDM and RPA quality flags equal to 1 or 2) were selected. The drift velocities in the ram direction are excluded in our study due to its uncertainties.

Poynting flux is calculated by combining the velocity and magnetic field measurements as described below: The IGRF magnetic fields and the cross-track velocities in the horizontal and vertical directions measured by the IDM are used to calculate the electric fields, with the in-track velocity component ignored. The magnetic field perturbations $\delta\mathbf{B}$ are given by the difference between the vector magnetic field measured by the onboard magnetometer and the IGRF vectors [Huang and Burke, 2004;

Knipp et al., 2011; Huang et al., 2014a]. We use a coordinate system centered on the spacecraft, with X directed towards the center of the Earth, Y pointing in the direction of the spacecraft orbit, and Z given by the vector product of X and Y. The in-track velocity component (V_y) is ignored and thus the downward-directed Poynting flux is estimated as

$$S_x = (V_x \cdot B_z - V_z \cdot B_x) \delta B_z - (-V_x \cdot B_y) \delta B_y$$

In this coordinate system X is positive downward and S_x corresponds to energy input to the IT system.

2.2 Neutral temperature and wind measurements from FPI at Resolute Bay

Resolute Bay, Canada, is located deep inside the polar cap at geographic 74.73°N, -94.89°E. The FPI at Resolute Bay has been operated since 2003 by the High Altitude Observatory (HAO) of the National Center for Atmospheric Research (NCAR). The Altitude Adjusted Corrected GeoMagnetic (AACGM) coordinates of Resolute Bay were 83.10° MLAT, -38.94° magnetic longitude (MLON) and 0 UT corresponded to 16.19 magnetic local time (MLT) at 250 km in 2005. The optical specifications of this FPI have been described by Wu et al. [2004].

In this paper, we utilize the 630 nm wavelength emission data (red line emission of atomic oxygen) with a typical height of the emission peak in the range of 210 to 300 km altitude. The spectral analyses of 630 nm emission line from O (¹D) contain information on the temperature and wind profiles along the line-of-sight where the emission occurs. It is assumed that the observations are heavily weighted to the emission peak at 250 km, so that the measurements can be assigned uniquely to this altitude [McCormac et al.,

1987]. The integration time of these emissions is 5 minutes. The FPI measures the temperature through determining the Doppler width of the O (¹D) emission line. The observations are made during the winters in the northern hemispheres (from September to April), and we demonstrate the results during two storms in January 2005 with good data quality. The FPI measures thermospheric neutral winds by monitoring wind-induced Doppler shifts in the airglow emission and the error depends on the airglow intensity. Because the data coverage is strongly affected by the cloud, we only utilize the wind observation when the cloud coverage is less than 50%.

2.3 Neutral density measured by CHAMP and GRACE satellites

Neutral densities from the CHAMP satellite were measured by the Space Three-axis Accelerometer for Research mission (STAR) accelerometer [Bruinsma *et al.*, 2004; Sutton, 2009]. The GRACE satellite measured densities from the superSTAR accelerometers based on the techniques described in Sutton *et al.* [2005] and Sutton [2009] with a precision an order of magnitude greater than the CHAMP/STAR instrument. During our period of interest in January 2005, the CHAMP satellite was in a 360 × 400 km orbit, while GRACE was in a 460 × 500 km orbit. For the purpose of our study, the density data were averaged in bins of 3° latitude, i.e., approximately 45 seconds of data for each bin. Moreover, neutral density measurements were normalized to a constant altitude of 360 km for CHAMP and 470 km for GRACE using the MSISE00 model. The density measured at the satellite location is scaled to a fixed height using the ratio of model densities at these two different altitudes from MSISE00.

2.4 TIE-GCM

The NCAR TIE-GCM is a first-principles, three-dimensional, non-linear representation of the coupled thermosphere and ionosphere system. It solves the momentum, energy and continuity equations for neutral and ion species in pressure coordinates [Roble et al., 1988], with a self-consistent calculation of ionospheric wind dynamo effects [Richmond et al., 1992]. In this study, the TIE-GCM (version 1.94) is run with a $5^\circ \times 5^\circ \times$ half scale height spatial resolution (longitude $\times$ latitude $\times$ vertical) and 5-minute temporal resolution for the two moderate storms in January 2005. The Weimer [2005] model is used to provide the high-latitude electric field. The auroral particle precipitation effects are specified using the Roble and Ridley [1987] method for given distributions of precipitating energy fluxes using the parameterizations of Emery et al. [2012]. In addition, the precipitation in the cusp region is specified with a characteristic energy of 100 eV and that of polar rain is specified with a characteristic energy of 500 eV. A uniform polar rain energy flux of $0.05 \text{ ergs/cm}^2/\text{s}$ is used over the polar cap. We compare the simulated results of TIE-GCM to the Poynting flux measurements from DMSP satellites and the neutral temperatures from ground-based FPI at Resolute Bay.

3. Results and Discussions

The solar wind conditions and geomagnetic activity indices during the two storms in January 2005 are used to define the time interval of storm main phases. The observation and simulation results are also presented in this section.

3.1 Solar wind condition and geomagnetic variation

The temporal variations of IMF B_y and B_z components, dynamic pressure of solar wind and SYM-H index are shown in Figure 1 for the first storm event from January 6 to 9 (left) and the second storm from January 20 to 23 (right), respectively. Solar wind data gaps are seen in the right panels for the second event. The maximum solar wind pressure of the second event (~ 100 nPa) is much higher than that of the first storm (~ 30 nPa). For both events, moderate geomagnetic variations have been observed with minimum SYM-H index of -112 nT and -101 nT, respectively. The storm onset for each storm is defined as the time of maximum SYM-H index, and the main phase lasts until the SYM-H index reaches its minimum value. The storm onset occurred at 09:27 UT on January 7 and 17:23 UT on January 21, respectively.

3.2 Poynting flux enhancement during storms

The high-latitude Poynting flux measured by DMSP satellites is investigated to show the magnetospheric energy input into the IT system during magnetic storms. The top row of Figure 2 depicts the high-latitude Poynting flux measured along DMSP satellite paths during the main phases of the first (09:27 UT on January 7~ 00:05 UT on January 8) and the second storm (17:23 UT on January 21~ 06:04 UT on January 22). Enhanced Poynting flux is observed at high latitudes poleward of the auroral zones as well as in the auroral zones. The corresponding TIE-GCM simulation results of Poynting flux along DMSP satellite tracks are depicted in the middle row. It should be noted that the contribution from the ram direction were excluded due to the uncertainties in the ion drift velocity. Since the orientations of F15 and F16 are about 9-21 local time, the projection of the anti-sunward ion drift to the satellites' orbit direction might have a significant

component resulting in underestimation of Poynting flux. With this possible underestimation, the DMSP observation of Poynting flux shown in Figure 2 are still larger than those from TIE-GCM simulations.

3.3 Neutral temperature and wind change at Resolute Bay

The ground-based FPI at Resolute Bay (Geographic 74.73°N, -94.89°E) was located deep inside the polar cap at 83.10° MLAT in January 2005. Figure 3 depicts the neutral temperature, neutral meridional wind and zonal wind at around 250 km measured by Resolute Bay FPI during the two moderate storms in January 2005. We only show the data with error below 50%. Data gaps occurred around local noon (from ~ 8 to 15 LT) in both cases when the instrument was turned off to avoid sunlight during high solar zenith angles [Wu et al., 2004]. The temperature errors were less than 30° K for the duration of the first storm, and for the majority of the second event, as indicated by the vertical error bars in the top panels of Figure 3. The wind errors were on the order of a few m s⁻¹. Since the temperatures were not calibrated, the absolute values may not be reliable. However, the temperature differences between pre-storm condition and during the storm demonstrate the true temperature changes. During the main phase of the first storm, the neutral temperature at 250 km increased by about 750° K with observed enhancements in the horizontal component of neutral wind (shown in the bottom two panels on the left). For the second storm event, a similar temperature increase of around 900° K was detected, but the change in the wind measurements was uncertain due to the data gaps.

The results from TIE-GCM simulation are illustrated by red lines in Figure 3. The horizontal neutral winds predicted by TIE-GCM were comparable to FPI measurements, but there are large discrepancies in temperature between measurements and model simulations. The simulated neutral temperatures are shifted up by 200° K (dashed lines in the top row of Figure 3) in order to roughly match the observed temperatures during the quiet interval before the first storm, which clearly demonstrates the underestimation of temperature enhancement in TIE-GCM. The simulated neutral temperature increases by about 260° and 280° K for the two events, respectively, much lower than the observed temperature changes (750° and 900° K). This implies that not enough neutral heating was predicted in the model. The neutral temperature was obtained through solving the thermodynamic equation in TIE-GCM. Besides the loss due to cooling, the neutral temperature is determined by heat transfer due to the vertical heat conduction, eddy diffusion and horizontal advection vertical winds, heating from solar radiation, Joule heating, chemical heating and molecular diffusion. There can be several explanations for the smaller thermosphere perturbations in the polar cap from the simulation. One possibility is not enough magnetospheric energy input in the polar cap region based on the empirical Weimer model. As illustrated in Figure 2, intense Poynting fluxes were detected from DMSP satellite measurements in the polar cap during the two storms, while little Poynting flux was produced from the model simulation, especially near the location of Resolute Bay at around 83° MLAT. As discussed by Huang et al. [2015], the empirical models tend to smooth out intense Poynting fluxes inside polar cap leading to insufficient neutral heating in the GCM simulations. In addition, under the hydrostatic equilibrium assumption in TIEGCM, the vertical wind is estimated by integrating the divergence of

the horizontal winds vertically, which is typically underestimated [Deng et al., 2008]. Moreover, the simple assumption of soft particle precipitation in the polar cap could be another possibility for the lack of heating in the model. The polar rain with characteristic energy of 500 eV and energy flux of $0.05 \text{ ergs/cm}^2/\text{s}$ were assumed in the TIE-GCM simulation, but the DMSP electron measurements showed that the energy and energy flux were not uniform in the polar cap and differed from the simple values assumed in the model.

3.4 Neutral density peaks at polar region

Storm-related neutral density maxima in the cusp and polar cap have been reported by Lühr et al. [2004] and Liu et al. [2010]. In this study, the neutral densities measured by CHAMP and GRACE have been investigated to show the occurrence of local density peaks during storm events. First, the neutral density measurements from CHAMP and GRACE were scaled to a constant altitude using MSISE00: 360 km for CHAMP and 470 km for GRACE. A 23-minute moving window, about 90° in latitude, was used to calculate the running mean of the neutral densities. The density perturbations were then calculated as the differences between the original data and mean values and were found to peak at high latitudes in both hemispheres. Finally, a threshold of 30% was applied to the density perturbations in order to indicate significant density perturbations. GRACE density measurements were also analyzed in a similar fashion to obtain the local maxima at 470 km.

297 The local maxima of density perturbations at 360 km (CHAMP measurements) and
298 470 km (GRACE measurements) during 24-hour interval for the storm event occurred on
299 January 7, 2005 were marked by red plus signs in the top panels of Figure 4. Blue lines
300 represent the magnetic latitudes of CHAMP in the AACGM coordinates system and the
301 vertical red line indicates the onset of the main phase. The locations of these peaks over
302 the northern hemisphere in AACGM are shown in the bottom panels of Figure 4. The
303 geomagnetic locations of Resolute Bay during this time interval are denoted by the
304 connected black dots inside 80° MLAT. Similar results are shown in Figure 5 for the
305 event on January 21, 2005. At both 360 km and 470 km, neutral density enhancements
306 were observed at locations poleward of 80° MLAT, suggesting energy dissipation and
307 transfer to neutrals at very high magnetic latitudes during storms. Although the minimum
308 values of the SYMH index were similar for these two events, the thermospheric response
309 was stronger for the second event at various altitudes as shown in Figures 3, 4 and 5 due
310 to the fact that the solar wind pressure enhancement is much larger during the second
311 event.

312
313 In summary, the temporal variations of magnetospheric energy input and neutral
314 properties at different altitudes for two storms in January 2005 are depicted in Figure 6.
315 The top row of Figure 6 shows the along-track integrated Poynting flux (ATIP) for each
316 DMSP path above 50° MLAT in the northern hemisphere. The dashed vertical line
317 marks the time of the storm onset. Clear ATIP enhancements were seen during both
318 storms with maximum values above 100 kW/m. There is a good correlation between the
319 temporal variation of ATIP and the solar wind dynamic pressure shown in the 3rd row of

Figure 1. Although the solar wind dynamic pressure of the second storm was much larger than that of the first storm, both events caused similar SYM-H decrease, as well as similar magnitude of ATIP maxima. The neutral densities observed by GRACE and CHAMP at 470 km and 360 km, respectively, are depicted in the 2nd and 3rd rows of Figure 6. The thermospheric neutral temperature variations at 250 km measured by FPI at Resolute Bay are demonstrated in the bottom row. The neutrals enhancements at all altitudes were observed as soon as the dentation of increasing ATIPs, indicating a quick and strong vertical ion-neutral coupling in the polar cap region. Hence, we conclude that the energy deposition and dissipation are substantial in the polar cap and the model improvement is essential to capture the strong heating at high magnetic latitudes.

4. Conclusion

In this study, we have analyzed various neutral measurements at different altitudes over the polar cap region for the two magnetic storm events in January 2005, including the neutral temperature at 250 km, the neutral density at 360 km and 470 km, as well as the Poynting flux observed by DMSP satellites. The results show clear Poynting flux enhancements in the polar cap while enhancements from all the neutral measurements were observed at high latitudes poleward of 80° MLAT suggesting that substantial heating was supplied to the polar cap during storms. Our analysis demonstrates the large altitudinal range of heating in the polar cap during storm events for the first time.

The simulation of TIE-GCM shows less energy input in the polar cap than the observation. The comparison of neutral temperature enhancements at Resolute Bay between FPI measurement and TIE-GCM simulation shows a consistent underestimation

of the neutral temperature in the model results. The simulated temperature increases by about 260° and 280° K for the two storm events, respectively, which are much smaller than the observed changes (750° and 900° K). This might result from the underestimation of Joule heating at high latitudes in the model as discussed in Huang et al. [2015]. Our results will be further confirmed by additional systematic and statistical studies regarding the atmospheric response at polar latitudes.

Acknowledgements

The authors wish to thank Dr. Marc Hairston for providing the SSIES data of DMSP satellite, and Dr. Eric Sutton for providing the neutral density data from CHAMP and GRACE satellites. The OMNI data used in this study are available at the OMNIWeb interface (<http://omniweb.gsfc.nasa.gov>). This research was supported by Air Force Office of Scientific Research through award FA9550-14-1-0280 and LRIR 14RV11COR. NCAR is supported by the National Science Foundation. The Resolute FPI observation and research effort are supported by NSF grant AGS1339918 and NASA grant NNX14AF93G.

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Figure 1. Temporal variation of IMF By component (first row), Bz component (second row), solar wind dynamic pressure (third row) and SYM-H index (bottom row) for the storm events on January 7, 2005 (left column) and January 21, 2005 (right column). The two dashed vertical lines in each panel denote the storm onset time and ending time of main phase.

YEAR: 2005 DAY: 006 (January 6) main phase

YEAR: 2005 DAY: 020 (January 20) main phase

YEAR: 2005 DAY: 006 (January 6) main phase

YEAR: 2005 DAY: 020 (January 20) main phase

Figure 2. Poynting flux measured along the trajectories of DMSP F13, F15 and F16 over the northern hemisphere during the two storms in January 2005. Top row: distribution of the Poynting flux along the tracks during the main phases. Data from successive crossings of the polar cap have been overplotted with the maximum values plotted last, i.e. on top of lower values. Bottom row: similar to the top row, but for the Poynting flux from TIE-GCM simulation.

Figure 3. Comparison of neutral temperature and winds between Resolute Bay FPI measurements (black diamonds with vertical error bars) and TIE-GCM simulation outputs (red curves) for the two storms on January 7 (left column) and January 21, 2005 (right column). The neutral temperature, meridional wind and zonal wind are plotted from top to bottom. The red dashed lines in the top row represent the simulated neutral temperature shifted up by 200 K. The vertical lines indicate the time for each storm onset.

Figure 4. Neutral mass density (g/cm^3) peaks over the northern hemisphere measured by CHAMP and GRACE for the storm event on January 7, 2005. The two uppermost line plots show the temporal variation of neutral densities measured by CHAMP and GRACE. CHAMP densities are normalized to 360 km altitude, while GRACE densities are normalized to 470 km altitude. The density peaks are illustrated by red plus signs. Blue lines illustrate the magnetic latitudes of CHAMP in AACGM coordinates. The vertical red line indicates the onset of the main phase. The locations of these peaks in the AACGM coordinate system are shown in the bottom row for CHAMP (left) and GRACE (right), respectively. The gray dots denote satellite trajectories. The connected black dots indicate the location of Resolute Bay during the time interval shown in the top two panels.

Figure 5. Neutral density measurements for the second storm on January 21, 2005. The plot format is the same as that in Figure 4.

Figure 6. Temporal variations of magnetospheric energy input and neutrals at different altitudes for two storms in January 2005. Top row: Along-Track Integrated Poynting flux (ATIP) in the high latitude regions over 50° MLAT observed by DMSP satellites. Second row: neutral density at 470 km measured by

518 GRACE. Third row: density at 360 km measured by CHAMP. Bottom row: neutral temperature at 250 km
519 measured by FPI at Resolute Bay. The dashed vertical lines indicate the onsets of storm main phases.
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