Responses of Lower Thermospheric Temperature to the 2013 St. Patrick’s Day Geomagnetic Storm

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Abstract The altitude- and latitude-dependent responses of neutral temperature in the lower thermosphere to the 2013 St. Patrick’s Day geomagnetic storm have been studied using neutral temperature measurements from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard the TIMED satellite and the Solar Occultation For Ice Experiment (SOFIE) instrument onboard the AIM satellite. Both SABER and SOFIE observations revealed that both temperature increase (having peaks of ~15–25 K) and decrease (having peak of ~15 K), which were associated with the storm, occurred in the two hemispheres. The magnitudes of temperature variations changed with latitude, altitude, and the phase of the storm. The peaks of the temperature increase occurred 0.5–1.5 days later than the peak of the AE index, depending on latitude and height. Global circulation changes initiated due to heating and ion drag in the auroral region are likely responsible for the temperature increases or decreases in the lower thermosphere.

Plain Language Summary Geomagnetic storms play important roles in changing the lower thermospheric state through the storm time changes of global wind circulation and the associated heat transfer. There were both either warming or cooling of the temperature in the lower thermosphere responding to storms. Using the neutral temperature measurements from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard the TIMED satellite and the Solar Occultation For Ice Experiment (SOFIE) instrument onboard the AIM satellite, we show that both temperature increase and decrease occurred in two hemispheres and are related to the phase of the storm. Global circulation changes initiated by heating and ion drag in the auroral region are likely responsible for the temperature increases or decreases in the lower thermosphere.

1. Introduction

During geomagnetic storms, the motion of charged particles by enhanced convective electric fields causes Joule heating. Joule heating can change the structure and chemistry of the ionosphere, thermosphere, and even as low as of the mesosphere in the auroral oval (Banks, 1979; Roble et al., 1987). Moreover, Joule heating and precipitating particles as well as ion drag, which are of maximum over the auroral oval during storms, can disturb the upper thermosphere even at low to middle latitudes through the storm time changes of global wind circulation and the associated heat transfer (e.g., Biondi & Meriwether, 1985; Burns et al., 1995; Killeen et al., 1995; Wang et al., 2008).

The storm effects on the neutral temperature in the lower thermosphere have been explored through theoretical calculations and observations. Based on the measurements from the Alaska incoherent scatter radar and from the Dynamic Explorer 2 satellite, theoretical calculations revealed that the Joule heating rate depended on altitude and was in the range of 1–20 K/day in the mesosphere and lower thermosphere at high latitudes (Banks, 1979; Roble et al., 1987).

However, some contradictory results on the responses of temperature in the lower thermosphere to geomagnetic storms have been obtained from observations. By analyzing the nocturnal temperature data measured...
by a Fabry-Perot interferometer at 23°S, Fagundes et al. (1996) found that the nighttime temperature in the mesosphere was unaffected by storms. Using the temperature measured by the Microwave Limb Sounder instrument onboard the Aura satellite, von Savigny et al. (2007) showed a warming at 85 km and 70°–80°S during the solar proton events (SPEs) on January 2005. Note that strong SPEs are usually associated with geomagnetic storms. By analyzing the temperature data derived from a meteor radar at Andenes (69°N), Pancheva et al. (2007) found a significant cooling (~25 K) at ~90 km during storms in late October 2003. By analyzing temperature data from the ALOMAR Na lidar (69°N) during the SPEs on January 2005, Nesse Tyssøy et al. (2008) found that the mean temperature above 90 km was warmer than the monthly mean temperature and this warming could be due to particle precipitation and Joule heating. Nesse Tyssøy et al. (2008) noted that the temperature variation below 90 km was dominated by atmospheric waves and was not related to the SPEs. Subsequently, Nesse Tyssøy et al. (2010) performed a statistical study on the temperature measured by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite during both May/June and October/November 2003. They found that particle precipitation enhanced the temperature above 100 km but cannot modify the temperature below 100 km. More recently, by analyzing the nighttime temperature measured by a sodium lidar at Fort Collins, Colorado (41°N), and then transferred to Logan, Utah (42°N), Yuan et al. (2015) presented a significant warming above 95 km (as much as 55 K at 105 km) during the peaks of the four coronal mass ejection-induced geomagnetic storms.

The above observations illustrated the different responses of the temperature in the lower thermosphere to storms. This indicated that the latitude dependence and altitude dependence of temperature changes during geomagnetic storms are not well characterized and understood, especially for the altitude below 100 km and in latitude regions outside the auroral oval. During the 2013 St. Patrick’s Day (17 March) geomagnetic storm (Verkhoglyadova et al., 2016; Zhang et al., 2017), the temperature measured by the SABER instrument onboard the TIMED satellite and the Solar Occultation For Ice Experiment (SOFIE) instrument onboard the Aeronomy for Ice in the Mesosphere (AIM) satellite provides a good opportunity to study the latitude and altitude dependence of temperature changes during geomagnetic storms, which will be the main subject of this paper.

2. Description of Data Sets

2.1. SABER Temperature Data

The SABER instrument (Russell et al., 1999) onboard the TIMED satellite has measured temperature and several trace species profiles from ~20 to ~110 km since the January of 2002. The latitude coverage shifts between 53°N–83°S and 83°N–53°S due to the yaw cycle of ~60 days of the TIMED satellite. The temperature measurement bias of SABER (V2.0, Level 2A) is about ±5 K in the upper mesosphere and lower thermosphere (Remsberg et al., 2008).

Since we focus on the storm time temperature changes relative to the quiet time, we show in Figure 1 the actual data for the Northern Hemisphere (NH) and the Southern Hemisphere (SH) measured by the SABER instrument on the quiet day of 15 March and the storm day of 17 March. Due to the yaw cycle of the TIMED satellite, the latitude ranges shown in Figure 1 are 35°N–50°N (left column) and 35°S–80°S (right column), respectively. Figure 1 illustrates the zonal variations of temperature, which are likely caused by the tides during both the quiet and storm days. From Figure 1 we can see that the temperature during the storm day was generally larger than that during the quiet day.

Since the temperature changes seen in Figure 1 could be caused by both the tides and the storm, it is difficult to quantify the temperature changes caused by the storm. Consequently, we should remove the temperature changes caused by tides as much as possible and then focus on the temperature changes caused by the storm. Here the zonal running mean was performed on the actual temperature data to remove tides and small-scale waves (Liu et al., 2014, 2016, 2017; Xu et al., 2014). The zonal running mean is performed as follows. We first rearranged the temperature profiles in each latitude bin in an increasing order with time. Second, the zonal running mean temperature was obtained by averaging these temperature profiles within a window of one universal time (UT) day in this latitude band. Finally, we dropped the first profile in the series and added the next one after the last profile in the series to get a second zonal mean and so on. During geomagnetic storms, predominantly at high latitudes, some nonmigrating tides are significantly enhanced.
surpassing even the migrating tides. The nonmigrating tides were removed through the zonal mean process (Liu et al., 2016). However, the migrating tides could not be completely removed in this way due to the limited local time (LT) sampling. Previous studies have revealed that typical amplitudes of tides (both migrating and nonmigrating) are ~2–4 K at high latitudes (Lübken et al., 2011; Stevens et al., 2017). The amplitudes of migrating tides are much smaller than the peaks of the observed temperature enhancements (~15–25 K), which will be discussed in section 3. Consequently, these migrating tides do not affect our results. We use the zonal running means to examine temperature changes during a storm with the understanding that the true peaks of storm time temperature changes are underestimated to some degree due to the zonal running mean. Figure 2 shows the quiet time baselines and the storm time changes of the zonal running SABER temperature within a latitude bin of 5° in the height range of 94–110 km around 17 March 2013.

2.2. SOFIE Temperature Data

The SOFIE instrument onboard the AIM satellite began science observations on 14 May 2007 (Russell et al., 2009). SOFIE performs solar occultation measurements in 16 spectral bands that are used to retrieve vertical profiles of temperature and several other trace species (Gordley et al., 2009). Each day SOFIE provides 15 spacecraft sunset (near local sunrise) measurements in the latitude range of 65°S–85°S and 15 spacecraft sunrise (near local sunset) measurements in the latitude range of 65°N–85°N (Gordley et al., 2009; Marshall et al., 2011). The SOFIE temperature (V1.3, Level 2) is in the height range of 10–102 km with a warm bias of 10–15 K in the Arctic summer and of 20–50 K in the Antarctic summer above 88 km (Stevens et al., 2012).
Figure 3 shows geographic and geomagnetic latitudes of SOFIE sampling latitudes (Figures 3a and 3c) and quiet time baselines and the storm time changes of the zonal running mean temperature (Figures 3b and 3d) in the NH and SH. Here the geomagnetic latitudes of SOFIE sampling calculated from the geographic latitudes through the altitude-adjusted corrected geomagnetic (AACGM) software (Shepherd, 2014).

3. Temperature Around the 2013 St. Patrick’s Day Geomagnetic Storm

A number of studies have aimed to address different aspects of the geospace system response to the St. Patrick’s Day (mid of March) storms in 2012, 2013, and 2015. These events provide great opportunities to understand the responses of the ionosphere and thermosphere, as well as their coupling, to geomagnetic storms (Zhang et al., 2017). Detailed interplanetary conditions and auroral activity for the 2013 St. Patrick’s Day geomagnetic storm can be found in Figure 4 of Verkhoglyadova et al. (2016).

3.1. Altitude and Latitude Responses of SABER Temperature

During the strong storm on 17 March, the peak of the temperature increases in the NH (the left column of Figure 2) was larger than 15 K above 100 km over the range 50°N to 35°N. Although temperature increases during 17–18 March had similar patterns over the range 50°N to 35°N, their peak decreased from ~25 to...
~15 K with decreasing latitudes and the peaks occurred on 17 March and early on 18 March. On the other hand, at 80°S, the peak of the temperature increase was larger than ~10 K on 18 March. At other SH latitudes, the peak of the temperature enhancement was on 17 March and early on 18 March. In a similar manner as that in the NH, the temperature increases also extended from 80°S to 35°S. Among the four representative latitude bands in the SH, the most prominent temperature increase had a peak of ~30 K and extended downward to about 96 km at 80°S. In addition, the time of this peak occurred earlier at higher height than that at lower height.

During the following two weak storms on 27 and 30 March, from Figure 2a, we can see that at 50°N there was evident temperature increase above 100 km on 27 and 30 March. The temperature increase at 45°N occurred in the height range of 98–108 km from 29 March to 1 April. At 80°S and 65°S, there was temperature increase above 100 km from 29 to 31 March (Figures 2b and 2d). The temperature increase might be induced by the geomagnetic activity on 27 and 30 March. We note that the temperature structure below about 97 km is not well correlated to the AE index and might be induced by the dynamic processes in the mesosphere.

Besides the temperature increase following AE peaks, there was also temperature decrease on 18 March above 102 km and at 35°N and 35°S–80°S. The temperature decrease followed the temperature increase. The prominent cooling occurred at 80°S and 35°N/S. This will be further discussed in section 4.

From Figure 2, we can see that the peak of the temperature increase occurred later than that of the AE index. The time delay, which is defined as the time difference between the peaks of the zonal running mean temperature change relative to that of the daily running mean AE index, depends on height and latitude. To show the time delay and its LT, altitude dependency more clearly, we show in Figure 4 the temporal variations of AE, the sampling LT of SABER measurements, and the zonal running mean temperatures at 110 and 105 km, respectively. Figures 4e–4h show the zonal running mean temperatures within a window of one UT day and sampled for all measurements (03–07 LT in the NH and 01–09 LT in the SH, black), and sampled before (03–05 LT in the NH and 01–04 LT in the SH, green) and after (05–07 LT in the NH and 06–09 LT in the SH, red) 05 LT, respectively. The SABER sampling was mainly at around dawn in the NH (Figure 4c). In the SH the SABER sampling was at predawn and postdawn (Figure 4d). About 05 LT is used as a separation time since it separates the predawn (before 05 LT) and postdawn (before 05 LT). This is because Joule heating and ion-neutral coupling reduce the magnitudes of horizontal winds significantly in the dawn sector (Burns et al., 1995; Wang et al., 2008).

The daily running mean AE reached its peak at around 12 UT of 17 March. At 50°N the zonal running mean temperatures sampled for all measurements reached their peaks shortly after 00 UT of 18 March at the heights of both 110 and 105 km (black lines in Figures 4e and 4g). The time delay is about 0.5 day at 110 km and 105 km. At the latitudes of 45°N–35°N, the time delay is also about 0.5 day, which can be
judged by comparing the peak of the temperature increase shown in the left column of Figure 2. At 80°S the running mean temperatures at 110 km (105 km) sampled for all measurements reached their peaks at 04 UT (10 UT) of 18 March. Thus, the time delays are about 0.7 day at 110 km and about 1 day at 105 km. However, by comparing the peak of the temperature increase shown in the right column of Figure 2, the time delays vary with latitude greatly (e.g., ~0.5 day at 65°S, almost 0.0 day at 50°S and 35°S).

As for the LT dependency of the time delay shown in Figure 4, the peak of the temperature increase is about 1–2 hr earlier for the data before 05 LT than that after 05 LT in the NH. In the SH, there is no obvious time delay between the data before and after 05 LT at 110 km. In the SH at 105 km, the temperature enhancement is about 1–2 hr earlier for the data before 05 LT than that after 05 LT.

### 3.2. Altitude Responses of SOFIE Temperature

Figures 3a and 3c show that the geographic latitudes of SOFIE sampling were at around 86°N and 75°S during the period of 17 March geomagnetic storm. In contrast, the geomagnetic latitudes of the SOFIE sampling ranged from 81°N–87°N and 60°S–88°S. Thus, SOFIE data were inside the polar cap in the NH but were more widespread in the SH. These data covered both the polar cap and the auroral oval. By comparing the changes of zonal running mean temperature and the daily running mean AE index shown in Figures 3b and 3d, we can find a possible correlation of temperature changes with the geomagnetic activities occurring on 17, 21, 27, and 30 March. A general feature is that the vertical structures of temperature changes are similar in the NH and SH; however, the timing is quite different between the NH and SH. These differences might be due to the different geomagnetic latitude coverage of SOFIE in the NH and SH and will be discussed below.

For temporal variations of the temperature changes, above 98 km and in both hemispheres, the peaks of the temperature increase were about 10–25 K during 18–19 March. Especially in the NH, there were also temperature increases with peaks on 22, 28, and 31 March (Figure 3b), following well the temporal pattern of the daily running mean AE index with some time delay. For the altitude variations of the temperature increases, their peaks increased with increasing height (e.g., ~15 K at 94 km, ~20 K at 96 and 98 km, and ~25 K at 102 km)
during 18–19 March in the NH. For the time delay of the peaks of the zonal running mean temperature increase relative to the daily running mean AE peaks, it increased with decreasing height and varied from about 1 day above 100 km to about 1.5 days at 96 km. This indicated that the peak of the temperature occurred at a later time with decreasing altitude. The time delay of temperature increase measured by SOFIE was longer than that measured by SABER at 50°N.

In contrast to the NH, the peak of the temperature increase measured by SOFIE in the SH was about 15 K above 98 km but was not obvious below 96 km during 18–19 March (Figure 3d). This is consistent with the peak of the temperature increase (~15 K) measured by SABER on 18 March at 80°S (Figure 2b). The similar geomagnetic latitudes and LT sampled by the SOFIE and SABER instruments might be responsible for the similar changes in temperature seen by the two instruments. By comparing the time delay of the temperature increase measured by both SABER and SOFIE, we find that the time delay is longer inside the polar cap than that in the auroral oval region (e.g., SABER measurements at 80°S and SOFIE measurements in both hemispheres). To fully illustrate the physical mechanism behind this, physical based model study should be performed, such as the National Center for Atmospheric Research Thermosphere Ionosphere Mesosphere Electrodyamics general circulation model (TIME-GCM).

Similar to the temperature decrease measured by SABER at 35°N and 35°S–80°S, there was also a temperature decrease seen by SOFIE on 17 March. Moreover, the temperature decrease measured by SOFIE reached its peak during the storm main phase and before the temperature increase. The peak of the temperature decrease occurred at relatively lower altitudes and at a later time with decreasing altitude. This was similar to the SABER observations in the polar region of the SH that a slight temperature decrease also occurred during the storm main phase and before the warming (Figure 2b). Thus, there were both heating and cooling at different latitudes associated with the storm on 17 March.

4. Discussions

The time delay of 0.5–1 day in the NH does not agree with the lidar observations at around 41°N–42°N by Yuan et al. (2015), who showed that the peak of the temperature increase just occurred when the geomagnetic storm reached its maximum. The disagreement might be the nighttime mean temperature used by Yuan et al. (2015) and the lidar location, which is near the equatorward edge of the auroral oval. The nighttime mean temperature could not remove the diurnal tides and could not resolve the time delay of 0.5 day. In contrast, our zonal running mean result removed nonmigrating tides and retained the temporal variations. To test the uncertainty of the time delay introduced by the zonal running mean, we performed a running mean in a same manner as in Figure 4 but used a window of 6 hr. The diurnal tidal signal was clear (not shown here) and peaked at around 12 UT on 17 and 18 March above 102 km. In contrast, the zonal running mean within a window of one UT day results peaked at around 00 UT (shown in Figure 3). Thus, the peak of zonal running mean temperature increase is not caused by tides but mainly associated with auroral heating and storm time changes in global circulation.

During storms, auroral electron and proton precipitation can heat the neutral air directly through collisions. They can also affect Joule heating and ion drag because particle precipitation increases ionospheric conductivity by enhancing ionization, as Joule heating and ion drag are proportional to ionospheric conductivity, which peaks at the height of about 130 km. Joule heating is the strongest in the auroral oval where electric fields are the largest. The magnitude of heating rate is about 1–20 K/day in the mesosphere and lower thermosphere at high latitudes (Banks, 1979; Roble et al., 1987). Although storm time enhancements in Joule heating and ion drag are limited to the auroral oval, its effects on the changes of circulation are global in the upper thermosphere during storms and have been studied through observations and model simulations (Burns et al., 1995; Killeen et al., 1995; Wang et al., 2008).

The thermal balance in the thermosphere is maintained by the combination of adiabatic expansion and compression, nonlinear heat convection, downward heat conduction, Joule heating, and radiative cooling from nitric oxide (NO) and CO₂ in the thermosphere (Killeen et al., 1995; Mlynczak et al., 2005). Joule heating and ion-neutral coupling reduce the magnitudes of horizontal winds, especially in the dawn and the dusk sectors in the low to middle latitudes (Burns et al., 1995; Wang et al., 2008). The changes of the horizontal winds could transport heat through nonlinear heat convection from high latitudes to middle latitudes. This increases the temperature wherein. In addition, the changes of the horizontal winds induce convergence...
and divergence and cause further the changes of vertical winds. The downward and upward vertical winds cause compressional heating and expansion cooling, respectively. Since the net changes of vertical wind were downward (Burns et al., 1995), there were temperature increases observed by both SABER and SOFIE. However, there were also upward vertical winds in the afternoon and evening and NO enhancement, which could extend from high to middle and low latitudes during storms (Burns et al., 1995; Zhang et al., 2014). This is likely the cause of the temperature decreases observed by both SABER and SOFIE. The exact mechanisms, which are responsible for the storm time temperature changes, will be explored through first principles numerical simulations (e.g., TIM-GE-M) in our research.

5. Conclusions

The temperatures measured by both SABER and SOFIE were used to study the effects of the 2013 St. Patrick’s Day (17 March) geomagnetic storm on the altitude- and latitude-dependent responses of neutral temperature in the lower thermosphere region. In particular, we studied the responses of temperature on a global scale. The main results of this study are as follows: (1) The temperature increases measured by both SABER and SOFIE extended downward to a height below 100 km in both hemispheres. (2) The peaks of the temperature increases varied from ~15 to ~30 K with increasing latitudes and altitudes. (3) The time delays of the peaks of the temperature increases relative to that of AE index varied from 0.5 to 1.5 days, which were dependent on latitudes and altitudes. (4) There were temperature decreases observed by both SABER and SOFIE. The temperature decrease measured by SABER occurred several days after the storm main phase. The temperature decrease measured by SOFIE occurred during the storm main phase inside the polar cap. (5) Changes in global circulation initiated by the storm time enhancement in heating and ion drag in the auroral region and the storm time NO enhancement are likely responsible for the temperature changes and the altitude and latitude dependencies of the time delays in the lower thermosphere.

References


