An observational and theoretical study of the longitudinal variation in neutral temperature induced by aurora heating in the lower thermosphere

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[1] In this paper, observations by thermosphere, ionosphere, mesosphere energetics and dynamics/Sounding of the Atmosphere using Broadband Emission Radiometry from 2002 to 2012 and by Envisat/Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) from 2008 to 2009 are used to study the longitudinal structure of temperature in the lower thermosphere. In order to remove the longitudinal structure induced by tides, diurnally averaged SABER temperatures are used. For MIPAS data, we use averaged temperatures between day and night. The satellite observations show that there are strong longitudinal variations in temperature in the high-latitude lower thermosphere that persist over all seasons. The peak of the diurnally averaged temperature in the lower thermosphere always occurs around the auroral zone. A clear asymmetry between the two hemispheres in the longitudinal temperature structure is observed, being more pronounced in the Southern than in the Northern Hemisphere. In both hemispheres, the longitudinal variation is dominated by the first harmonic in longitude. The total radiative cooling observed by SABER has a structure in longitude that is similar to that of temperature. Modeling simulations using the Thermosphere-Ionosphere-Electrodynamics General Circulation Model reproduce similar features of the longitudinal variations of temperature in the lower thermosphere. Comparison of two model runs with and without auroral heating confirms that auroral heating causes the observed longitudinal variations. The multiyear averaged vertical structures of temperature observed by the two satellite instruments indicate that the impact of auroral heating on the thermodynamics of the neutral atmosphere can penetrate down to about 105 km.


1. Introduction

[2] It is well known that the middle and upper atmosphere is affected by both the energy input of solar radiation from above and the energy and momentum fluxes of various waves from the lower atmosphere. In the high-latitude auroral regions, there are additional energy sources of auroral heating that include Joule heating and energetic particle heating. Joule heating, however, is the dominant auroral heating source. Knipp et al. [2004] showed that between 1975 and 2003 the averaged daily contribution to neutral heating from energetic particle precipitation is about one third of that from Joule heating.

[3] Xu et al. [2013] analyzed the thermospheric mass densities observed by the GRACE (Gravity Recovery and Climate Experiment) and CHAMP (Challenging Minisatellite Payload) satellites. They found that auroral heating can induce an enhancement of thermospheric mass density surrounding the magnetic poles that leads to variations of the diurnally averaged thermospheric density in geographical longitude that are not associated with atmospheric tides.

[4] In the polar region, the solar energy flux and the auroral heating are the primary energy sources of the atmosphere above 80 km [Thayer and Semeter, 2004]. Theoretical modeling studies show that auroral heating mainly contributes to the energy input at altitudes above the mesopause; it decreases sharply below about 100 km [Thayer and Semeter, 2004; Jee et al., 2008]. The depth over which auroral heating can affect...
the neutral atmospheric dynamics is an open question. It depends on many aspects of the interaction between the magnetosphere and the middle and upper atmosphere that are poorly understood due to the complexity and variability of solar and geomagnetic activity and the atmospheric response.

[5] The TIMED (thermosphere, ionosphere, mesosphere energetics and dynamics) satellite was launched on 7 December 2001 to explore the global structure of the dynamics and chemistry in the stratosphere, mesosphere, and lower thermosphere using remote sensing technology. SABER (Sounding of the Atmosphere using Broadband Emission Radiometry), one of the payloads on TIMED, measures CO2 radiation centered in the 15 μm band to retrieve the global temperature with high-vertical resolution from the lower stratosphere to the lower thermosphere [Russell et al., 1999; Rensberg et al., 2008].

[6] The European Space Agency’s Envisat (Environmental Satellite) was launched into a sun-synchronous polar orbit at about 800 km altitude in March 2002. MIPAS (the Michelson Interferometer for Passive Atmospheric Sounding), one of the instruments on Envisat, measures 5.3 μm NO emissions that enable the retrieval of the kinetic temperature from about 100 to 170 km [Funke et al., 2010; Bermejo-Pantaleón et al., 2011]. MIPAS passes each longitude twice per day, at around 10 and 22 LT (local time). There are 14.3 orbits per day with global coverage from pole to pole. During 2008–2009, MIPAS observations of lower thermospheric temperature were made approximately 1 out of every 10 days. In this study, the MIPAS temperatures during 2008–2009 are used.

[7] This work is motivated by results of a previous study [Xu et al., 2013] that used the GRACE and CHAMP satellites observations. That work showed that the diurnally averaged thermospheric mass density has strong longitudinal variations due to the auroral heating surrounding the magnetic poles. Diurnal averaging was performed to ensure that the longitudinal variations are not due to atmospheric tides [see Xu et al., 2013, Figure 2].

[8] The purpose of this paper is to investigate the longitudinal structure of the atmospheric temperature in the lower thermosphere using the SABER and MIPAS data. A pair of first-principle model simulations is also employed to elucidate the causal relationship between auroral heating and the observed longitudinal structures in the lower thermospheric temperature. The rest of the paper is organized as follows: Section 2 presents the data sets and the analysis method. The results are presented and discussed in section 3. Section 4 summarizes the findings of this study.

2. Data Sets and Analysis Methodology

[9] SABER and MIPAS observations provide an opportunity to investigate the temperature structure from the mesopause to the lower thermosphere (~170 km). The two data sets are analyzed separately.

[10] First, temperatures measured by SABER are used to analyze the longitudinal variation in the diurnally averaged temperature below 115 km. We use temperature profiles from Level 2, Version 1.07 of the published SABER data.

[11] The SABER temperature data are first sorted into overlapping latitude bins that are 10° wide with centers offset by 5° extending from 85°S to 85°N and into longitude bins that are 10° wide. Because the TIMED satellite orbit processes slowly, it takes more than 60 days to complete the full 24 h coverage in local time.

[12] The diurnally averaged temperature can be expressed as the combination of the zonal mean and the longitudinal variation of diurnally averaged temperature (ΔT(λ)) for each latitude bin as follows:

$$T(\lambda) = T_0 + \Delta T(\lambda).$$  

(1)

$$T(\lambda) = \frac{1}{2\pi} \int_0^{2\pi} T(\lambda,t) dt$$

is the diurnally averaged temperature and

$$T_0 = \frac{1}{2\pi} \int_0^{2\pi} T(\lambda,t) dt$$

is the zonal mean of the diurnally averaged temperature. t is local time (LT) in hour. The second term on the right-hand side of equation 1 is the longitudinal variation of diurnally averaged temperature, which can be expressed as

$$\Delta T(\lambda) = \sum_{i=1}^{8} A_i \cos[\lambda_i - \lambda],$$

(2)

where λ is the longitude (in radians), Ai and λi are the amplitude and phase (the longitude position of the temperature maximum) of the longitudinal variation of temperature. i = 1, 2, ..., 8 denotes the harmonics of the longitudinal variation. The diurnal averaging removes the longitudinal variations due to both migrating and nonmigrating tides. Least square fitting is used to extract all components in equation 2. This gives all of the harmonic components of the longitudinal variation of the diurnally averaged temperature.

[13] For the TIMED/SABER observations, high latitudes (poleward of 53°) are sampled for the periods of 60–65 days on alternate yaw cycles [Russell et al., 1999]; this is long enough to cover 24 h in local time. SABER looks northward for 60–65 day periods centered around the middle of February, June, and October and looks southward for 60–65 day periods centered around the middle of April, August, and December in each year since 2002. With the high-latitude data, we can investigate the longitudinal variation in the diurnally averaged temperature of both the Northern and Southern Hemispheres alternately every 2 months.

[14] In contrast to the SABER sampling from the slowly processing TIMED satellite orbit, MIPAS is on the sun-synchronous Envisat satellite and made observations only at about 10 and 22 LT at low and middle latitudes. Near the poles, the local times of ascending and descending parts of the orbit are closer together. Thus, it is not possible to calculate diurnal averages from the MIPAS data. Instead, we use the averaged temperature from these ascending and descending observations ($T(\lambda) = 0.5(T_{asc} + T_{dec})$) to replace the diurnally averaged temperature in equations 1 and 2. The analysis is as follows:

$$T(\lambda) = T_0 + \sum_{i=1}^{8} A_i \cos[\lambda_i - \lambda].$$

(3)

[15] Here $T_0 = \frac{1}{2\pi} \int_0^{2\pi} T(\lambda) d\lambda$ is the zonal mean of the averaged temperature between ascending and descending observations. Least square fitting is also used to extract all components of the longitudinal variations in equation 3. This approximation cannot completely remove aliasing from tides, especially semidiurnal tides, but it reduces the effect of tides on the results (mainly diurnal and terdiurnal tides).
Despite the possibility of aliasing by tides, the MIPAS observations are valuable since they give information about the global temperature between 100 km and 170 km, extending well beyond the altitude range of the SABER temperature.

3. Results and Discussion

3.1. Results Below 115 km Observed by SABER

[16] Global distributions of the diurnal average temperature were calculated for six individual months by using multiyear SABER observations from 2002 to 2012. We take the temperature at the altitude of 115 km as an example. Figure 1 gives the global distributions of the diurnally averaged temperature $T(\lambda)$ at 115 km (left column) and the longitudinal variation of the diurnally averaged temperature with the zonal mean removed ($\Delta T(\lambda)$) at the same heights (right column) in the Southern Hemisphere for April, August, and December. Figure 2 shows the same parameters in the Northern Hemisphere for February, June, and October. The white crosses in these figures indicate the locations of the south and north magnetic poles, which are located at (64°S, 140°E) and (81°N, 250°E), respectively. From the perturbation figures (Figures 1 and 2, right columns), we can see that there is a large longitudinal asymmetry in the diurnally averaged neutral temperature at high latitudes at 115 km in each hemisphere. The high-temperature and low-temperature regions are separated by approximately 180° in longitude. In the Southern Hemisphere, the warm region is around 100°–180°E, whereas that in the Northern Hemisphere occurs around 240°–300°E. In both hemispheres, the longitudes of the high-temperature regions are near the longitudes of the auroral zone centered around the magnetic poles (denoted by white crosses in the figures). The two figures show that, in addition to the latitudinal variation of the temperature, which varies with seasons, there are also very strong longitudinal variations in the temperature.

[17] The analysis of the thermospheric mass densities observed by the GRACE and CHAMP satellites reveals that the diurnally averaged thermospheric density has longitudinal variations due to the aurora heating surrounding the magnetic poles [see Xu et al. 2013, Figure 2]. A comparison between the GRACE and CHAMP thermospheric mass density observations and the TIMED/SABER lower thermospheric temperature observations indicates that their structures are very similar. Therefore, it suggests that auroral heating may also be responsible for the longitudinal structure of the temperature and that its impact can penetrate downward to the lower thermosphere.

[18] We use the least squares fitting to decompose all terms in equation 2 from February 2002 to July 2012. The perturbation is dominated by the contribution from the first harmonic ($i = 1$). The interannual variation of the diurnally averaged temperature in the lower thermosphere can therefore be represented by the amplitude and phase of the dominant component ($A_1$ and $\lambda_1$). Figure 3 gives the amplitudes and phases (the longitudes of the temperature maxima) of the $i = 1$ component of temperature at the altitudes of 100, 110, and 115 km and at the latitudes of 65°S and 65°N. From Figure 3a, we can see that the amplitudes at the altitudes of 115 km and 110 km at 65°S are very large during these years in all seasons; the amplitudes reach several tens of K. It is interesting that the phases at the altitudes of 115 and 110 km are quite invariant at about 140°E in all seasons and years, which means that the temperature maximum occurs near the longitude of the south magnetic pole at all times. At the altitude of 100 km, the amplitudes are smaller than those at altitudes above but nevertheless can reach 10 K in some seasons. The most obvious difference is that the phase at 100 km has very large seasonal and interannual variations. The inconsistency of the phase suggests that the drivers of the longitudinal temperature variations at 100 km are different from those above. Specifically, the phase variation suggests that auroral heating does not play a major role in determining the longitudinal variations of temperature at 100 km.

[19] Figure 3b indicates that many of the features of the amplitudes and phases at 65°N are similar to those at 65°S. In particular, the phases of $i = 1$ at 110 and 115 km are stable at 240°–300°E during more than 10 years but the phase at 100 km has large variations. The north magnetic pole is located at 81°N, 250°E. Thus, the high-temperature region is also near the longitude of the north magnetic pole. The stationary planetary waves (SPWs) studies by Xiao et al. [2009] and Mukhtarov et al. [2010] also show that the phases of SPWs are almost constant in the lower thermosphere. They suggested that auroral heating is the main cause of phase distribution of SPW in the lower thermosphere. Figures 1–3 thus give evidences that the temperatures at 110 and 115 km altitudes reach maxima near the magnetic poles. This supports the conclusion that auroral heating may be responsible for the longitudinal variation as in the thermospheric temperature, as was seen for density in Xu et al. [2013].

[20] Observational analysis and theoretical modeling results show that Joule heating can affect the atmosphere above 100 km in the high-latitude region [Brekke and Rino, 1978; Thayer and Semeter, 2004; Jee et al., 2008]. However, there have been no reports of observational analysis discussing the depth over which auroral heating influences the temperature of the neutral atmosphere. We calculate the averaged spectrum of the longitude variation in the diurnally averaged temperature from 2002 to 2012. Figures 4a and 4b show the amplitudes and phases (the longitudes of the temperature maxima) for each spectral component at the latitudes of 65°N and 65°S and at the altitude of 115 km. From these figures, we can see that the dominant longitudinal variation is the $i = 1$ structure. The phases of this component are near the longitudes of 135°E in the Southern Hemisphere and 260°E in the Northern Hemisphere; these are near the longitudes of the magnetic poles in the respective hemispheres. Figures 4c and 4d give the global distribution of the amplitude and phase of the $i = 1$ temperature perturbation. The multiyear average of the amplitude and phase of the longitudinal variation in temperature is interpreted as a signature of auroral heating. From this figure, it is evident that auroral heating affects the neutral atmosphere above 105 km in the high-latitude region poleward of 50°.

[21] Below about 100 km, the magnitude of the multiyear averaged longitude variation is less than 3 K. Furthermore, the phase is highly variable so the multiyear average cancels much of the signal. The small amplitude and variable phase of the perturbation below the mesopause are not consistent
with the interpretation of temperature signal caused by auroral heating. Other processes likely cause the temperature perturbations there. The analysis does not provide any evidence for a link between temperature and the longitude of the aurora below 100–105 km. In contrast, at the altitude of 115 km, the longitudinal variations reach 25 K in the Southern Hemisphere and 17 K in the Northern Hemisphere. With the very stable phase of the temperature maximum in each year and in each hemisphere, there is little cancelation of the amplitude of the longitudinal variation seen in individual seasons (see Figure 3).

[22] An asymmetry between the Southern and Northern Hemispheres is also evident in Figures 4a and 4c. The $i=1$ longitudinal variation in the Southern Hemisphere is much stronger than that in the Northern Hemisphere. The reasons for this are discussed in section 3.4.

Figure 1. (left column) The multiyear (February 2002 to July 2012) averaged distribution of the diurnally averaged temperature at the altitude of 115 km observed by TIMED/SABER in the Southern Hemisphere for April, August, and December. (right column) The longitudinal variation of the diurnally averaged temperature with the zonal mean removed. The white crosses indicate the position of the south magnetic pole.
3.2. Results Between 100 km and 170 km Observed by MIPAS

[23] Temperature profiles extending to a higher altitude than the SABER data can be derived from the MIPAS data using the NO 5.3 μm emission. The number of MIPAS observations is smaller because observations were made approximately 1 out of every 10 days. As a result, the data are noisier than those of SABER. In addition, data are available at only two local times; the precise times vary with latitude but do not change with season or year. To minimize the impact of these limitations and to bring out the temporal mean longitudinal structure, we calculate the 2 year (2008–2009) averaged distribution of the MIPAS temperature and its longitudinal variation (zonal mean removed) using temperature profiles from both the ascending and descending portions of the satellite orbit.

[24] The averaged spectra of the longitudinal variation in temperature derived from the MIPAS data from 2008 to 2009 are shown in Figure 5. Figures 5a–5d show the amplitudes (Figures 5a and 5c) and phases (Figures 5b and 5d) for the harmonic components at the latitudes of 65°N and 65°S and at the altitudes of 115 km and 160 km. From Figures 5a and 5c, we can see that the first harmonic, $i=1$, is the dominant component in the longitudinal variation of the temperature, which is similar to the SABER observations for 115 km shown in Figure 4a. The phases of the perturbation in Figures 5b and 5d are near the longitudes of

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**Figure 2.** The same as Figure 1, but for the Northern Hemisphere for February, June, and October. The white crosses indicate the positions of the north magnetic pole.

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150°E and 230°–310°E in the Southern and the Northern Hemispheres, respectively. As in the SABER results, the longitudes of the maximum temperature are also near the longitudes of the magnetic poles in the respective hemispheres.

[25] There is a difference in the spectra shown in Figures 5a and 5c with Figure 4a. In Figures 5a and 5c, the MIPAS amplitudes of higher harmonics \((i > 1)\) are stronger than the SABER ones in Figure 4a, although the \(i = 1\) amplitude is the dominant component in both figures. There is probably a substantial contribution from aliasing by tides since complete diurnal averaging cannot be performed for the MIPAS data. Also note that the local time difference between ascending and descending node observations becomes smaller near the poles. There are many fewer MIPAS observations (approximately 1 out of every 10 days for 2 years), so the impact of noise projecting onto the spectral decomposition is also higher. The differences in the results using SABER and MIPAS observations could also be due to sampling differences (different calendar years and different seasonal distribution of the profiles) or to instrumental or retrieval biases in one or both of the instruments.

[26] The global structures of the amplitude and phase of \(i = 1\) in MIPAS temperatures are shown in Figures 5e and 5f. The features of the amplitude and phase in the MIPAS temperature data are again similar to those of the SABER data. It is interesting that the phase distribution in Figure 5e is almost upright, especially from 100 km to 170 km in the high latitudes of the Southern Hemisphere; the phase is near 150°E, which is near the southern magnetic pole. The upright contour lines of phase indicate that there is little variation of the phase with altitude. Note, however, that there is some variation of phase with latitude. An asymmetry between the Southern and Northern Hemispheres is also evident in Figure 5e; this feature is again similar to that seen in the SABER observations shown in Figure 4c. Figure 5f shows that the structure of the phase in the north hemisphere is more complex than that in the south hemisphere. This is probably due to the relatively large contamination of aliasing by the tides in the north hemisphere, as the amplitude of the \(i = 1\) component in the north hemisphere is much weaker than that in the south hemisphere (see Figures 5a, 5c, and 5e).

[27] Figure 6 gives the results at the altitudes of 150 km in the Southern Hemisphere. From the top panels of the figure, we can see that the high temperature is near the south magnetic pole. However, the temperature distribution has various structures and variations with high zonal harmonics (see Figure 5a). In order to determine the dominant structure of the longitudinal variations in temperature, we reconstruct the temperature using equation 3, but with only the zonal mean and the first two components \((i = 1\) and \(i = 2\)) of the longitudinal variation. The bottom panels of Figure 6 give the results. The left is the reconstructed temperature \(T_0 + \sum_{i=1}^{2} A_i \cos[i(\lambda - \lambda_i)]\). The right is the longitudinal variation of the temperature with the zonal mean removed \(\sum_{i=1}^{2} A_i \cos[i(\lambda - \lambda_i)]\). The figure clearly shows the structure in which the warmer temperature is located near the magnetic pole.
Using the above reconstruction method, we give the results of 2 year averaged distributions of the temperature (left column) and the longitudinal variation of the temperature with zonal mean removed (right column) from the MIPAS data at 115 km, 140 km, and 160 km in Figures 7 and 8 for the Southern and Northern Hemispheres, respectively, in order to investigate the longitudinal variations of the temperature at different altitudes. In these two figures, the left columns are the polar view of the distributions of the temperature, reconstructed from the zonal mean and two lowest zonal harmonics, and the right columns are the same but with the zonal mean temperature removed.

From Figures 7 and 8, we can see that there is a region of high temperature at high latitudes in each hemisphere. In the Southern Hemisphere, the longitude of the temperature maximum is around 60–180°E. In the Northern Hemisphere, the longitude of the temperature maximum is around 210–330°E. As in the SABER data at 115 km, regions of warmer temperatures are located in the auroral zone centered near the magnetic poles in both hemispheres. Figures 7 and 8 show that the longitudes of the maxima of temperatures do not change with altitudes. This feature is also similar to the vertical structure of the thermospheric mass densities observed by the GRACE and CHAMP satellites. The orbits of CHAMP and GRACE are separated by 100 km in altitude, but the zonal structures of the mass density of the thermosphere from these two satellites are very similar [see Xu et al., 2013, Figures 2 and 3]. These results also support the conclusion that auroral heating is responsible for the zonal structure of the neutral temperature and that its impact can penetrate downward to the lower thermosphere.

### 3.3. Differences Between the SABER and MIPAS Temperatures

The comparison between Figures 4 and 5 below shows that there are differences in the amplitudes of the longitudinal variations in temperature between SABER and MIPAS observations, although the structures are similar. The most noticeable difference is that the MIPAS shows much smaller longitudinal variation of the temperature variance at the same altitude. For instance, at 115 km, SABER gives the amplitude $A_1$ at 65°S of about 25 K, whereas MIPAS gives only 8.4 K (see Figures 4a and 5a).

There are several factors that could contribute to the differences. (1) The MIPAS temperature is retrieved from the NO 5.3 μm emission while the SABER temperature is obtained from the CO$_2$ 15 μm emission. (2) The MIPAS observation mode is different from SABER; as a result, diurnal averaging cannot be performed and aliasing from tides, especially semidiurnal tides, cannot be removed. (3) The SABER results are multiyear averages from 2002 to
2012 but include only 6 months of observations from each year in the high-latitude region (poleward of 50°). The MIPAS results are the average from 2008 to 2009 but with only 1 day of observation out of every 10 days.

In addition to the possible reasons for the differences between the two data sets listed above, differences due to the uncertainties or systematic errors in the SABER and MIPAS temperature retrievals cannot be excluded. Atomic oxygen has a large effect on the retrieval of temperature from the CO$_2$ 15 μm emission. Atomic oxygen densities from the NRLMSIS-00 model are used for the SABER v1.07 temperature retrieval above 105 km because of the lack of simultaneous atomic oxygen measurements. Garcia-Comas et al. [2008] evaluated the errors in the SABER temperature retrieval due to the uncertainties in the quenching rates of CO$_2$ by N$_2$, O$_2$, and O. They found that the systematic errors in the retrieved temperatures above 100 km are large.

Christensen et al. [2013] compared temperatures derived from the O$_2$(0,0) emission spectrum observed by NIRS (the Near Infrared Spectrometer) of the Remote Atmospheric and Ionospheric Detection System aboard the International Space Station with the temperatures from the TIMED/SABER.

Figure 5. The 2 year averaged spectrum of the longitude variation in the MIPAS temperature from 2008 to 2009. (a–d) The zonal spectra of the amplitudes and phases at the geographical latitudes of 65°N and 65°S and at the altitudes of 115 km (Figures 5a and 5b) and 160 km (Figures 5c and 5c). (e and f) The global distribution of the temperature amplitude and phase of the $i = 1$ component (Figures 5e and 5f).
They found that the average SABER temperatures are warmer than the NIRS ones above 90 km. In contrast to SABER, MIPAS temperatures are rather insensitive to the atomic oxygen. However, MIPAS has a potential systematic bias in the retrieved temperature, especially during nighttime, that ranges between 20 K near 125 km and $-40$ K near 110 and 150 km in the low latitude [see Bermejo-Pantaleón et al., 2011, Figure 10]. These systematic errors in SABER and MIPAS would not significantly affect the longitudinal variations in temperature field, since they would be present at all longitudes. On the other hand, SABER has a good vertical resolution (~2 km), while MIPAS has a lower vertical resolution of ~10–20 km at about 105 km [see Bermejo-Pantaleón et al., 2011, Figure 3]. The different vertical resolutions might also be contributing to the different amplitudes in the longitudinal variations in SABER and MIPAS temperatures.

To further check the robustness of our results from the SABER and MIPAS retrieved neutral temperatures and to make use of the SABER measurements from a wider altitude range (above 115 km), here we examine the radiative cooling in the thermosphere measured by SABER. The cooling rates of CO$_2$ and NO depend directly on the exponential of temperature and on the densities of atomic oxygen and the emitting species (CO$_2$ or NO) [e.g., López-Puertas et al., 1992; López-Puertas and Taylor, 2001, p. 129]. The CO$_2$ radiative cooling is a good proxy for the latitudinal and longitudinal distributions of the temperature, although it is also affected by the uncertainties in the concentration of atomic oxygen and, to a lesser extent, carbon dioxide. Since NO varies in phase with temperature in the auroral region, longitudinal variations in the NO cooling will be in phase with those of temperature but may be even stronger.

In the thermosphere, CO$_2$ 15 μm and NO 5.3 μm infrared radiations are the dominant cooling processes [Beig et al., 2008; Mlynczak et al., 2010]. Therefore, we calculate the total cooling rate (CO$_2$ + NO) observed by SABER averaged from 2008 to 2009 for the same months as in Figures 1 and 2. The cooling rates from the most recent version of SABER, v2.0, were used here.

Figure 9 gives the global distributions of the longitudinal structure of the cooling rate (with zonal mean removed) at 115 km (left column) and 130 km (right column) in the Southern Hemisphere for April, August, and December. Figure 10 shows the cooling rates in the Northern Hemisphere for February, June, and October.

From these two figures, we can see that there is a strong temperature perturbations in the cooling rate at high latitudes in each hemisphere, and the peaks of the cooling rate are near the magnetic poles. We also analyze the radiative cooling rate for higher altitudes up to 150 km. The large cooling rate persists at all altitudes with the maximum at the same longitude and has a very similar structure (not shown).
From Figures 9 and 10, we can also see that the longitudinal variations of the cooling rates in the Southern Hemisphere are slightly stronger than those in the Northern Hemisphere. We also analyzed the cooling rate in 2012, which is in or near solar maximum conditions. The longitudinal structure of the cooling rate is similar to that during the solar minimum years of 2008–2009 but the amplitudes are larger.

Comparison of the temperature structures shown in Figures 1, 2, 7, and 8 with the radiative cooling rates shown in Figures 9 and 10 indicates that the cooling rates have longitudinal structures that are very similar to those of temperatures.

The analysis of the cooling rates provides additional evidence that the longitudinal variations in the temperature are physically real and robust. In this paper, we have focused on the horizontal structure of the temperature and not the absolute values. Due to the large differences between the retrieved temperatures of SABER and MIPAS in the thermosphere, the results should be regarded as qualitative.

3.4. TIEGCM Simulations and Discussion

The results above indicate that observations from SABER and MIPAS give similar features of the longitudinal variations in temperatures in the lower thermosphere.

Figure 7. The polar view of the 2 year (2008–2009) averaged distribution of the (left column) MIPAS temperature and (right column) the longitude variation of the temperature with zonal mean removed at the altitudes of 115 km (top panels), 140 km (middle panels), and 160 km (bottom panels) in the Southern Hemisphere. The temperatures have been reconstructed using the first two zonal harmonics. The white crosses indicate the position of the south magnetic pole.
In order to further demonstrate the effect of the auroral heating on the lower thermosphere, two simulations are made using the National Center for Atmospheric Research TIEGCM (Thermosphere-Ionosphere-Electrodynamics General Circulation Model) [Roble et al., 1987, 1988; Richmond et al., 1992]. The TIEGCM is driven by specified values of solar EUV flux, parameterized using the \( F_{10.7} \) index, and of auroral activity, parameterized from the \( K_p \) index. The first model run, with \( K_p = 3.7 \), includes auroral heating, whereas the second model run, with \( K_p = 0 \), has no auroral heating. Both runs are driven with \( F_{10.7} = 80 \). Figures 11 and 12 show the longitudinal variations in the diurnally averaged temperature distributions (i.e., with the zonal mean temperature removed) for the two TIEGCM runs at 115 km, 140 km, and 160 km for the Southern and Northern Hemispheres, respectively. We can see that the longitudinal variations in temperature are very weak (for instance, less than 6 K in the Southern Hemisphere at 160 km) when there is no auroral heating. On the other hand, when auroral heating is included, the longitudinal variations in temperature are very large and are dominated by the \( i = 1 \) structure. As shown by the left columns in Figures 11 and 12, the maxima in the lower thermospheric temperatures are located around the magnetic poles at 115 km but are shifted to lower latitudes at higher altitudes. These characteristics are present only when auroral heating is included in the model (\( K_p \) is not equal to 0). The feature that the longitudinal variation is stronger in the Southern Hemisphere is also consistent with that in the SABER and MIPAS observations.

Figure 8. The same as Figure 7, but for the polar view of the Northern Hemisphere.
One issue that needs to be addressed is the hemispheric asymmetry in the magnitude of the longitudinal variation of the temperature, that is, why is the longitude variation in the Southern Hemisphere larger than that in the Northern Hemisphere? The answer to this question is related to the positions of magnetic poles relative to the geographic poles. The southern and northern magnetic poles are located at about (64°S, 140°E) and (81°N, 250°E), respectively, in the geographic coordinate system. The displacement of the magnetic pole from the geographic pole in the Southern Hemisphere is much larger than that in the Northern Hemisphere, forming a stronger perturbation in the Southern Hemisphere [Yue et al., 2013].

In the geographic coordinate system, the longitudinal variation of the diurnally averaged temperature is a direct result of the displacement between the magnetic pole and geographic pole. If the region of heating is centered at the geographic pole, the longitudinal variation in heating disappears. The larger the displacement of the center of heating, which is the magnetic pole, off the geographic pole, the greater the longitude variation in the heating. Thus, the large displacement between the magnetic pole and geographic pole in the Southern Hemisphere contributes to a stronger longitudinal variation in temperature there.

Another difference is that the southern magnetic pole is located more toward midlatitudes; the auroral region there has relatively smaller solar zenith angles than that in the north. Thus, theoretically speaking, ionospheric plasma densities and conductivity are larger in the auroral region of the Southern Hemisphere. Joule heating, which is the dominant heating source of the auroral heating, depends on the ionospheric conductivity and electric field [e.g., Thayer and Semeter, 2004]. Therefore, in general, the auroral

**Figure 9.** The polar view of the distribution of the longitude variation of the cooling rate (with zonal mean removed) at (left column) 115 km and (right column) 130 km in the Southern Hemisphere for April, August, and December observed by SABER.
heating near the longitude of the magnetic pole in the Southern Hemisphere is larger than that in the Northern Hemisphere and vice versa for the opposite longitude. Thus, the longitudinal difference in the energy input in the Southern Hemisphere is larger than that in the Northern Hemisphere, which leads to a larger amplitude of the longitudinal variation in temperature.

Furthermore, the extension of the warm temperature region toward lower latitudes, which is similar to the longitudinal variations of the thermospheric densities observed by CHAMP and GRACE [Xu et al., 2013], is probably due to the additional neutral wind circulation from high latitudes toward the lower latitude induced by the auroral heating in the thermosphere. Zhang and Shepherd [2000] and Jee et al. [2008] presented evidence from UARS/Wind Imaging Interferometer observations and modeling simulations, respectively, that Joule heating can increase the neutral temperature and cause clear changes in the global wind circulation. The exact latitudinal location of the temperature enhancements induced by auroral heating, however, depends on the thermodynamics and dynamics of the thermosphere-ionosphere system. For instance, local auroral heating can cause a local heating to the neutrals and, consequently, an upwelling of neutral gas from lower heights. The upwelling and expansion of the neutral gas, on the other hand, lead to adiabatic cooling. Thus, there can be an altitude dependence of the locations of neutral temperature enhancement or depletion. Joule heating is also accompanied by changes in the neutral wind circulation that produce downwelling of neutral gas and adiabatic heating to the neutrals that leads to enhanced temperatures in regions away from the Joule heating zone [Burns et al., 1995; Wang et al., 2012]. This is probably the explanation for the movement of high-temperature regions from near the magnetic poles at lower altitudes to relatively lower latitudes at higher altitudes that is seen in both model simulations and observations. The exact cause of this motion, however, is an interesting topic and requires further investigation.

Figure 10. The same as Figure 9, but for the polar view of the Northern Hemisphere.
4. Summary

[47] In this work, the temperatures observed by TIMED/SABER from February 2002 to July 2012 and Envisat/MIPAS from 2008 to 2009 are used to study the longitudinal structure of the diurnally averaged temperature in the lower thermosphere. The results show that the temperature in the lower thermosphere is not uniform in the zonal direction but has strong longitudinal variations at high latitudes. The maximum of the diurnally averaged temperature in the lower thermosphere is near the longitude of the magnetic pole in both the Northern and Southern Hemispheres. The radiative cooling rates of CO$_2$ and NO from SABER are also investigated and give additional support for the zonal temperature structure. These observations suggest that the longitudinal structure of the diurnally averaged temperature in the lower thermosphere is most likely related to auroral heating, which occurs in the auroral region near the magnetic poles. Comparisons of the TIEGCM simulations of two cases, with and without auroral heating, further demonstrate that the observed longitudinal variations in temperature are indeed caused by auroral heating. As a result of the displacement of magnetic poles from the geographic poles, auroral heating and its resultant neutral temperature increases are localized.

Figure 11. The polar view of the distribution of the longitude variation of the diurnally averaged temperature with zonal mean removed at the altitudes of (top panels) 115 km, (middle panels) 140 km, and (bottom panels) 160 km at Day 80 simulated by the TIEGCM model in the Southern Hemisphere. Left column: with auroral heating. Right column: no auroral heating. The white crosses indicate the position of the south magnetic pole.
and occur in the longitude sector near the magnetic pole in each hemisphere. The observations and simulations show that the longitudinal variations in temperature are stronger in the Southern Hemisphere. The asymmetry between the two hemispheres is probably caused by the difference in the distance between the magnetic and geographic poles for the two hemispheres.

Observations and modeling simulations indicate that the longitudinal variation in temperature is dominated by the first harmonic in longitude. The vertical distribution of the longitude variation in temperature determined from satellite observations indicates that the effect of auroral heating on neutral temperature can penetrate downward to about 105 km.

Global temperature observations in the lower thermosphere are technically difficult. The temperature retrievals from SABER and MIPAS both have uncertainties due to low signal to noise and the absence of simultaneous profiles of atomic oxygen density. However, very consistent signatures of auroral heating are seen in SABER and MIPAS temperatures, SABER cooling rates, and TIEGCM simulations, providing confidence that the observed features are real.

The analysis in this paper shows a first look into the effect of auroral heating on the atmospheric thermodynamical structures in the high latitude lower thermosphere using the TIMED/SABER and Envisat/MIPAS observations. A complete description of the temperature response to auroral heating will require 24 h observations with full longitudinal

Figure 12. The same as Figure 11, but for the polar view of the Northern Hemisphere.
coverage in the high latitude during all seasons. These measurement needs should be taken into account in planning for future satellite missions.

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