Enhancements of nighttime neutral and ion temperatures in the \( F \) region over Millstone Hill

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1. Introduction

Neutral temperature in the upper thermosphere is usually high in the daytime and low at night because of the change of solar heating with solar zenith angle. On average, the highest thermospheric temperature takes place 1–3 h after local noon as a result of the balance between solar heating and molecular conduction loss [e.g., Hargreaves, 1992], but the time at which the lowest temperature occurs at night changes greatly [Oliver et al., 2012]. In addition, nighttime ion temperatures or daytime ion temperatures below 250 km are generally considered to be close to neutral temperature because of the collisions between ions and neutrals. Therefore, the observations of ion temperature in the \( F \) region are often used to extract variations of thermospheric temperature [e.g., Oliver and Glotfelty, 1996, and references therein]. However, the similarities and differences between neutral and ion temperatures in the \( F \) region are not understood well, given that the coordinated observations of neutral and ion temperatures are sparse.

As expected, temperatures of neutral gas and ions at night gradually decrease from their higher daytime temperatures due to the absence of solar irradiation. However, previous observations show that both neutral and ion temperatures after sunset can increase instead of continuously decaying. Nighttime enhancement of neutral temperature in the tropical upper thermosphere, which is referred to as the midnight temperature maximum (MTM), has been reported from both ground-based and satellite measurements since the 1970s [e.g., Sobral et al., 1978; Spencer et al., 1979; Burnside et al., 1981; Coker and Mendillo, 2002]. Using 6300A airglow emission observations at three different locations in South America, Coker and Mendillo [2006] found that the MTM feature occurring near 3 LT can extend into midlatitudes (39°S). They suggested that the high-order and upward propagating tidal modes from the lower atmosphere and their interactions may be responsible for the generation of the MTM on the basis of the National Center for Atmospheric Research Thermosphere-Ionosphere-Electrodynmamic General Circulation Model simulations. Recently, Akmaev et al. [2009, 2010] and Miyoshi et al. [2009] have indicated that superposition of tides, including high-order zonal wave numbers and frequencies, was the likely source for the MTM.

Besides nighttime enhancement in neutral temperature, a similar phenomenon was reported in ion temperature observations. Oliver et al. [2012] utilized the Saint Santin (45°N) incoherent scatter radar (ISR) observations to examine
variations of nighttime ion temperature. They found an enhancement in nighttime ion temperature near 4 LT with an averaged amplitude of 40 K, which occurred only in the winter season in their statistical analysis. Oliver et al. proposed two possible mechanisms to explain the observed nighttime enhancement in ion temperature, including the convergence of global winds at the global pressure minimum and an extension of the MTM from low to middle latitudes. Both mechanisms imply that the nighttime enhancement in neutral temperature leads to a subsequent increase in ion temperature through the ion-neutral collision. However, observations of neutral temperature are not available at Saint Santin to verify their hypotheses.

In this study, we investigate the temporal variations of nighttime neutral and ion temperatures over Millstone Hill (42.5°N, 71.5°W). Ionosphere measurements obtained from the Millstone Hill incoherent scatter radar (ISR) during 1–11 August 2011 and 12–23 January 2012 were analyzed since these two periods represented summer and winter seasons, respectively, and each was from one of longest continuous duration ISR operations at this site. More importantly, nighttime neutral temperature data observed by the red line Fabry-Pérot interferometer (FPI) over Millstone Hill were available during these periods. The simultaneous nighttime observations of neutral and ion temperatures presented an ideal opportunity to examine the physical processes of energy flow between neutral gas and ions, which might shed some light on the coupling between the thermosphere and the ionosphere.

2. Data Set and Geophysical Condition

In this study, we made use of both ionosphere and thermosphere measurements over Millstone Hill. The ionospheric observations were measured by the Millstone Hill ISR, which provided parameters, including electron density, electron temperature, ion temperature, and line of sight ion velocity. The red line (6300Å) FPI over Millstone Hill measures airglow and gives zonal and meridional winds and neutral temperature observations at south/north, east/west, and vertical directions (note that the elevation angle is 45° when the direction is nonvertical). The ion temperature data at 250 km obtained from the ISR observations with a long pulse of 480 µs were compared to the neutral temperature, since the FPI temperature was also taken at around 250 km, the rough altitude of the peak 6300Å airglow emission at night. The effect of a difference in the peak altitude of the 6300Å airglow emission on the comparison with the ISR data is discussed in section 3.

The observations periods of 1–11 August 2011 and 12–23 January 2012 were chosen for analysis since both the ISR and the FPI were operated during these intervals. The duration of these observing periods was restricted to about 10 days since radar operations over Millstone Hill rarely lasted more than 10 days. In addition, these two periods were chosen to represent summer and winter seasons, respectively.

Figures 1 and 2 show the variations of 3-hourly geomagnetic activity index Ap and solar radiation proxy F10.7 during 12–23 January 2012 and 1–11 August 2011, respectively. As shown in Figure 1a, F10.7 varied from 116.8 to 157.0 solar flux units (1 SFU = 10⁻²² W/m²/Hz) during 12–23 January 2012; the solar activity during this period was moderate. The geomagnetic activity during this period was generally low (Figure 1b), although elevated geomagnetic activity can be seen on 13, 16, and 22–23 January. Correspondingly, the maximum Ap values were 18, 18, and 48 nT. As shown in Figure 2, F10.7 decreased gradually from 124.9 on August 1 to 83.4 on August 12, so the solar activity during this period was low or moderate. Geomagnetic activity from 1 to 11 August 2011 was generally quiet except for 5–6 August, when there was a severe geomagnetic disturbance and the peak Ap reached 179.
3. Results and Discussions

Figure 3 shows the temporal variations of ion temperature at 250 km and neutral temperature over Millstone Hill during 12–23 January 2012. In this winter interval, ion temperature exhibited an obvious diurnal variation; it was high in the daytime and low at night except on 22/23 January 2012, when nighttime temperature was comparable to that in the daytime because of the impact of the moderate geomagnetic storm. Note that we refer to the night of 22/23 January as being from 18 LT on 22 January to 7 LT on 23 January; the same format is used hereafter. The interesting features seen in the nighttime ion temperature are the premidnight and postmidnight enhancements. Furthermore, both the premidnight and the postmidnight enhancements were observed every day in the observation period except the night of 21/22 January, when the postmidnight enhancement in ion temperature was absent. The premidnight enhancement was usually present at 19–24 LT with an enhancement amplitude of about 20–40 K. The postmidnight enhancement amplitude varied from 30 to 90 K. In addition, the peak enhancement occurred near 3–4 LT. These characteristics of the postmidnight enhancement in the ion temperature over Millstone Hill in Figure 3 are consistent with those over Saint Santin [Oliver et al., 2012].

Neutral temperature observations measured by the colocated FPI over Millstone Hill allowed us to examine whether the nighttime enhancement in the ion temperature was also present in neutral temperature. In Figure 3, the averaged FPI neutral temperatures from five different directions in 1 h local time bins are depicted by the black dots. While it is notable that the neutral temperature was about 50 K higher than the ion temperature, the systematic bias associated with calibration of the FPI neutral temperature should not affect the determination of the relative temperature changes on which we are focusing. In this case, we are concentrating on neutral temperatures for seven nights (13–16, 18/19, and 20–23 January) since more data were available these nights. As shown in Figure 3, the postmidnight enhancements were also observed in neutral temperature. Additionally, the postmidnight enhancements in neutral temperature are in agreement with those of the ion temperature enhancements. The premidnight enhancements were also seen in neutral temperature on 15/16, 18/19, and 20–22 January, whereas no obvious premidnight enhancement in neutral temperature was observed in the remaining days. Note that the premidnight enhancements in neutral temperature were larger on 20–22 January and smaller on January 15/16 than those in ion temperature. In addition, the premidnight enhancement of neutral temperature on January 20 occurred earlier than that of the ion temperature. As shown in the monthly averaged neutral temperature profile (the red dashed line in Figure 3), the amplitude for the postmidnight enhancement was about 33 K. This indicates that the nighttime enhancement in the neutral temperature can occur frequently in the winter season. For a given day, the magnitude of the nighttime enhancement can be large. For example, the amplitude of the postmidnight enhancement in neutral temperature was around 100 K on 19 January. However, there was no obvious premidnight enhancement in the averaged profile because of the day-to-day variation of its magnitude and the time of its occurrence.

Figure 4 shows the variation of ion and neutral temperatures in the F region over Millstone Hill during the winter period of 12–23 January 2012. The red solid circles stand for ISR ion temperature at the altitude of 250 km with standard deviation, while black solid circles with standard deviation represent the averaged neutral temperatures measured by FPI from five directions. Note that the monthly averaged neutral temperature from 19 night observations is shown in red dashed line. The vertical dashed lines represent zero local time (midnight).
1–11 August 2011. For the ion temperature at 250 km, it was also high in the daytime and low at night except on 5/6 August, when the nighttime temperature was higher than (or comparable to) that in the daytime because of the impact of severe geomagnetic storm. Note that the elevated nighttime ion temperature on 6/7 and 7/8 August may be also associated with moderate geomagnetic activity. Unlike the obvious premidnight and postmidnight enhancements in winter ion temperature, the nighttime temperature in summer generally presented relatively weak and short-lived enhancements just after the midnight, such as on 2, 5, 8, and 10 August. Neutral temperature observations during this summer period from the FPI over Millstone Hill are also shown in Figure 4. The interesting feature during this period is the postmidnight enhancement in neutral temperature which occurred 5, 8, 9, and 11 August; however, there did not appear to be any corresponding enhancement in ion temperature on these days. Thus, the neutral temperature displayed a different temporal variation postmidnight but appeared to be much closer to that of the ion temperature premidnight. In Figure 4, the monthly averaged neutral temperature (red dashed line) showed an increase of about 40 K as compared with its lowest temperature at midnight. For a given day, neutral temperature enhancement can be profound. For example, on 10/11 August, the neutral temperature increased by about 100 K in 3 h before 3 LT. However, it is surprising that no corresponding enhancement was observed in the ion temperature during that same period.

Let us now discuss possible mechanisms of the nighttime enhancements in ion and neutral temperatures. As shown in Figure 3 (the winter period), both the ion and neutral temperatures displayed the premidnight and postmidnight enhancements. Premidnight enhancement in ion temperature in the winter should be associated with the photoelectron heating from the conjugate summer hemisphere [e.g., Schunk and Nagy, 1978]. When the sun is setting over the Millstone Hill station and the conjugate summer hemisphere is still under sunlight conditions, the ionosphere over Millstone Hill would be heated by conjugate photoelectrons. Figure 5 shows the variations of electron and ion temperatures during 12–23 January 2012. The electron temperature was clearly elevated by more than 400 K around 22–23 LT almost every night of the considered period. We believe that the premidnight enhancement in the ion temperature in winter might be caused by the energy transfer from electrons to the ions associated with the conjugate heating, leading to a subsequent enhancement in neutral temperature, as seen, for example, on 18/19 January. In addition, the lack of preenhancement in the F region over Saint Santin during winter nighttime [Oliver et al., 2012] may be due to less photoelectron heating from the conjugate ionosphere of Saint Santin, which has a lower magnetic conjugate latitude compared to Millstone Hill [Zhang et al., 2004; Lei et al., 2007]. Richards et al. [2009] demonstrated that photoelectron heating from the conjugate hemisphere is the major contributor for the postsunset enhancement in electron temperature at FPI-ISR which has a higher latitude than Millstone Hill. Moreover, the downward electron heat flux may have contributed to the large increase in electron temperature during the geomagnetic disturbances, although the geophysical conditions were generally quiet during this period.

For the postmidnight enhancement in ion temperature, the observed features over Millstone Hill are consistent with those in Saint Santin as reported by Oliver et al. [2012] They found that the winter-time postmidnight enhancement in the ion temperature was only statistical. Oliver et al. related the postmidnight enhancement of ion temperature to that of neutral gas. Our results in Figure 3 support Oliver et al.’s idea. It should be pointed out that there was not a one-to-one correspondence of the postmidnight enhancement between electron
and ion temperatures, although weak postmidnight enhancement in electron temperature occurred on 14, 17, and 22 January (Figure 5). Therefore, the mechanisms for the premidnight and postmidnight enhancements in either ion or neutral temperature in winter should be different.

Oliver et al. [2012] further suggested that either the convergence of global winds or the extension (or propagation) of the MTM into midlatitude is the possible mechanism. They preferred the former theory to explain the observations over Saint Santin, given that the local time of the simulated MTM in Akmaev et al. [2009] occurs about 2 h earlier than the observed postmidnight enhancement in ion temperature. In order to explore the possible effect of neutral winds on the postmidnight neutral temperature enhancement, the variations of zonal and meridional winds along with their horizontal gradients in 2 h local time bins during 12–23 January 2012 are shown in Figure 6. The zonal (meridional) winds were calculated by averaging the horizontal vectors from the east and the west (north and south) FPI direction. The zonal (meridional) wind gradients were calculated by subtracting the horizontal vector obtained by the west (south) FPI direction from the one obtained by the east (north) direction and dividing by the distance between two emission regions. The positive value in the zonal (meridional) wind stands for the eastward (northward) wind. As shown in Figure 6, the zonal wind with peak magnitude of about 100 m/s changed its direction from eastward to westward around 3 LT on 14/15, 15/16, and 18/19 January, and the southward meridional wind achieved its maximum around 1 LT with a magnitude of 100 m/s on those days. These characteristics are consistent with the climatology of the neutral winds over Millstone Hill [e.g., Fejer et al., 2002; Emmert et al., 2003; Zhang et al., 2012], whereas the patterns for zonal (meridional) winds on 20–23 January are quite different from previous results.

With respect to the wind gradient, climatology in latitudinal gradients of the meridional wind was described by Emmert et al. [2003], in which the north looking winds were about 50 m/s more southward than the south looking winds during winter nighttime with the peak gradient occurring ~3 LT. Our analyses of the longitudinal gradient in the zonal wind and the latitudinal gradient in the meridional wind during winter nighttime are both shown in Figure 6 (vertical lines). The peak gradient in the zonal wind was about $3 \times 10^{-4}$ s$^{-1}$ (negative sign) during both the morning and evening periods on 20 January, which was much larger than the average gradient in the meridional wind. Therefore, the longitudinal gradient in the zonal wind cannot be ignored. In Figure 6, the latitudinal gradient in the meridional wind on 14–16 January is consistent with the climatology of Emmert et al. [2003] in that the averaged gradient in the meridional wind during the postmidnight was about 40 m/s per 500 km (negative sign). However, the gradient in the meridional wind on 19 and 21–23 January was quite different from that on 14–16 January in terms of either the direction or the magnitude. Obviously, the wind gradient in Figure 6 varied with time in such a way that the convergent wind was not coincident with the occurrence of the postmidnight temperature enhancement, as shown in Figure 3, indicating that the convergence wind mechanism did not affect the temperature enhancement over Millstone Hill. We may conclude that during this time period in January 2012, the wind convergence did not really occur and was not responsible for the observed temperature enhancement.

For the summer case, as shown in Figure 4, the nighttime enhancement in the ion temperature took place on 2, 5, 7, 8, and 10 August. The occurring time and amplitude of ion temperature enhancement were not consistent with those of the neutral temperature enhancement, especially during the postmidnight. Figure 7 shows the temporal...
variations of electron and ion temperatures during 1–11 August 2011. It is clear that the electron temperature during nighttime had little difference from the ion temperature at the same time. Thus, the energy transfer from electron or ions to neutrals is an unlikely way to explain the strong postmidnight enhancement in neutral temperature for the summer case.

Figure 6. Variation of zonal (blue solid circles, eastward positive) and meridional (red solid circles, positive northward) winds from the Millstone Hill FPI in 2 h local time bins during 12–23 January 2012. The upward vertical lines represent the positive wind gradient (or wind divergence), whereas the downward lines stand for the negative wind gradient (or wind convergence). See text for more details.

Figure 7. Similar to Figure 5 but for the summer case (1–11 August 2011).

[16] One could argue that the observations measured by FPI represented the temperature around the peak altitude of the 6300A airglow emission rather than at a fixed altitude of 250 km and that such an altitude discrepancy could cause the different features seen in the nighttime ion and neutral temperatures. To address this issue, we calculated the peak altitude of the 6300A airglow emission versus local time.
during 1–12 August 2011 on the basis of the 6300A emission rates model in Vlasov et al. [2005] and Nicolls et al. [2006]. The required parameters, including electron density, concentration of atomic oxygen, molecular oxygen, and molecular nitrogen, were provided by the ISR observations or the MSIS model [Picone et al., 2002]. Figure 8 illustrates the altitude variation of the maximum 6300A airglow emission during 1–12 August 2011. It is obvious that the peak emission height was lower in the daytime and higher at night. Indeed, the nighttime peak height was generally higher than 250 km during this period. Figure 9 demonstrates the comparison of the FPI neutral temperature with the ion temperature at the peak emission height. It is immediately evident that the variation of ion temperature at the peak emission height cannot explain the prominent enhancement at postmidnight.

**Figure 8.** Peak altitude of the calculated 6300A airglow emission from 1 to 12 August 2011 versus local time. See text for more details.

**Figure 9.** Similar to Figure 4, but ion temperature is shown at the peak altitude of the calculated 6300A airglow emission rather than at a fixed altitude.
[17] Oliver et al. [2012] suggested that the temperature enhancement at night would only be seen in winter rather than summer if the ion temperature enhancement is associated with wind convergence due to the pressure minimum. The summer case is shown in Figure 10, which has the same format as Figure 6 and shows the variations of zonal and meridional winds along with their horizontal gradients during 1–11 August 2011. Both zonal and meridional winds showed significant day-to-day variability. The meridional wind was generally southward during this period, and the peak meridional wind during postmidnight generally occurred around 2–3 LT, as on 3, 5, 9, and 12 August. These characteristics in meridional wind are in agreement with the wind climatology of Emmert et al. [2003]. However, the peak magnitude of meridional wind on August 12 reached 200 m/s, which was larger than the averaged wind speed in Emmert et al. [2003]. Another difference from the results of Emmert et al. [2003] is that the southward meridional winds on 4/5 and 5/6 August were fairly weak around midnight. The zonal winds during 1–12 August 2011 differed from the summer wind pattern reported in Fejer et al. [2002] and Zhang et al. [2012]. For instance, the averaged peak westward wind during nighttime was about 100 m/s. For the summer case, the gradients in the zonal wind were comparable to those in the meridional wind. Additionally, the magnitude of the averaged latitudinal gradient, being about 50 m/s per 500 km during the postmidnight, is similar to that in Emmert et al. [2003]. For this summer case, there was not an obvious correlation between the midnight neutral temperature enhancement and the negative wind gradient (i.e., the convergence of the wind component). Moreover, our observations indicate that (1) the postmidnight enhancement in neutral temperature did occur in summer over Millstone Hill, and this is not expected based on the pressure minimum mechanism as proposed by Oliver et al.; and (2) the expected pressure minimum needed to produce convergent winds by Oliver et al. did not coincide in winter or summer with the midnight temperature enhancement.

[18] Then, we would ask whether the MTM feature seen in low and middle latitudes [e.g., Colerico et al., 2006] can extend to Millstone Hill, a geographic middle latitude station in the subauroral region. As shown in the simulations of Akmaev et al. [2009, Figure 5], the MTM feature at 285 km in the solstice season is seen at the equatorial region around 22–23 LT, and it extends into middle and high latitudes at later local times. Specifically, in the summer hemisphere at around 40–50°S, the MTM occurs at 0–1 LT. This occurrence time is consistent with the FPI neutral temperature over Millstone Hill (Figures 4 and 9). Thus, the extension of MTM to the latitude of Millstone Hill is a possible mechanism for the observed postmidnight enhancement of neutral temperature. Furthermore, Akmaev et al. [2012] revealed that the latitudinal structure of the MTM reflects the corresponding structure of the main terdiurnal tide modes. Unfortunately, the nightly neutral wind observations (Figure 10) were too short to extract the possible terdiurnal tide component. It is also unclear whether the neutral temperature enhancement in summer is related to the wind surge, especially the meridional wind component. Further physical modeling is required to understand possible mechanisms for the formation of the postmidnight enhancements in neutral temperature in summer and winter and for the contrasting temporal behavior between neutral and ion temperatures in summer.

4. Conclusions

[19] Observations from ISR and FPI at Millstone Hill during 1–11 August 2011 and 12–23 January 2012 were used to examine the similarities and differences in the temporal variation of nighttime ion and neutral temperatures in the F region. During the winter nighttime (12–23 January 2012), the observed ion temperature correlated with the neutral temperature; the postmidnight enhancements, which generally occurred during 3–4 LT with peak amplitudes of about 30–90 K, were seen in ion and neutral temperatures. However, the
temporal variations of neutral temperature showed a contrasting behavior compared with ion temperature during summer nights (1–11 August 2011), since postmidnight enhancements only exhibited in neutral temperature.

[20] Photoelectron heating from the conjugate summer hemisphere in winter might be the main contributor to premidnight enhancement in ion temperature, resulting in a subsequent enhancement in neutral temperature on some days of 12–23 January 2012. However, the causes for the postmidnight enhancements in neutral temperature in summer and winter are not yet understood. Our preliminary analysis of the wind gradient from the FPI observations does not support an alternative explanation offered by Oliver et al. [2012] that the convergent winds cause the nighttime enhancement in neutral temperature. Nevertheless, our results indicate that the extension of midnight temperature maximum (MTM) to the latitude of Millstone Hill is a possible mechanism for the observed postmidnight enhancements of neutral temperature in winter and summer.

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