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Key Points:

- The nighttime oxygen ions decrease remarkably at the low and middle latitudes of winter hemisphere in the topside ionosphere
- The latitudes of large-scale oxygen ion depletion (center $\sim 30^\circ$) are mostly lower than the midlatitude trough of nighttime hydrogen ions
- The winter depletion of nighttime oxygen ions is largely due to the charge exchange reactions between oxygen ions and atomic hydrogen

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Large-Scale Depletion of Nighttime Oxygen Ions at the Low and Middle Latitudes in the Winter Hemisphere

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Abstract By analyzing the latitudinal distributions of ionospheric ions observed by the Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions satellite at 670 km altitude in different seasons, we found that the large-scale depletion of nighttime oxygen ions is prevalent at the low and middle latitudes of winter hemisphere (center $\sim 30^\circ$) under different geomagnetic conditions. The latitudinal width of the winter oxygen ion depletion (WOD) region is about 20° – 60° at different longitudes, and its upper boundary latitudes are mostly lower than the midlatitude trough ($|\lambda| \geq 50^\circ$) of nighttime hydrogen ions (H^+) near the plasmapause. In the WOD region, the density ratio of oxygen and hydrogen ions and that of their neutral densities (O and H) approximately agree with the chemical equilibrium relationship of charge exchange reactions ($H + O^+ \leftrightarrow H^+ + O$) predicted by previous theory, indicating that the charge exchange reactions are mainly responsible for the large-scale oxygen ion depletion at the low and middle latitudes in winter hemisphere.

Plain Language Summary Previous studies focused on the nighttime midlatitude trough of ionospheric electrons (e^-) and light ions (H^+ and He^+). Although the percentage of nighttime oxygen ions was found to decrease in winter hemisphere at 400 km altitude, it is not clear whether the winter oxygen ion depletion (WOD) is a common phenomenon in the topside ionosphere. Moreover, the mechanism of the WOD has not been understood clearly. Here, our statistical results indicate that the large-scale depletion of nighttime oxygen ions is prevalent at the low and middle latitudes of winter hemisphere under different geomagnetic conditions. By analyzing the relationship among the latitudinal changes in the ion bulk velocity, densities and their neutral densities, we found that the charge exchange reactions mainly cause the nighttime oxygen ion depletion at the low and middle latitudes in winter hemisphere in the topside ionosphere.

1. Introduction

In the Earth's topside ionosphere, there are multiple-scale irregular structures of plasma density. One of the typically irregular structures is the nighttime midlatitude trough with a significant decrease in plasma electron density [e^-] or total electron content at middle latitudes ($\sim 50^\circ$ – 70°) (Chen et al., 2018; He et al., 2011; Lee et al., 2011; Liu et al., 2021; Rodger, 2008; Xiong et al., 2013). Besides the nighttime midlatitude trough, plasma density also decreases in the South Atlantic Magnetic Anomaly (SAMA) in the topside ionosphere (Horvath & Lovell, 2009b; Li et al., 2011, 2015). The steep density gradients in irregular structures can deteriorate the accuracy of the GPS positioning (Wanninger, 1993) and cause the Doppler and delay spread of HF signals (Stocker & Warrington, 2011).

Like the nighttime ionospheric electrons, the light hydrogen and helium ions (H^+ and He^+) also showed prominent midlatitude troughs at the night-time 870 km (Horvath & Lovell, 2009a). However, the density of heavy oxygen ions (O^+) is larger in the midlatitude trough of light ions in the winter southern hemisphere. Utilizing a Wide Sweeping Langmuir Probe onboard the International Space Station, Debchoudhury et al. (2022) observed the decrease in the percentage of nighttime oxygen ions in winter hemisphere at 400 km altitude. However, it is not clear whether the winter oxygen ion depletion (WOD) is a common phenomenon in the topside ionosphere. Moreover, the mechanism of the WOD has not been understood clearly.

Here, by analyzing the latitudinal distributions of ions observed by the Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER), we found that the large-scale depletion of nighttime oxygen ions also occurs in the winter hemisphere at 670 km altitude, and the winter depletion of nighttime oxygen ions is mainly due to the charge exchange reactions. Observational Data and statistical methods are introduced in

Section 2. Statistical results are presented in Section 3. Potential causes of the winter decrease of nighttime oxygen ions are discussed in Section 4, and conclusions are summarized in Section 5.

2. Data and Methodology

The number density and bulk velocity of hydrogen and oxygen ions (H^+ and O^+) are measured by the thermal plasma analyzer (Instrument d'Analyse du Plasma [IAP]) on board the DEMETER satellite (Berthelier et al., 2006). The 1-min averaged geomagnetic indices (K_p , SYM-H, and AE) come from the OMNI database in the Coordinated Data Analysis Web. SYM-H approximately represents Dst index (Li et al., 2011).

During a solar minimum year from 21 March 2007 to 21 March 2008, the DEMETER satellite flew in a Sun-synchronous circular orbit at ~ 670 km, and its orbit covered the magnetic local time (MLT) range from 8.5 to 12.1 hr in daytime and from 19.9 to 23.9 hr in nighttime. The Earth's rotation allows the IAP to record the density and bulk velocity of global ions in the daytime and nighttime. To obtain the semiannual variations of the nighttime oxygen and hydrogen ions, the IAP data in nighttime are respectively divided into two subsets during northern summer (21 March 2007–21 September 2007) and during southern summer (21 September 2007–21 March 2008), and then the data in each subset are divided into two subsets for geomagnetically quiet times ($K_p \leq 3$ and $Dst \geq -30$ nT and $AE \leq 200$ nT) and active times ($K_p > 3$ and $Dst < -30$ nT and $AE > 200$ nT). Finally, we calculated the averages of ion densities ($[H^+]$ and $[O^+]$) and the medians of ion bulk velocity components (V_x and V_z) in each longitude-latitude grid ($4^\circ \times 2^\circ$) under different geomagnetic conditions.

3. Large-Scale Depletion of Nighttime Oxygen Ions in Winter Hemisphere

Figures 1 and 2 are the statistical results from the IAP data of DEMETER during geomagnetically quiet and active times. The left and right panels display the number densities of nighttime oxygen and hydrogen ions ($[O^+]$ and $[H^+]$) and their ratio ($[O^+]/[H^+]$) at 670 km altitude during the northern and southern summers, respectively. The IAP data are mostly inside the geographic latitude of Earth's plasmapause (λ_{pp}). λ_{pp} is calculated through an empirical model of the plasmapause (Moldwin et al., 2002). Moreover, the latitude (λ_{dip}) of magnetic dip equator is determined when the magnetic inclination $I \sim 0^\circ$ in the model of International Geomagnetic Reference Field.

From the northern summer (21 March–21 September) to the southern summer (21 September–21 March), the density of nighttime oxygen ions ($[O^+]$) on the summer side of magnetic dip equator is generally higher than the winter side, except for the SAMA and its eastern-southern region (enclosed within red closed contours). The maximum density of nighttime oxygen ions is located at the middle and high latitudes ($|\lambda| \geq 50^\circ$) of summer hemisphere and around the dip equator (λ_{dip}). However, in winter hemisphere, the density of nighttime oxygen ions decreases remarkably at the low and middle latitudes ($[O^+] \leq 350 \text{ cm}^{-3}$ between the two red open contours). The center of the WOD region is located at about 30° in the winter hemisphere, and its latitudinal width is about 20° – 60° at different longitudes. Unlike the semiannual shift of the WOD region, the density of nighttime oxygen ions is always low in the SAMA and its eastern-southern region in all seasons (enclosed within red closed contours).

Under different geomagnetic conditions, the longitudinal distributions of the nighttime oxygen and hydrogen ions ($[O^+]$ and $[H^+]$) are consistent with the shape of magnetic dip equator, but their latitudinal distributions are nearly opposite at the same altitude. The density of nighttime hydrogen ions is higher at the low and middle latitudes of both hemispheres ($|\lambda| \sim 10^\circ$ – 50°) than other latitudes. Since the hydrogen ions are dominant in the plasmasphere (also called “protonosphere”), its latitudinal outer boundary agrees with the location of empirical plasmapause (λ_{pp}). Near and beyond the plasmapause ($|\lambda| \geq \lambda_{pp}$), the sudden decrease of nighttime hydrogen ions forms a prominent midlatitude trough. The location relationship between the nighttime midlatitude trough and the plasmapause is consistent with previous studies (Weygand et al., 2021; Yizengaw et al., 2005). The latitudes ($|\lambda| > 50^\circ$) of the midlatitude trough of hydrogen ions are mostly higher than the WOD region in the winter hemisphere, except for a small overlap between the 10° and 50° longitudes. Moreover, the oxygen ion density is obviously lower in the WOD region than the midlatitude trough of hydrogen ions.

During the geomagnetically quiet times, the density ratio of the two ion species ($[O^+]/[H^+]$) is mostly less than or equal to 1.0 in the WOD region (shown between the open red contours in Figures 1e and 1f). Enhanced geomagnetic activities cause slightly the enhancement of nighttime oxygen ions but the decrease of hydrogen ions in the

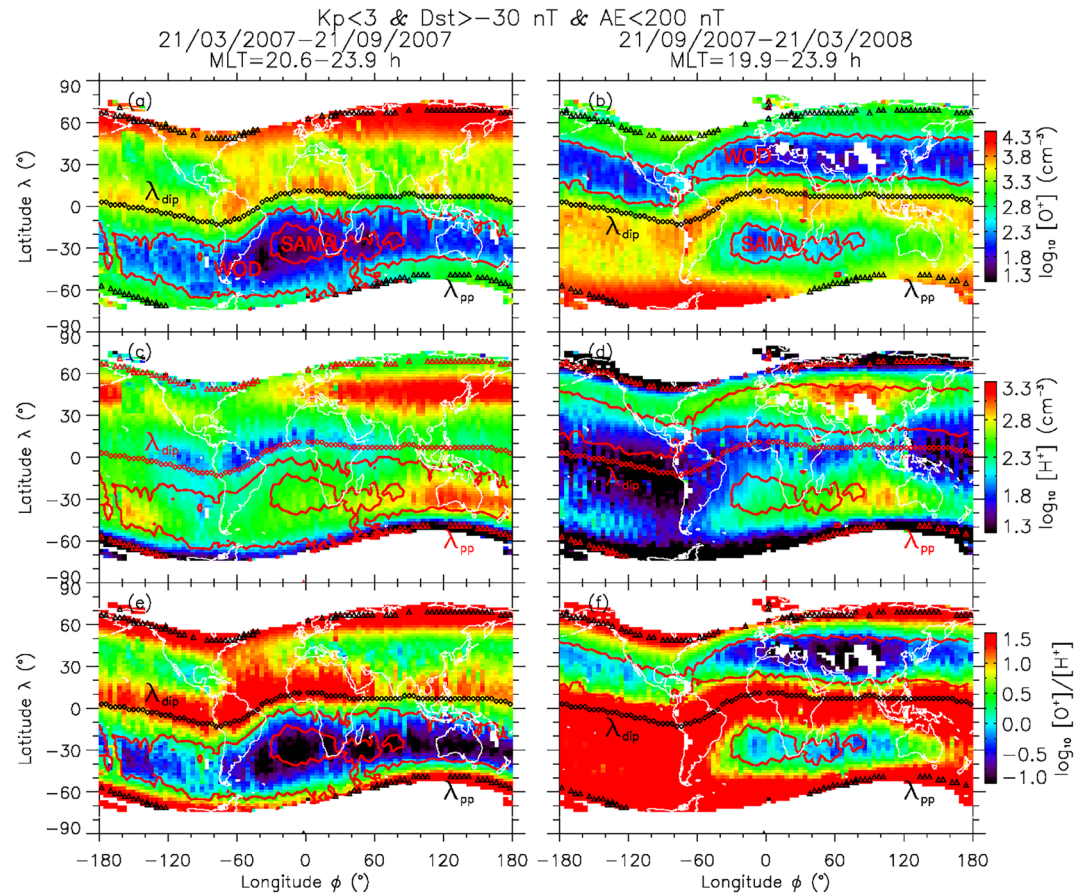


Figure 1. The densities of nighttime oxygen and hydrogen ions ($[O^+]$ and $[H^+]$) and their ratio ($[O^+]/[H^+]$) at 670 km altitude under geomagnetically quiet conditions in different seasons. The left and right panels show the ion distributions during the northern summer and the southern summer, respectively. The winter oxygen ion depletion is roughly located between the open red contours. The South Atlantic Magnetic Anomaly and its eastern-southern region are shown inside the closed red curves. MLT is the magnetic local time. λ_{dip} (diamonds) is the magnetic dip equator, and λ_{pp} (triangles) is the location of an empirical plasmopause (Moldwin et al., 2002).

topside ionosphere (Figures 2a and 2d). As a result, the density ratio of the two ion species increases slightly during the geomagnetic activities (shown between the open red contours in Figures 2e and 2f).

4. Discussions

The different latitudinal distributions of oxygen and hydrogen ions suggest that the two ion species have different sources (S) or losses (L) in the topside ionosphere. The density of ionospheric plasma (N) depends on its production (S), loss (L) and transport velocity (V). The change in plasma density is determined by continuity equation,

$$\frac{\partial N}{\partial t} = S - L - \nabla \cdot (NV) \quad (1)$$

The chemical production (S) and loss (L) of plasma mainly result from photoionization and/or charge exchange reactions (Li et al., 2015; Waldrop et al., 2006). The plasma transports (Velocity V) can be driven by neutral wind and/or $E \times B$ (E is an eastward electric field vector and B is geomagnetic field vector) (He et al., 2009, 2011; Lu et al., 2013).

4.1. Effect of Plasma Transports on the Nighttime Oxygen Ions

If ignoring the influence of plasma density gradient, the transport term of plasma is reduced as

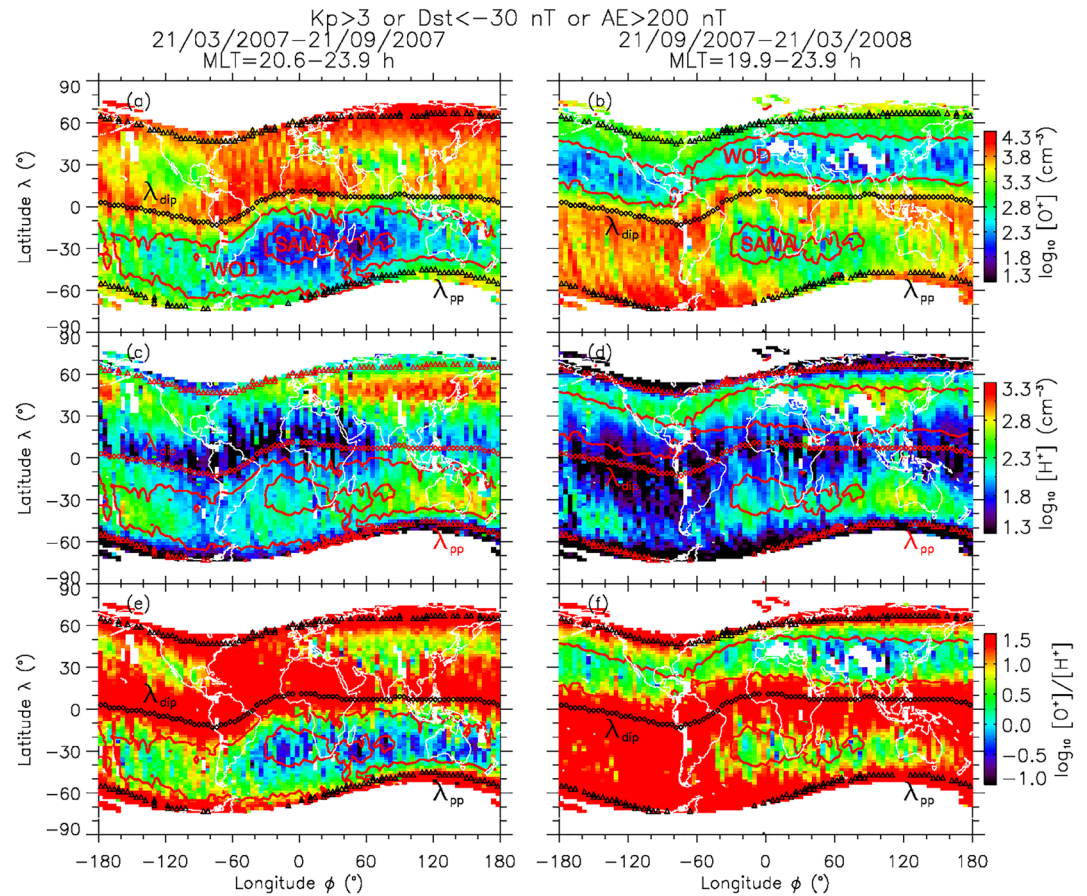


Figure 2. Similar to Figure 1, but during the geomagnetically active times.

$$\nabla \cdot (N\mathbf{V}) = N \left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} \right) \quad (2)$$

Here, the transport velocity of ions is measured by the IAP onboard the DEMETER satellite.

Figures 3 and 4 display the bulk velocities of nighttime ions (V_x and V_z) measured by the DEMETER satellite at 670 km altitude during the geomagnetically quiet and active times, respectively. The vertical transport velocity (V_z) of nighttime ions measured by the DEMETER satellite (Figures 3a, 3b, 4a, and 4b) is comparable to its theoretic value around midnight (see Figure 5 in the paper of Lu et al., 2020), and its latitudinal transport velocity (V_x) in the summer hemisphere (Figures 3c, 3d, 4c, and 4d) is also consistent with the neutral winds blowing from the summer to winter hemispheres (Mauersberger et al., 1976). In most regions, the latitudinal transport velocity of ions is faster than its vertical transport velocity ($|V_x| > |V_z|$).

During the northern summer (left panels), Dst, the most ions move upwards ($V_x < 0$ m/s) and southwards ($V_z > 0$ m/s) in the northern hemisphere and around the magnetic dip equator ($|\lambda| \geq \lambda_{pp} - 10^\circ$). Since the heavy oxygen ions are mostly distributed at lower altitudes, the upward transports perhaps increase the density of oxygen ions in the summer hemisphere. However, the upward moving oxygen ions are not likely to be piled up at the middle and high latitudes ($|\lambda| \geq 50^\circ$) of the summer hemisphere in the present of faster latitudinal movements ($|V_x| > |V_z|$). In other words, the ion transports cannot explain the higher density of nighttime oxygen ions at the middle and high latitudes ($|\lambda| \geq 50^\circ$) of the summer hemisphere, indicating that there are other non-transport sources of oxygen ions in the nighttime summer hemisphere.

In the winter southern hemisphere, the ions mostly experience the downward and northward transports ($V_x > 0$ and $V_z > 0$ m/s) in most of the WOD region. The downward and northward transports can partly account for the

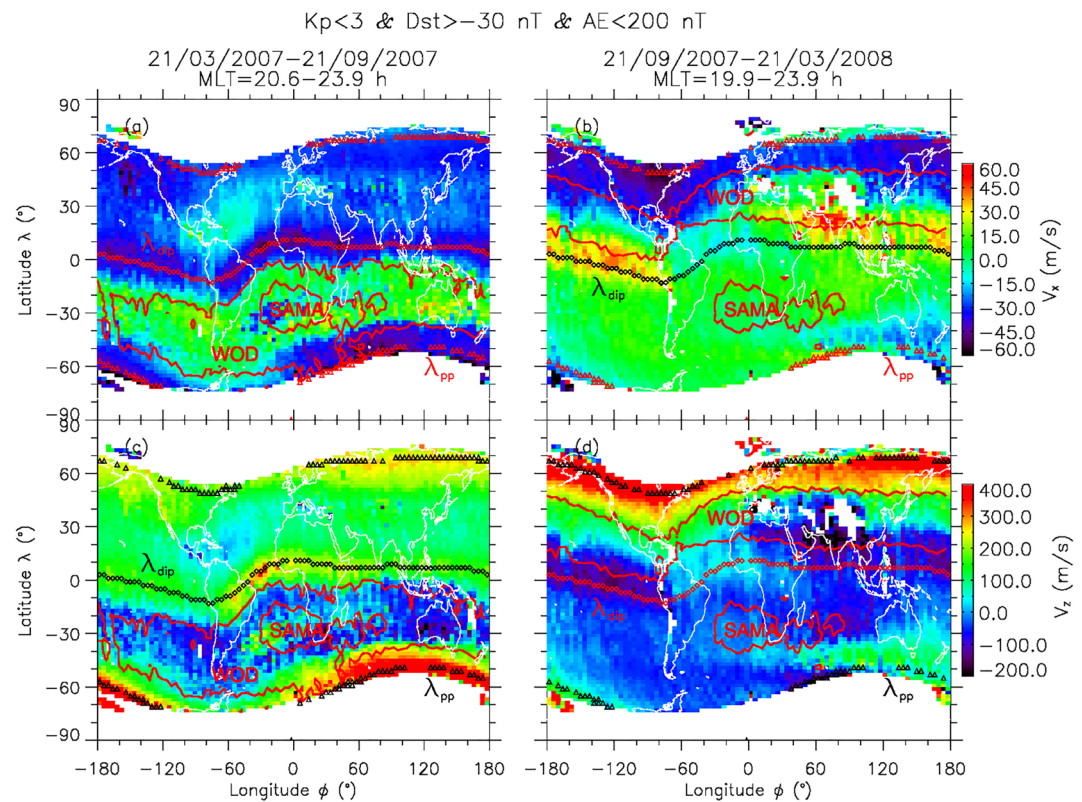


Figure 3. The vertical and latitudinal bulk velocities (V_x and V_z) of the nighttime ions measured by Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions at 670 km altitude during the quiet times. The positive and negative V_x values represent the downward and upward vertical drifts of ions, respectively. The positive and negative V_z values represent the southward and northern transports of ions, respectively.

large-scale oxygen ion depletion at the low and middle latitudes of the winter southern hemisphere, if there is no other source of oxygen ion there. Outside the poleward boundary of the WOD, the transports of ions become upward and southward, and thus the density of oxygen ions is higher there.

Although the slow transport of ions modifies the latitudinal distribution of the nighttime oxygen ions to some extent, it cannot account for the accumulation of nighttime hydrogen ions (larger $[H^+]$) at the low and middle latitudes in both hemispheres. Moreover, only the ion transport cannot explain the large-scale oxygen ion depletion in the winter northern hemisphere, as indicated by the right panels in Figures 1 and 2. During the northern winter, the movement of ions are mostly upward ($V_x < 0$ m/s) and southward ($V_z > 0$ m/s) in the north of the WOD center in the northern hemisphere, but they become downward and northward in the south of the WOD center (indicated by the right panels in Figures 3 and 4). The higher density of hydrogen ions in the WOD region suggests the existence of a non-transport source of hydrogen ions such as the charge exchange with oxygen ions ($H + O^+ \leftrightarrow H^+ + O$).

The non-transport source is further confirmed by the higher density of oxygen ions in the summer southern hemisphere. As indicated by the right panels in Figures 3 and 4, the downward and northward ion transports should reduce the oxygen ions in the summer southern hemisphere, if there is no a non-transport source there. On the contrary, the satellite observations indicate that the density of nighttime oxygen ions is still higher in most regions of the summer southern hemisphere, except for the SAMA region (the right panels in Figures 1 and 2). These inconsistencies indicate that the chemical reactions (e.g., photoionization and/or charge exchange) play more significant roles in modifying the latitudinal distributions of ions at 670 km altitude.

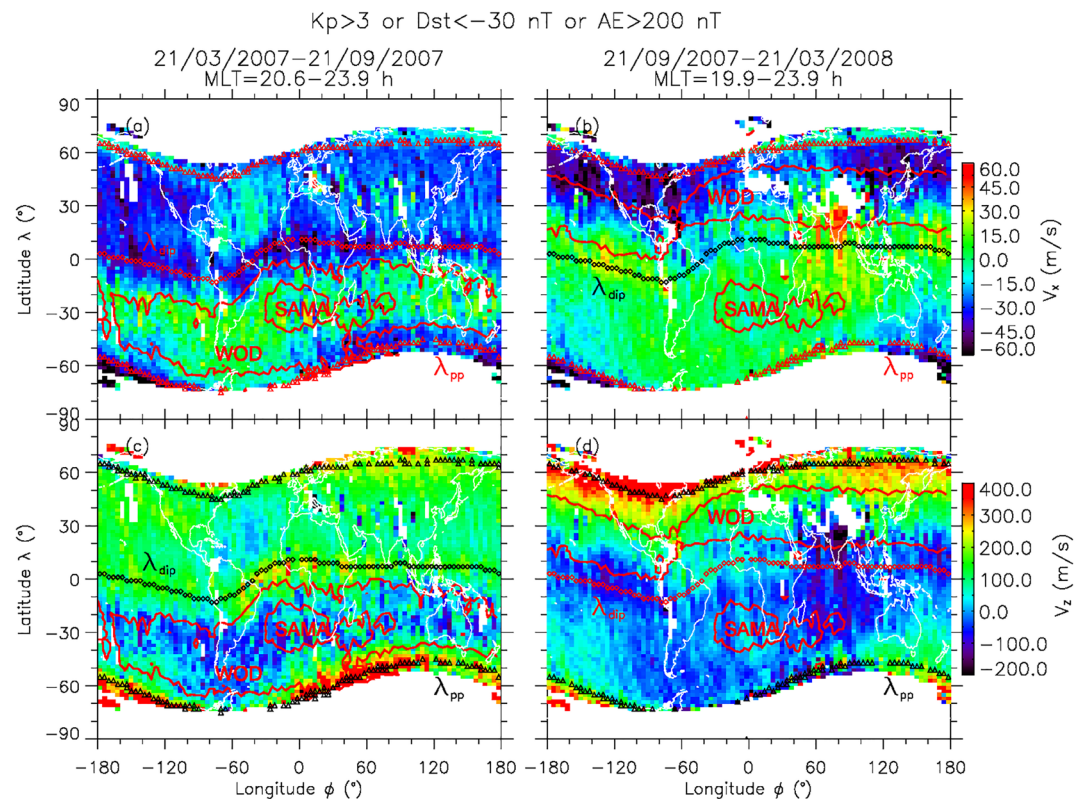


Figure 4. Similar to Figure 3, but during the active times.

4.2. Source of Nighttime Oxygen Ions in Summer Hemisphere

To examine the effects of photoionization and charge exchange reactions, we calculated the density and temperature of neutral atmospheric compositions through the NRLMSISE-00 atmospheric model (Picone et al., 2002). Figure 5 displays the latitudinal distributions of ionized and neutral temperatures (T_i and T_n) at 670 km altitude in nighttime (LT \sim 22.5 hr), and Figure 6 displays the densities of the nighttime neutral atomic oxygen (O) and hydrogen (H) and their density ratio (8[O]/9[H]) in different seasons.

In both hemispheres, the temperatures of ions and neutral compositions (T_i and T_n) are higher near the polar region ($|\lambda| \geq 50^\circ$) than other latitudes in the nighttime. The high ionized and neutral temperatures are likely associated with the polar ionospheric heating by precipitating particles (Richards, 2013) and/or Joule heating (Kalafatoglu Eyiguler et al., 2018). However, the heating by precipitating particles or Joule heating should be conjugate in both hemispheres, they cannot explain the higher temperatures at the middle and high latitudes ($|\lambda| \geq 50^\circ$) in the summer hemisphere than the winter hemisphere. Since the middle and high latitudes ($|\lambda| \geq 50^\circ$) of summer hemisphere are mostly in the polar-day region ($|\lambda| \geq 66.5^\circ$), those latitudes likely accept sunlight through the scattering of atmosphere. The polar-day sunlight can account for the higher temperatures of ions and neutral compositions at the middle and high latitudes ($|\lambda| \geq 50^\circ$) of summer hemisphere.

Interestingly, the density ([O]) of neutral atomic oxygen is also maximum at the middle and high latitudes ($|\lambda| \geq 50^\circ$) of summer hemisphere (Figures 6a and 6b). This is perhaps due to the heating expansion of the dense atmosphere at lower altitudes (Li et al., 2015). Like the daytime, the enough atomic oxygen in the polar-day region can be ionized to more oxygen ions ($O + h\nu \rightarrow O^+ + e^-$). The photoionization of neutral oxygen caused by the polar day can supply the continuous source for the nighttime oxygen ions at the middle and high latitudes ($|\lambda| \geq 50^\circ$) of summer hemisphere. Thus, the density of nighttime oxygen ions can maintain a higher level at the middle and high latitudes of summer hemisphere (Figures 1 and 2), even though there are the downward and northward transports of ions there (Figures 3 and 4). The photoionization of neutral atomic oxygen in the polar-day region is a significant source of the nighttime oxygen ions in summer hemisphere in the topside ionosphere.

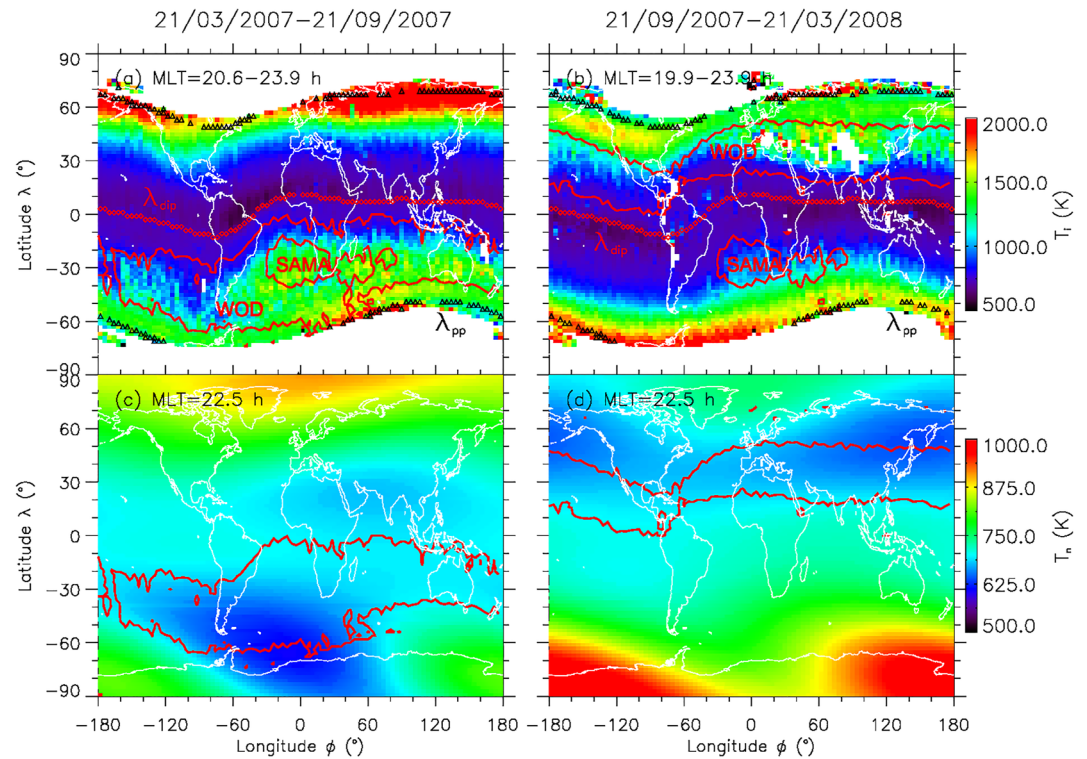


Figure 5. The temperatures of ions and neutral compositions at 670 km altitude. The ion temperature (T_i) is measured by the Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions satellite. The neutral temperature (T_n) is calculated by through the NRLMSISE-00 atmospheric model (Picone et al., 2002).

4.3. Effect of Charge Exchange Reactions on the Nighttime Oxygen Ions

Unlike the polar-day region of summer hemisphere, the nighttime ionosphere at the low and middle latitudes cannot accept sunlight, especially in the winter hemisphere. The nighttime ionospheric ions at the low and middle latitudes mainly experience $\mathbf{E} \times \mathbf{B}$ drifts, neutral wind transports and/or charge exchange reactions ($\text{H} + \text{O}^+ \leftrightarrow \text{H}^+ + \text{O}$). However, only the $\mathbf{E} \times \mathbf{B}$ drifts and/or neutral wind transports cannot explain the nearly opposite latitudinal distributions of oxygen and hydrogen ions at 670 km altitude, suggesting that the charge exchange reactions also modify the densities of nighttime oxygen and hydrogen ions in the topside ionosphere.

During the charge exchange reactions, the production (S) or loss (L) of oxygen and hydrogen ions relies on the relative concentrations of neutral atomic oxygen (O) and hydrogen (H). At the low and middle latitudes of winter hemisphere, the density of atomic oxygen ($[\text{O}]$) is much lower than that of atomic hydrogen ($[\text{H}]$), as indicated by Figures 6a and 6d. The more atomic hydrogen in winter hemisphere is due to the cross-equator winds blowing from the summer hemisphere to the winter hemisphere (Mauersberger et al., 1976). At the low and middle latitudes of winter hemisphere, the more atomic hydrogen and the less atomic oxygen ions are conducive to the loss of oxygen ions and the production of hydrogen ions during the charge exchange reactions ($\text{H} + \text{O}^+ \leftrightarrow \text{H}^+ + \text{O}$). Since hydrogen and oxygen have almost identical ionization potentials, the charge exchange is a very easy process.

If other source or loss (e.g., transport) of ions is very weak or absent, the density ratio of oxygen and hydrogen ions ($[\text{O}^+]/[\text{H}^+]$) and that of their neutral compositions ($[\text{O}]/[\text{H}]$) agree with a chemical equilibrium relationship (Hanson & Ortenburger, 1961):

$$\frac{[\text{O}^+]}{[\text{H}^+]} = K \frac{[\text{O}]}{[\text{H}]} \quad (3)$$

The equilibrium constant K is about 8/9 in the coupling region of ionospheric F2 region and protonosphere (Hanson & Ortenburger, 1961). Equation 3 is valid only when the charge exchange reactions are dominate.

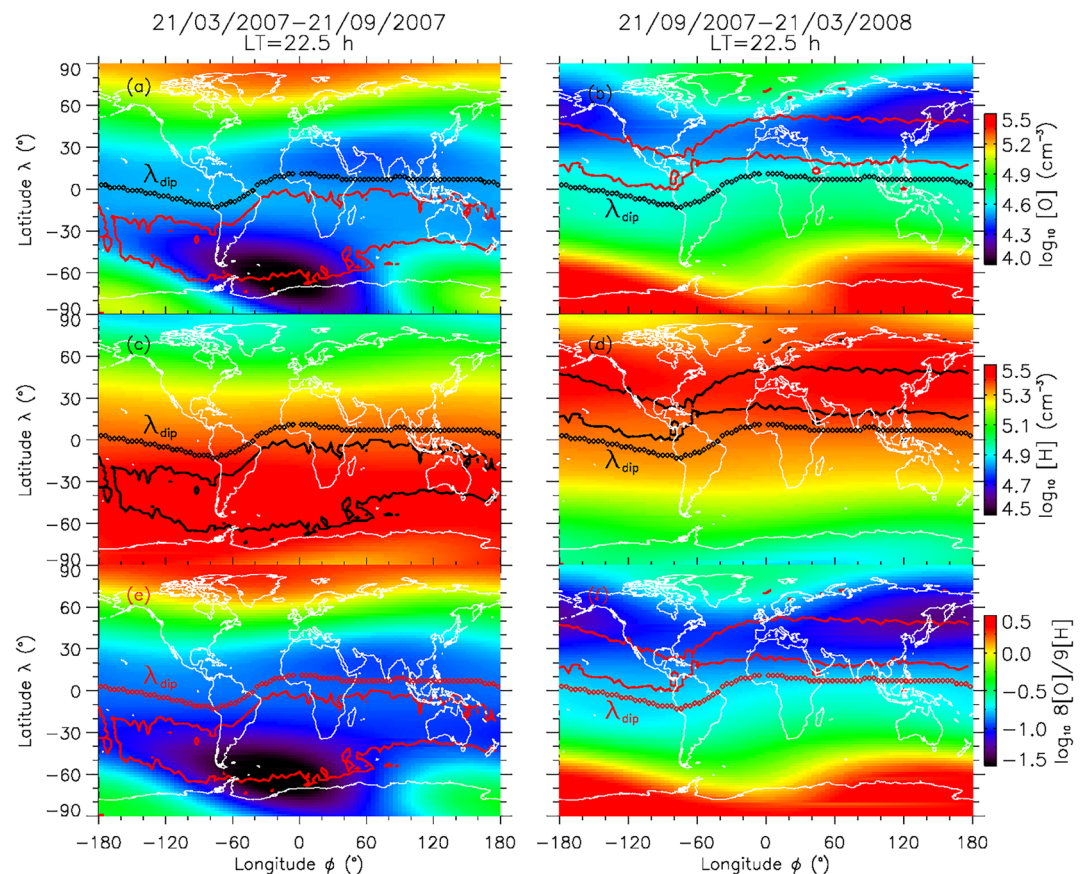


Figure 6. The number densities of neutral atmospheric compositions in nighttime at 670 km altitude. The density ($[O]$) of atomic oxygen and that ($[H]$) of atomic hydrogen are calculated through the NRLMSISE-00 atmospheric model (Picone et al., 2002).

Comparing Figures 1e and 1f with Figures 6e and 6f, it can be found that the density ratio of the two ion species ($[O^+]/[H^+]$) is nearly equal to that of their neutral compositions ($8[O]/9[H]$) in the WOD region (between the open red contours), approximately agreeing with the chemical equilibrium relationship of charge exchange reactions (Equation 3). This demonstrates that the charge exchange reactions are mainly responsible for the large-scale oxygen ion depletion at the low and middle latitudes in winter hemisphere. The chemical equilibrium of charge exchange reactions exists only in the WOD region with high-density atomic hydrogen but slow transport velocity. At other latitudes, the ionized and neutral densities do not satisfy the chemical equilibrium, indicating that the $\mathbf{E} \times \mathbf{B}$ drifts or plasma diffusions also modify the ion density distributions in the topside ionosphere. However, the charge exchange reactions still exist in the topside ionosphere and therefore lead to the opposite changes in the oxygen and hydrogen ion densities at the low and middle latitudes in summer hemisphere (Figures 1 and 2).

As indicated by the continuity Equation 1 the densities of nighttime ions rely on the competition between their production and loss. On the one hand, the heavy oxygen ions and the light hydrogen ions could have different responses to the same neutral wind transports or $\mathbf{E} \times \mathbf{B}$ drifts. On the other hand, different ion species at the same altitude have also different chemical sources or losses. The nighttime oxygen ions are mainly produced by the photoionization of neutral oxygen ($O + h\nu \rightarrow O^+ + e^-$) in the polar-day region, and they also experience the loss due to charge exchange reactions ($H + O^+ \leftrightarrow H^+ + O$). Unlike the multiple sources of oxygen ions, the production and loss of hydrogen ions (H^+) is mainly caused by charge exchange reactions in the topside ionosphere (Zhao et al., 2005). The different sources and losses result in the difference of the latitudinal distributions of oxygen and hydrogen ions in the topside ionosphere.

5. Summary and Conclusions

Our statistical results demonstrate that the large-scale depletion of nighttime oxygen ions is prevalent at the low and middle latitudes of winter hemisphere (center $\sim 30^\circ$) at 670 km altitude under different geomagnetic conditions. The latitudinal width of the WOD region is about 20° – 60° at different longitudes, and its upper boundary latitudes are mostly lower than the midlatitude trough ($|\lambda| \geq 50^\circ$) of nighttime hydrogen ions (H^+) near the plasmopause. The density of nighttime oxygen ions is lower in the WOD region than the midlatitude trough of nighttime hydrogen ions.

By analyzing the relationships among the latitudinal changes in the ion bulk velocity, densities, and their neutral densities, we found that only the latitudinal and vertical transports of ions cannot fully account for the nearly opposite latitudinal distributions of nighttime oxygen and hydrogen ions in the topside ionosphere. In the WOD region, the density ratio of the oxygen and hydrogen ions ($[O^+]/[H^+]$) is nearly equal to that of their neutral densities ($8[O]/9[H]$). This agrees with the chemical equilibrium relationship of charge exchange reactions ($H + O^+ \leftrightarrow H^+ + O$) predicted by previous theory, indicating that the charge exchange reactions are mainly responsible for the large-scale depletion of nighttime oxygen ions at the low and middle latitudes in winter hemisphere in the topside ionosphere.

The chemical equilibrium of charge exchange reactions exists mainly in the WOD region with high-density atomic hydrogen but slow transport velocity. At other latitudes, the ionized and neutral densities do not satisfy the chemical equilibrium, indicating that plasma transports ($\mathbf{E} \times \mathbf{B}$ drifts or diffusions) and other chemical sources also modify the ion density distributions in the topside ionosphere. The photoionization of neutral atomic oxygen in the polar day region ($|\lambda| \geq 50^\circ$) in the summer hemisphere can supply the continuous source for the nighttime oxygen ions in the topside ionosphere, and thus the oxygen ion density can maintain higher levels at the middle and high latitudes of summer hemisphere. The chemical reactions result in the strong coupling of topside ionosphere and upper atmosphere at the 670 km altitude.

Data Availability Statement

DEMETER IAP data are available at the Web site <http://demeter.cnrs-orleans.fr/>. Geomagnetic indices (K_p , SYM-H/Dst, AE) are publicly available from OMNI database in the CDAWeb http://cdaweb.gsfc.nasa.gov/sp_phys. The density and temperature of neutral compositions from the NRLMSISE-00 atmospheric model are publicly available at the web <https://figshare.com/s/0bff3225c7623deb9ec4>. The NRLMSISE-00 model is publicly available at the Web site <http://ccmc.gsfc.nasa.gov/modelweb>.

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