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Key Points:

- H_T increased by 100 km for a marginal increase in solar activity by 11.76 sfu
- Unusual equatorial minimum and temporal evolution of H_T at equatorial latitudes
- Charge exchange at altitudes as low as ~550 km during the deep solar minimum

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Unique latitudinal shape of ion upper transition height (H_T) surface during deep solar minimum (2008–2009)

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Abstract The ionospheric upper transition height (H_T) is found to increase dramatically by ~100 km from 2008–2009 to 2010 only for a marginal increase in solar activity ($F_{10.7}$) by 11.76 solar flux units. The latitudinal variation of H_T surface during 2008–2009 period exhibits a local minimum at equatorial latitudes and increase at low latitudes. Further, the H_T at equatorial latitudes exhibits slower rate of increase than at low latitudes. These interesting features are new and different from those reported in literature. A quick loss of O^+ and increase in H^+ ions are observed around ~550 to 650 km indicating that the charge exchange reaction is responsible for the slower rate of increase and lowered H_T at equatorial latitudes. These new aspects of H_T are more conspicuously observed during this deep solar minimum period where the resonant charge exchange reaction is taking place at altitudes as low as ~550 km.

1. Introduction

The topside ionosphere is primarily composed of electrons, the dominant O^+ and H^+ ions along with a minor He^+ contribution. The photoionization, chemical and transport processes applied at lower altitudes determine the abundances of the two major O^+ and H^+ ions in the topside ionosphere. The dominant ion at the F_2 layer peak is O^+ which decreases exponentially with height so that the lighter ions H^+ and He^+, which have the scale height much larger than that for O^+ become dominant at greater altitudes. The altitude where the dominant ions changes from O^+ to lighter ions ($H^+ + He^+$) is defined as the ionospheric upper transition height (H_T). The vertical distributions of O^+ and H^+ ions are controlled by several processes like photoionization of atomic oxygen (O) at lower altitudes, ion temperature (which influences the scale height), abundances of neutral oxygen and hydrogen (which affects the charge exchange process), and field-aligned transport induced by *F* region neutral winds. Therefore, the transition height (H_T) is an important parameter that responds to the changes in the underlying photochemical and transport processes in the ionosphere. The transition height is also an important parameter considered in many empirical models to describe the altitudinal distribution of ion density and composition [*Bilitza et al.*, 2007, and references therein]. As the transition height represents the base of the plasmasphere, an accurate description of this parameter plays a critical role in models that reconstruct the ion/electron density profiles by smoothly connecting the upper ionospheric profiles with plasmaspheric profiles deduced from topside measurements [*Reinisch et al.*, 2007].

A number of studies on the transition height and its spatial and temporal variations can be found in the literature. All these studies principally employ two different observational techniques to determine the transition height: (i) ion composition measurements by in situ sensors [e.g., *Miyazaki*, 1979; *Kutiev et al.*, 1980; *Gonzalez et al.*, 1992; *Heelis et al.*, 2009] or by incoherent scatter radars [e.g., *Hysell et al.*, 2009] and (ii) altitudinal profiles of ion density measured by topside or ground-based sounders [e.g., *Titheridge*, 1976; *Webb et al.*, 2006; *Kutiev et al.*, 1994; *Marinov et al.*, 2004; *Kutiev and Marinov*, 2007] and GPS radio occultation [e.g., *Yue et al.*, 2010]. A detailed description of the variation of transition height is provided by *Titheridge* [1976] who used theoretical ion density profiles (described by analytical functions) to fit with topside profiles observed by Alouette-1 by iteratively changing the temperature, temperature gradient, and transition height until a best fit was obtained. The best fit transition heights derived by *Titheridge* [1976] show a broad minimum around the geomagnetic equator and low latitudes with a sudden enhancement around the plasmapause location near 55°N during daytime of solar minimum period (1962–1965). This sudden enhancement is attributed to a large vertical flux of protons and polar wind causing a depletion of H^+ ions outside the plasmasphere where the flux tubes are continually refilling [*Titheridge*, 1976]. Using in situ observations of ion composition from the Taiyo satellite, *Miyazaki* [1979] also showed a similar broad minimum in the transition height (about 800 km) at the dip equator and an increase to ~1200 km at ±30° dip latitudes during the solar minimum period of 1975–1976. *Miyazaki* [1979] explained this increase in the transition height as due to charged particle temperature increase and upward movement of O^+ ion density. On the other hand, the transition heights derived using the shape and/or scale height of topside ion density profiles [*Marinov et al*., 2004; *Kutiev and Marinov*, 2007; *Yue et al*., 2010] show a distinct maximum around the geomagnetic equator and a decrease with latitudes away from the equator. This discrepancy observed in *Marinov et al*. [2004], *Kutiev and Marinov* [2007], and *Yue et al*. [2010] perhaps arises because of (i) their assumption of constant scale height of O^+ above the F_2 peak and (ii) the influence of $E \times B$ drift on the profile shape at equatorial latitudes [*Tulasi Ram et al*., 2009, 2010]. Many of the above studies (except *Yue et al*. [2010]) present the latitudinal variation of H_T either during (June and December) solstices or combining the data from solstices and equinoxes together. One of the common features observed from these studies is that the H_T in the summer hemisphere is higher than in the winter hemisphere because of field-aligned upward transport of O^+ by summer to winter transequatorial neutral wind. However, there were not many studies (except *Yue et al*. [2010] and *Tulasi Ram et al*. [2010]) on the latitudinal behavior of H_T exclusively during equinoxes where the transequatorial neutral wind effects were minimized and the effect of $E \times B$ is maximized over equatorial latitudes.

Recently, *Heelis et al*. [2009] have reported that the O^+/H^+ transition heights during the past deep solar minimum of 2008 were remarkably low resulting in an unusually contracted ionospheric shell. They have attributed these extremely low transition heights to very low levels of EUV (extreme ultraviolet) heating and photoionization in the upper atmosphere. In addition to EUV heating and photoionization, *F* region meridional winds produce a significant latitudinal gradient in the transition height across the magnetic equator. In this paper, we report further important results on the local time and latitudinal variations of H_T during equinoxes observed during the transition from the deep solar minimum period 2008 to slightly higher solar activity levels in 2010 and responsible mechanisms are discussed in terms of equatorial $E \times B$ drift and the O^+/H^+ charge exchange reaction.

2. Data and Observations

The Coupled Ion-Neutral Dynamics Investigation (CINDI)-Retarding Potential Analyzer (RPA) on board the C/NOFS (Communication/Navigation Outage Forecast System (C/NOFS)) with its elliptical orbit (perigee near 400 km and apogee near 860 km) provides unprecedented altitudinal coverage of in situ ion density, temperature and composition measurements in the equatorial and low latitudes. In this study, the CINDI-RPA data during exclusively equinoctial months of 2008–2009 (September–October 2008 and March–April 2009) and 2010 (March, April, September, and October 2010) were considered. The transition heights (H_T) in this study is defined as the altitudes at which the O^+ density becomes equal to the light ions ($H^+ + He^+$) density in a manner similar to that employed by *Tulasi Ram et al*. [2010]. The derived transition heights are accumulated in 1 h local time and 1° latitudinal intervals to study the temporal and spatial variations of the transition height surface at equatorial and low-latitude regions (between ±13° geomagnetic latitudes).

The local time and latitudinal variations of $O^+/(H^+ + He^+)$ transition height surface during the equinoctial months of September–October 2008 and March–April 2009 are presented in Figure 1a. The monthly average $F_{10.7}$ centimeter solar flux values for the above months are 67.7, 67.75, 68.42, and 70.11 solar flux units (1 sfu = 10^{-22} W m^{-2} Hz^{-1}), respectively, which are indicative of extremely low solar activity conditions. It can be seen from this figure that the H_T increases rapidly at sunrise in response to rapid production of O^+ and thermal expansion of neutral and ionized atmosphere via EUV heating. The H_T decreases after sunset and collapses to its lowest values ~450 km during the postmidnight to predawn hours. For better clarity, the line plots showing magnetic latitudinal variation of H_T at 1 h intervals from sunrise to noon (06–12 LT) were presented in the right-hand side of Figure 1a. An important feature that can be observed from both contour and line plots of Figure 1a is that the latitudinal variation of the H_T exhibits a clear minimum around geomagnetic equator. This local minimum at the magnetic equator persists up to local noon (~1200 LT). During the afternoon hours, the H_T at equatorial latitudes increases and a maximum at the magnetic equator

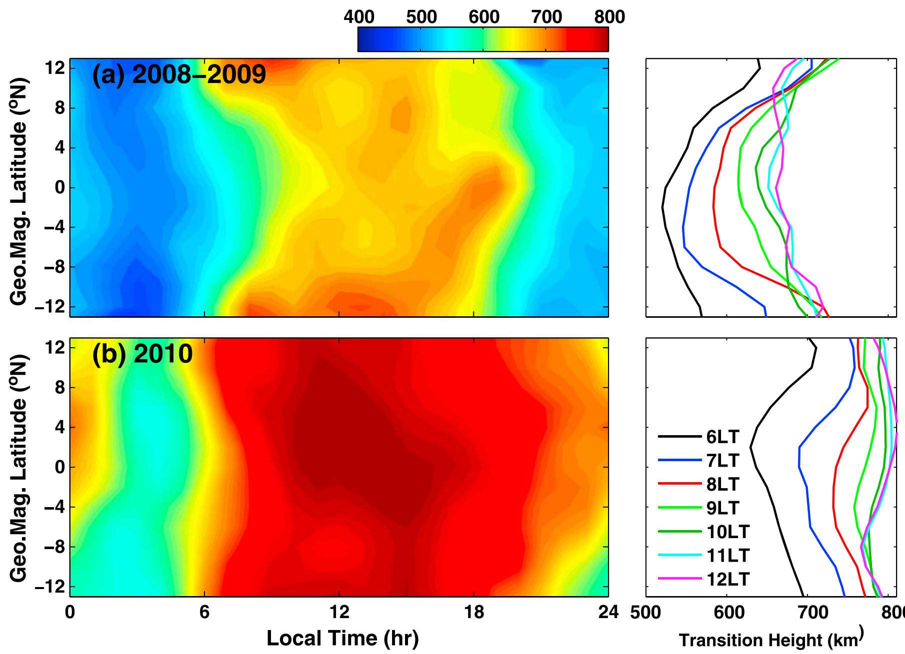

Figure 1. The local time and geomagnetic latitudinal variations of $O^+/(H^+ + He^+)$ transition height (H_T) surface during equinoctial months of (a) the extremely low solar activity period 2008–2009 and (b) slightly higher solar activity period 2010. The right-hand side panels show the line plots of magnetic latitude variation of H_T during 06–12 LT for better clarity.

is seen from 1700 LT. This maximum remains prominent until 2000 h, when the transition height collapses rapidly to levels near 500 km that are retained throughout the night up to sunrise. This latitudinal variation is in significant contrast with the broad minimum of H_T from equator to plasmapause (~55°N) observed by *Titheridge* [1976]. It is also different from that observed by *Yue et al*. [2010], *Marinov et al*. [2004], and *Kutiev and Marinov* [2007] in which the H_T shows a distinct maximum at equator and decreases at latitudes away from the equator during the periods of low solar activity.

Figure 1b shows the similar local time and latitudinal variations of H_T surface during the equinoctial months (March, April, September, and October) under slightly higher solar activity conditions in 2010. The monthly average $F_{10.7}$ solar flux values during this period increased only marginally and are 82.12, 76.24, 81.81, and 80.89 sfu, respectively. The 4 months average of $F_{10.7}$ centimeter solar flux is only increased by 11.76 sfu (i.e., from 68.5 sfu in 2008–2009 to 80.26 sfu in 2010). However, it is interesting note from Figure 1b that the transition heights during 2010 are, in general, higher by ~100 km than those observed during 2008–2009 period at almost all local times and latitudes owing to the overall increase in solar activity. The line plots of magnetic latitude versus H_T during 06–12 LT were shown in the right-hand side for better clarity. The latitudinal variation of H_T during 2010 also shows a local minimum at the magnetic equator across sunrise (06–07 LT). However, it is much shorter lived than in the previous case, extending only out to about 0900 h. At this local time a local maximum in the transition height appears and persists well beyond sunset and toward midnight. It should be mentioned here that this local equatorial minimum in H_T is not observed during the sunrise hours of higher solar activity year 2011 (not shown in figure). However, the H_T during 2011 is much higher and beyond the apogee of C/NOFS (inaccessible) during most of the daytime hours.

Comparison of Figures 1a and 1b also suggests that during the extreme solar minimum at the magnetic equator the transition height rises less rapidly after sunrise but is lowered more rapidly after sunset, that at periods of higher solar activity. To investigate these features in more detail, the local time variations of H_T at three selected latitudinal bins of the equator and low latitudes (−12° and 12° geomagnetic) during 2008–2009 and 2010 are presented in Figures 2a and 2b, respectively. In the 2008–2009 period the H_T at low latitudes (blue and red curves) exhibits a rapid increase around sunrise and quickly reaches a maximum at ~0800 LT. The H_T then decreases slowly throughout the day until 2000 LT when it drops dramatically.

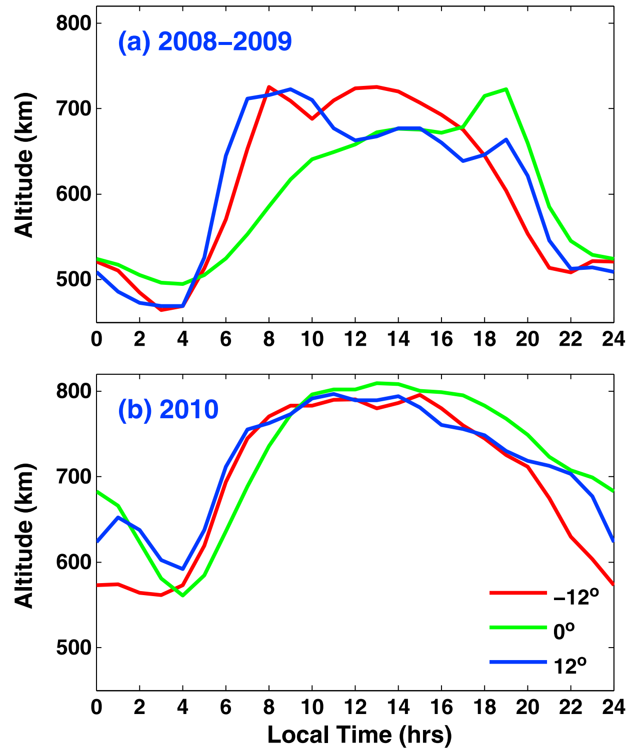

Figure 2. The local time variation of H_T at three selected latitudinal bins of equator (green) and ±12° geomagnetic latitudes (blue and red) during the equinoctial months of (a) 2008–2009 and (b) 2010 periods.

The low-latitude H_T during 2010 period (Figure 2b) also exhibits similar surge around sunrise but continues to increase slowly during the daytime to reach a maximum in the afternoon hours before decreasing almost linearly with time until well after midnight.

During the deep solar minimum period of 2008–2009 (Figure 2a), the rapid increase in H_T around sunrise is distinctly absent at the magnetic equator. In fact, it increases continuously during the day, reaching a peak just after sunset before rapidly decreasing over a period of 2 to 3 h. This contrasts rather markedly with the behavior seen during the 2010 period when H_T behaves much as it does at latitudes off the equator, with an increase after sunrise to a maximum near local noon and a gradual decrease throughout the afternoon and evening hours.

The important points that can be noted from Figures 1 and 2 are first that the transition heights are increased by ~100 km from 2008–2009 to 2010 due to a marginal increase of solar activity ($F_{10.7}$ solar flux) by 11.76 sfu. Further, during the extreme solar minimum period, the latitudinal variation of H_T surface exhibits a minimum at the magnetic equator that extends from sunrise to local noon. This contrasts rather sharply with the behavior seen at slightly higher solar activity levels when H_T shows a very shallow minimum at the magnetic equator that extends only from sunrise to 0900 LT.

It is known that the spatial and temporal variations of H_T can be controlled by several factors including the total ion density via production and the ion temperature via thermal expansion of neutral and ionized atmosphere. Therefore, the in situ ion density and temperatures measured by C/NOFS-CINDI during the same period were examined. Figure 3 shows the latitudinal and local time (between 05 and 11 LT) variations of total ion density (Ni) and ion temperature (Ti) at different altitudes between 450 km and 700 km during the equinoctial months of 2008–2009 period. Figures 3a–3f show the variations in total ion density (Ni), and Figures 3g–3l show the variations in ion temperature (Ti).

Figure 3a shows that the ion density increases rapidly after sunrise at 450 km indicating that the production and upward field-aligned transport of O^+ are the dominant processes at this upper F region altitude. Near 0800 LT the total ion density shows a local maximum at the magnetic equator indicating that upward $E \times B$ drifts at the equator also contribute to upward transport of O^+ over the equator. At higher altitudes, no clear latitudinal variation of ion density is observed indicating that at this altitudes/local time periods $E \times B$ drift effects become insignificant. In Figure 3g, the ions are in good thermal contact with the neutral gas near 450 km altitude. But at higher altitudes the ion temperature increases rapidly at sunrise and is inversely proportional to the ion density as one would expect for heat that is distributed throughout the magnetic flux tubes.

In Figure 4 we examine separately the latitude and local time distributions of the constituent O^+ (Figures 4a–4f) and H^+ (Figures 4g–4l) densities measured by C/NOFS-CINDI in the altitude range from 450 km to 700 km for the extremely low solar activity period of 2008–2009. It can be seen from these figures that at relatively low altitudes of 450 and 500 km, the O^+ density is higher than H^+ at all latitudes and local times except the predawn period of 05–06 LT, when they are comparable. After sunrise, the O^+ density increases rapidly at lower altitudes,

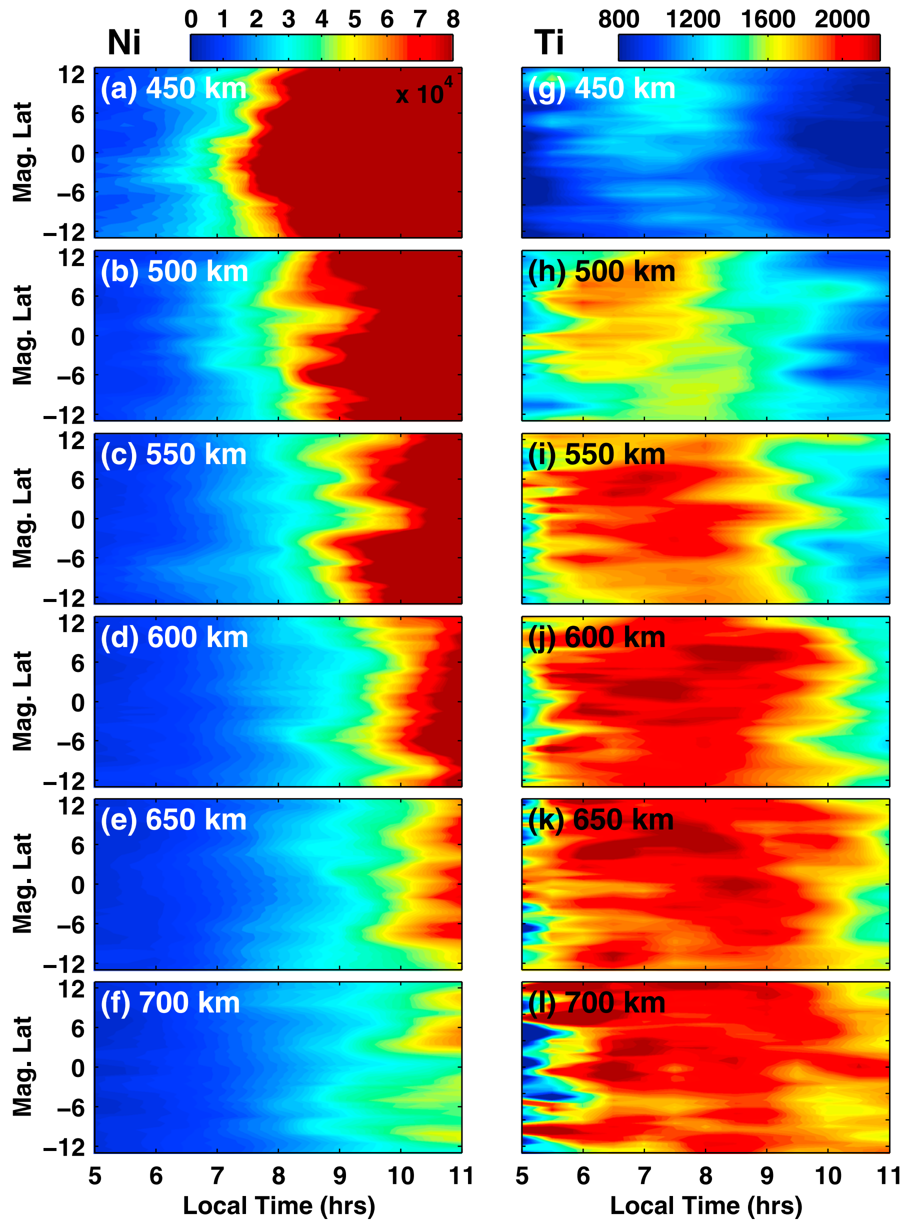

Figure 3. The latitudinal and local time (between 05 and 11 LT) variations of (a–f) total ion density and (g–l) ion temperature at different altitudes starting from 450 to 700 km during equinoctial period of 2008–2009. The scale shown for Ni is multiples of $10^4\ cm^{-3}$.

but the increase at higher altitudes is delayed in local time since the rapid production of O^+ takes place below the *F* peak at altitudes below the satellite. At low altitudes (450–500 km), the O^+ density shows some enhancement at the equator, but at higher altitudes and later local times, a local minimum in the O^+ density appears as indicated by arrows. By contrast, during this equinoctial period, the H^+ density shows a local peak at the equator throughout the daytime. This behavior is associated with a more gradual rise in the transition height at the equator compared to the rapid rise seen at latitudes away from the equator. We note that the local minimum in O^+ at the equator appears only at altitudes where H^+ becomes the dominant ion with a local maximum at the equator.

Figure 5 shows similar latitudinal and local time (between 05 and 11 LT) variations of O^+ and H^+ densities during the relatively higher solar activity period of 2010. In this case the O^+ density does not show a predominant local peak at the equator when it is the dominant species. Thus, the transition height rises at the same rate at all

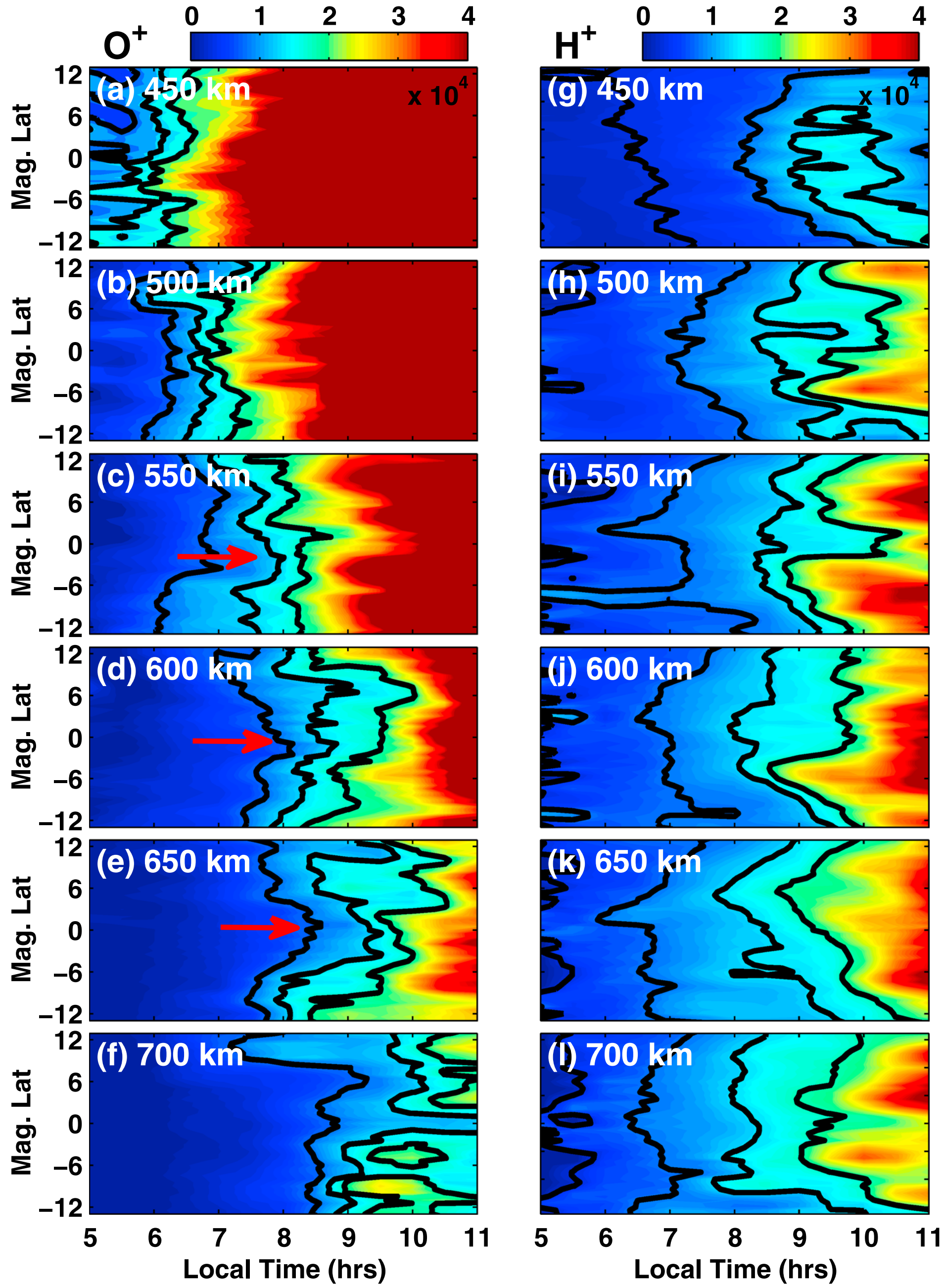

Figure 4. The latitudinal and local time (between 05 and 11 LT) variations of (a–f) O^+ and (g–l) H^+ concentrations at different altitudes starting from 450 to 700 km during equinoctial months of 2008–2009 period. The scales shown for O^+ and H^+ is multiples of 10^4 cm^{-3}.

latitudes that are shown here. The O^+ remains the dominant ion at all latitudes below about 650 km. Below this altitude the O^+ shows little variation with latitude beyond a small gradient that produces slightly higher densities at northern magnetic latitudes than at southern magnetic latitudes. We note that the 13° inclination of the C/NOFS orbit produces a bias in the data that prefers northern magnetic latitudes are sampled where the magnetic equator is at geographic southern latitudes. Thus, the northern magnetic latitudes are sampled at smaller solar zenith angles than southern magnetic latitudes. Above about 650 km we note that O^+ density shows a local minimum (as indicated by arrows) at the magnetic equator while H^+ shows enhancement and becomes the dominant ion. The change in solar activity produces these signatures at later local times and higher altitudes than seen previously (2008–2009 period).

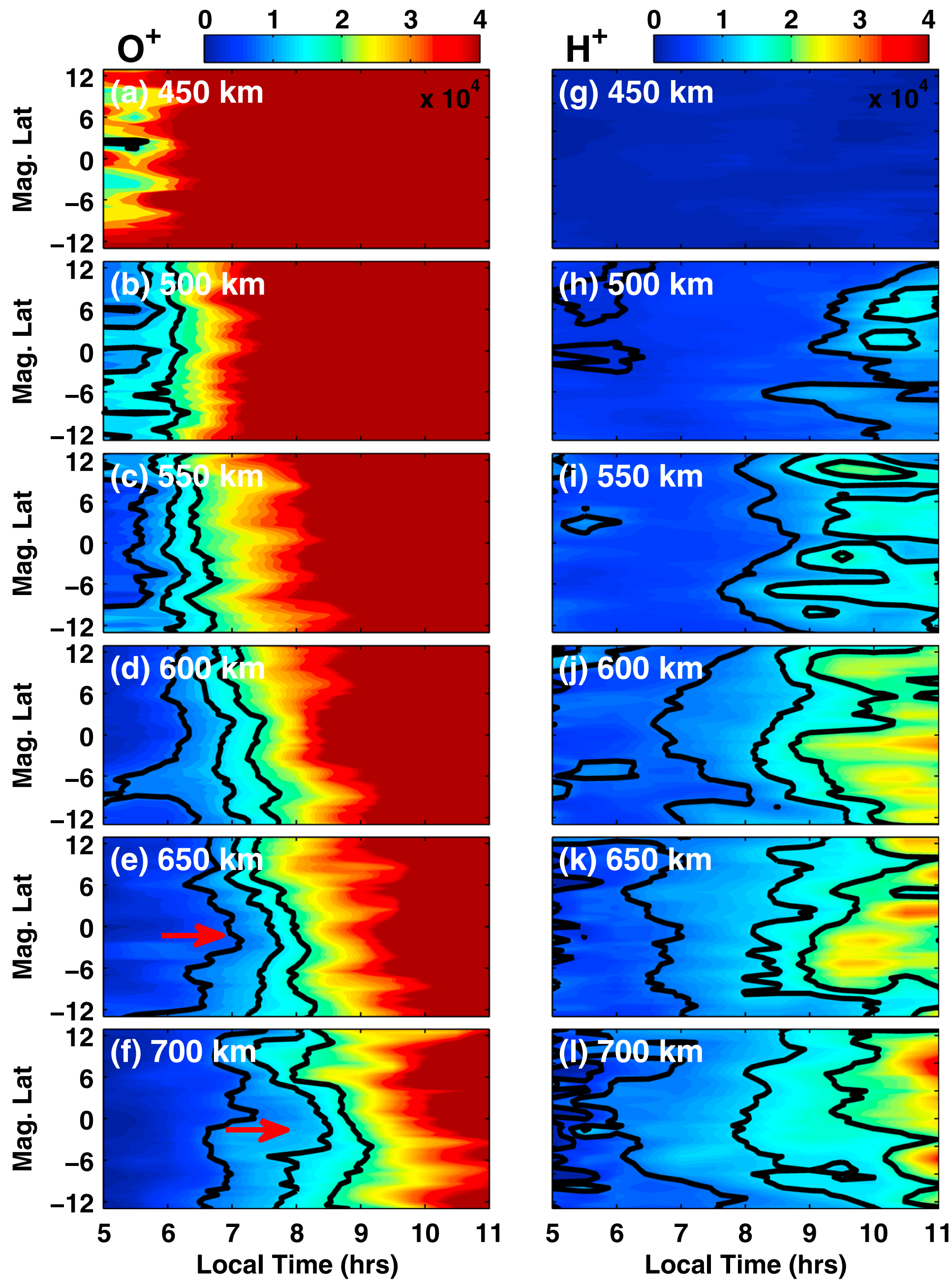

Figure 5. The latitudinal and local time (between 05 and 11 LT) variations of (a–f) O^+ and (g–l) H^+ concentrations at different altitudes starting from 450 to 700 km during the equinoctial months of slightly higher level of solar activity period 2010. The scales shown for O^+ and H^+ is multiples of 10^4 cm^{-3}.

3. Discussion

It is generally accepted that the variation of transition height is primarily controlled by the varying amounts of O^+ due to production, loss, and transport in the *F* region [*Titheridge*, 1976; *Kutiev et al.*, 1980; *Gonzalez et al.*, 1992; *Heelis et al.*, 2009, and references therein]. At sunrise, the transition height increases rapidly due to rapid production of O^+ ions at *F* region heights and upward field-aligned plasma flows. The thermal expansion of ionosphere and atmosphere by photoelectron heating is the other important factor that contributes to this sunrise increase in the transition height [*Titheridge*, 1976; *Miyazaki*, 1979; *Heelis et al.*, 2009]. In addition, the upward $E \times B$ drift at the equator would also expect to contribute for the upward transport of O^+ ions.

In the topside ionosphere, H^+ ions are produced via resonant charge exchange from O^+ and a chemical equilibrium condition [*Hanson and Ortenburger*, 1961] is attained when

$$n[H^+]/n[O^+] = 9/8\, n[H]/n[O] \tag{1}$$

At the beginning, one could think of this latitudinal structure of equatorial minimum and low-latitude increase in H_T surface as due to effect of $E \times B$ drift on O^+ at the equator and the resultant equatorial fountain or equatorial ionization anomaly (EIA) structure. However, this structure is not observed in either total ion density (Ni) or O^+ density at lower altitudes (450 to 550 km) where the EIA is pronounced than at altitudes above 550 km. Similarly, this structure in H_T and O^+ is observed starting from sunrise to local noon but becomes unclear at afternoon hours where the EIA actually maximizes. Also, this latitudinal structure in H_T and O^+ density is observed only during the extremely low solar activity period of 2008–2009, however, not observed during the slightly higher solar activity period 2010 when the EIA is expected to be stronger. Therefore, it can be understood that the equatorial fountain process or EIA is not the likely candidate responsible for this latitudinal structure observed in H_T and O^+ density.

The observations discussed here show that at the magnetic equator the transition height rises much less rapidly with local time during the extreme solar minimum than it does during even moderately increased solar activity levels. They also show that the transition height is increased in altitude by ~100 km at all locations in the equatorial region. We can conclude that over the altitude regions we have considered the satellite is much closer to the *F* peak during the moderately increased solar activity levels than during the extreme solar minimum. In the following discussion we consider separately the regions away from the magnetic equator and those very close to the magnetic equator.

In the regions away from the magnetic equator, after sunrise the O^+ concentration rises rapidly and the H^+, which is produced by charge exchange between O^+ and neutral H, flows upward to occupy a large flux tube volume above the observation altitude. At extremely low levels of solar activity the observations are taken at altitudes much above the *F* peak. At sunrise the plasma distribution departs significantly from diffusive equilibrium and the transition height rises rapidly as O^+ is produced by photoionization. The H^+, produced by charge exchange, begins to fill the flux tubes, and the transition height is gradually lowered as a state of diffusive equilibrium for O^+ and H^+ is reached until it drops sharply at sunset. For more moderate levels of solar activity, the observations are made closer to the *F* peak and a state of diffusive equilibrium is reached more rapidly. Thus, the transition height rises in accord with the O^+ production rate and drops at sunset as expected.

In regions very close to the magnetic equator, the flux tube volumes are quite small compared to the regions at higher latitudes. Thus, after sunrise the plasma reaches a state of diffusive equilibrium much more rapidly. At extremely low solar activity, this equilibrium is observed in a region where the neutral O/H ratio is small and the flux tube volume is small. In this case the O^+/H^+ transition height evolves in the same way as the neutral transition height. Note, for example, the depletion of O^+ and enhancement in H^+ density that is evident around 550–650 km in Figure 4. Under these conditions the transition height raises throughout the day as the neutral temperature rises and drops dramatically at sunset as recombination of O^+ dominates the plasma distribution. At more moderate levels of solar activity the diffusive equilibrium behavior is observed where the neutral O/H ratio is larger and the transition height varies with time in much the same way as at other latitudes. We note that it is the unique combination of small flux tube volume between the *F* peak and the magnetic apex height and the relatively large neutral hydrogen concentration in this volume that leads to the significant minimum in the transition height at the equator and to the dramatically different evolution of the transition height with local time. However, this hypothesis could be investigated further, perhaps, by model simulations.

4. Conclusions

A detailed study on the ionospheric upper ($O^+/(H^+ + He^+)$) transition height and its latitudinal and local time variability during the equinoctial months of deep solar minimum period 2008–2009, as well as in more moderate but low solar activity in 2010, is carried out using C/NOFS-CINDI ion composition measurements. The transition heights are increased by ~100 km from 2008–2009 to 2010 though the solar activity is only increased marginally. The transition heights (H_T) at low latitudes generally exhibit a rapid increase after sunrise; however, the rate of increase of H_T over equator is significantly lower than at latitudes displaced from the equator. This difference in the temporal gradients of H_T between equatorial and low latitudes is predominantly seen during the deep solar minimum period of 2008–2009. As a result, the latitudinal variation of H_T surface exhibits a pronounced minimum over equatorial latitudes that persist from sunrise to local noon. This interesting latitudinal shape of H_T surface is more conspicuous during 2008–2009 and becomes less significant during 2010. The latitudinal, altitudinal, and local time variations of total ion density (Ni), temperature (Ti), and O^+ and H^+ densities suggest that this latitudinal structure of H_T surface is not related to plasma dynamics of the equatorial anomaly. A clear depletion of O^+ and simultaneous enhancement of H^+ at equatorial latitudes suggest that the resonant charge exchange reaction between O and H dominates the observations between 550 and 650 km during the deep solar minimum period of 2008–2009. The unique combination of small flux tube volume between the *F* peak and the magnetic apex height and the relatively large neutral hydrogen concentration in this volume leads to the unique latitudinal shape and temporal evolution of the transition height surface during extreme solar minimum.

Acknowledgments
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