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Characteristics of global plasmaspheric TEC in comparison with the ionosphere simultaneously observed by Jason-1 satellite

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[1] We compared the global plasmaspheric total electron content (pTEC) with the ionospheric TEC (iTEC) simultaneously measured by Jason-1 satellite during the declining phase of solar cycle 23 (2002–2009) to investigate the global morphology of the plasmaspheric density in relation to the ionosphere. Our study showed that the plasmaspheric density structures fundamentally follow the ionosphere, but there are also significant differences between them. Although the diurnal variations are very similar to each region, the plasmasphere shows much weaker variations, only approximately 1 TECU day-night difference. By analyzing the day-night differences in the plasmasphere, we found that the plasmaspheric contribution to the nighttime ionosphere does not increase with solar activity and the largest contribution occurs during June solstice. The plasmasphere shows similar seasonal variations to the ionosphere, except for the semiannual variation, which is essentially absent in the plasmasphere. There is also an important difference in the annual variation: although the annual variation in the ionosphere exists regardless of longitude, it occurs only at American sector in the plasmasphere. As solar activity increases to moderate level, the pTEC substantially enhances from approximately 2 to 4 TECU at the initial increase of solar activity below F10.7p = 100 and then quickly slows down while the iTEC almost linearly enhances. Although it is well known that magnetic storms are the major source of plasmaspheric density depletion, pTEC does not show this aspect of the plasmasphere probably due to the relatively small K_p values for high magnetic activity ($K_p > 2.5$) in the current study.

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1. Introduction

[2] The Jason-1 was developed jointly by the Centre National d'Etudes Spatiales, France, and the National Aeronautics and Space Administration (NASA), USA, as the follow-on of the Topex/Poseidon mission, which was in orbit from 1992 to 2005 to monitor the surface of the global ocean [*Fu et al.*, 1994]. The satellite was launched on 7 December 2001 by Boeing Delta II 7920 rocket shared with another NASA mission, TIMED, and takes the orbit of its predecessor, Topex/Poseidon, to ensure better intercalibration and data continuity. The Jason-1 satellite carries a dual-frequency radar altimeter to continuously monitor sea surface height accurately to within a few centimeters all over the globe. To achieve this level of accuracy, the ionospheric correction, which is a primary factor for propagation delays between sea surface and satellite, has to be determined by precisely estimating the total electron content (TEC) along the vertical raypath from the satellite to the surface of the ocean. The TEC provides a direct measurement of the ionospheric TEC (iTEC) almost every second in a vertical column extending from the satellite orbit altitude of 1336 km to the ground. In addition to the iTEC, Jason-1 can also provide the TEC within the altitude regions between Jason-1 (1336 km) and GPS (20,200 km) satellite orbits by using the onboard GPS receiver. The orbit altitudes of 1336 km ($R = 1.21R_E$, R_E = the Earth's radius) and 20,200 km ($R = 4.17R_E$) correspond to L = 1.21 and L = 4.17 at the magnetic equator, respectively. The TEC within this region can be considered to be the plasmaspheric TEC in the low- and middle-latitude regions as can be seen in Figure 1. Therefore, Jason-1 is the first satellite that is able to observe the ionosphere and plasmasphere simultaneously.

[3] The plasmasphere is a region of relatively dense ($n \geq 10^8$ m^{-3}) and cold ($E \leq 1$ eV) plasma in the inner magnetosphere. It is nothing more than the continuation of the

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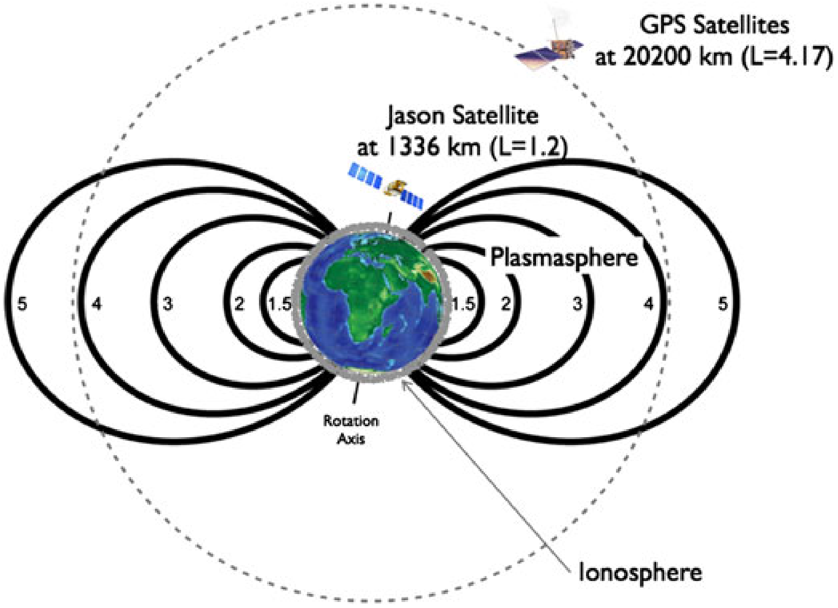

Figure 1. Jason-1 satellite measures not only the iTEC from the satellite orbit (1336 km) to ocean surface but also the plasmaspheric TEC from the onboard GPS receiver to GPS satellite orbit (20200 km) simultaneously.

ionosphere into the magnetosphere in the low- and middle-latitude regions below approximately 60° magnetic latitude. The boundary between the ionosphere and the plasmasphere is defined to be the transition region from atomic oxygen to atomic hydrogen ions as the primary ion constituent, which occurs at around 500 to 2000 km altitudes being lower at night and varying with geophysical conditions such as solar and magnetic activities [*Prölss*, 2004]. Because there is little production of the ions and electrons in the plasmasphere, most of the plasma constituents in the region come from the underlying ionosphere and therefore it is strongly influenced by the ionospheric density structure. When flux tubes are depleted, the plasmaspheric flux tubes may be continuously refilling from the ionosphere due to the low pressure in the plasmasphere. However, as they fill up there will be a return flow to the ionosphere mainly at night when the low plasma density and temperature in the ionosphere cause the plasma in the plasmasphere to flowback to the mid-latitude ionosphere. This return flow is important for maintaining the nighttime ionosphere. Since the 1960s, the plasma density distributions in the plasmasphere have been studied using whistler observations and theoretical models [*Park et al.*, 1978; *Ganguli et al.*, 2000, and references therein]. It is important to note that whistlers measure the TEC along magnetic flux tubes and are most sensitive to the electron density near the equatorial plane, whereas the pTEC data given here are vertical TEC measurements that are most sensitive to densities just above the Jason-1 satellite altitude. Thus, the two TEC measurements are not directly comparable. Furthermore, because GPS satellites began to operate and measure the TEC including not only the ionosphere but also the plasmasphere, it has been extensively used for space weather applications, and there have been several efforts to identify how much the plasmaspheric density contributes to the GPS TEC [*Lunt et al.*, 1999; *Webb and Essex*, 2004; *Yizengaw et al.*, 2008; *Mazzella*, 2009].

[4] The ionosphere shows significant density variations with several geophysical parameters such as local time, season, latitude and longitude, and solar and magnetic activities. Because the plasmasphere is mainly filled with the ions and electrons originating from the ionosphere on a daily basis, it can be expected that the plasmaspheric density structure also shows variations with these geophysical parameters. For example, the seasonal variations in the plasmasphere have been discussed in a number of studies, in particular, in relation to the longitudinal variations [*Clilverd et al.*, 1988; *Carpenter and Anderson*, 1992; *Guiter et al.*, 1995; *Richards et al.*, 2000; *Clilverd et al.*, 2007; *Menk et al.*, 2012]. However, there are only a few studies on how the plasmaspheric densities are structured in relation to the ionosphere [e.g., *Belehaki et al.*, 2004] because the simultaneous observations for the plasmaspheric and ionospheric densities were very limited. *Belehaki et al.* [2004] extracted the plasmaspheric electron content from the differences between GPS TEC and electron content estimated from the observations of a ground-based ionosonde at Athens (38N, 23.5E) and demonstrated not only the diurnal and seasonal variations of the plasmaspheric density but also its storm-time behavior. In this study, we analyzed multiyear observations for the plasmasphere and ionosphere obtained from the Jason-1 satellite to investigate general characteristics of the plasmaspheric density structure on a global scale in comparison with the ionospheric density.

2. TEC Data

[5] The Jason-1 satellite, as mentioned earlier, observed the ionosphere and plasmasphere simultaneously for the period of 2002 to 2009 but mainly for a 4 year period from 2003 to 2006. Jason-1's orbit altitude of approximately 1336 km reduces interactions with the Earth's atmosphere and gravity field, which makes orbit determination easier and more precise. The orbit inclination of 66° enables the satellite to cover most of the globe's oceans. The repeat

cycle of the orbit is just under 10 days (9.9156 days to be precise, i.e., 10 days minus 2 h): in other words, the satellite passes over the same point on the Earth's surface to within 1 km every 10 days. This cycle is a trade-off between spatial and temporal resolution designed for the study of large-scale ocean variability.

[6] The TEC from sea surface to the satellite orbit of 1336 km corresponds to the iTEC, whereas the TEC between the Jason and the GPS satellites orbiting at 20,200 km altitude corresponds to the plasmaspheric TEC (pTEC). The iTEC data have been continuously collected since the launch of satellite until the present and the details of the data can be found in *Jee et al.* [2010]. The pTEC is calculated from the measurements of a GPS receiver, TurboRogue Space Receiver (TRSR), on board the Jason-1 satellite by using a well-known estimation technique to convert the observed slant TECs from ground receivers to the vertical TECs [e.g., *Mannucci et al.*, 1998]. The TRSR is a high-performance GPS receiver designed to provide backup precise orbit determination for Jason-1. It measures precise GPS pseudorange and continuous carrier phase data from up to 12 GPS satellites (approximately six satellites on average). The TEC obtained from the pseudorange and carrier phase data provided by TRSR corresponds to the slant TEC of the plasmasphere between 1336 and 20,200 km altitude. The slant TEC data from different viewing geometries were combined by mapping to the vertical direction using the thin shell approximation [*Mannucci et al.*, 1998]. The median height of the plasmasphere (shell height) is assumed to be approximately 2000 km above the altitude of Jason-1 satellite, which is determined from the ionosphere-plasmasphere model results [*Shim and Scherliess*, 2009]. For the calculation of the plasmaspheric shell height, it was assumed that the plasmasphere starts from the altitude of the Jason-1 satellite. The slant TEC data in the procedure were included only for the elevation angles above 60° to reduce the error associated with the multipath mapping procedure. Satellite biases, one of the largest sources of error in the analysis of the TEC data, were also subtracted from the slant TEC values before their conversion to vertical TEC. However, the bias of the receiver TRSR was not available and therefore obtained by assuming that the minimum vertical TEC value is zero, which possibly occurs in the high latitude regions.

[7] Unlike the iTEC data, however, the pTEC data are available only for a limited period as shown in Figure 2. Figure 2 shows the relative amount (in percentage) of Jason GPS TEC (i.e., pTEC) data for each year (top) and the solar F10.7 cm flux (bottom) during the period of observation. The amount of pTEC data was largest in 2005, and the data for the rest of the years are presented in percentage with respect to the year 2005. The solar activity during the observations was in the declining phase of solar cycle 23, which ranges from medium (F10.7p ~ 142) to low (F10.7p ~ 76) F10.7 cm flux. We used F10.7p = (F10.7 + F10.7a)/2 for solar activity throughout this study because F10.7p better represents the solar EUV flux that is responsible for the ionospheric density [*Richards et al.*, 1994; *Liu and Chen*, 2009]. It should be noted that the TOPEX TEC measurements are known to have a systematic bias of approximately 2–5 TECU above the true iTEC [*Jee et al.*, 2010, and references therein]. Because the Jason satellite uses exactly same method to measure the iTEC and therefore provides the iTEC data with

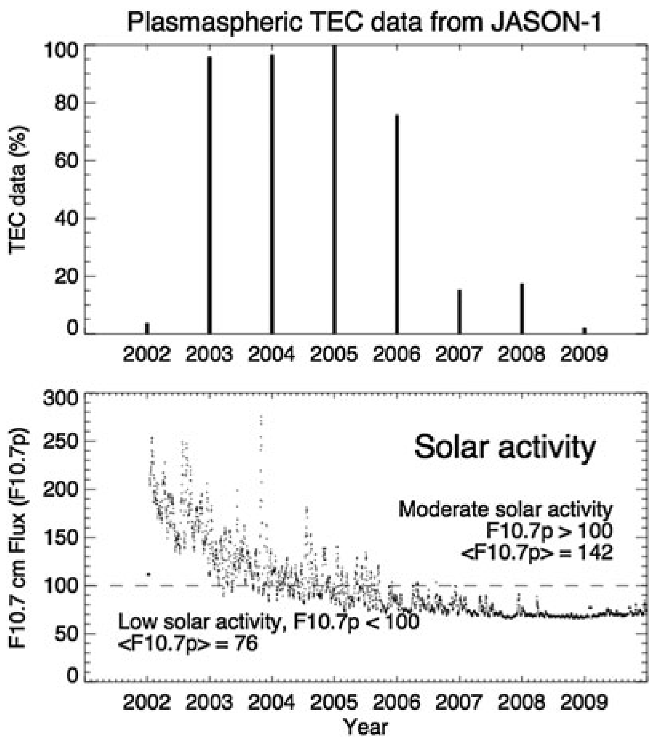

Figure 2. Relative amount of plasmaspheric TEC data (top) and the solar F10.7 cm flux during the period of observation from Jason-1 satellite. The dotted line at the bottom plot indicates the low and moderate solar activities with their mean values for this study.

the same accuracy as the TOPEX measurements [*Yasyukevich et al.*, 2010], the same bias must be applied to the Jason iTEC measurements. In this study, the bias is taken into account by subtracting 3 TECU from the iTEC data.

[8] Finally, it should be kept in mind that the iTEC and pTEC have a fundamental limitation to represent the ionospheric and plasmaspheric TECs. As solar activity decreases, the whole ionosphere-plasmasphere system settles down to the lower altitude region. In this situation, the TEC measurements with fixed altitudes such as iTEC and pTEC may not be the optimal measurements for representing the ionosphere and plasmasphere, respectively, because the transition height between the two regions is changing with solar activity whereas the measurement heights are fixed. The effect of varying transition height might be negligible for the iTEC, but for the pTEC, this effect can be significant. For instance, if the transition height occurs below (or above) the Jason satellite orbit altitude, the pTEC will be smaller (or larger) than the defined plasmaspheric density. Note that the maximum plasma density of the plasmasphere occurs in the bottom boundary of the region and its contribution to the pTEC is also the largest. Therefore, the changes of the transition height around the fixed measurement height can cause significant differences between the TEC measurements and the defined plasmaspheric TEC. In reality, however, there is no observation to measure the plasmaspheric TEC starting from the transition height, but numerical models can provide such a plasmaspheric density.

3. Global Morphology of the Plasmasphere

[9] To compare the global morphology of the plasmasphere with the ionosphere, the global maps of iTEC and pTEC were constructed in magnetic latitude and local time coordinates for different seasons, solar activity, and magnetic activity conditions as shown in Figure 3. Figures 3a and 3b show the longitudinally averaged TEC maps for low (F10.7p $<$ 100) and high (F10.7p $>$ 100) solar activities, respectively. The left two columns in each figure show the ionospheric and plasmaspheric TEC maps for three different seasons in the low ($K_p < 2.5$) magnetic activity conditions, and the right two columns show the same but for high ($K_p > 2.5$) magnetic activity. Note that the color scales in the figures are different for iTEC and pTEC. The most noticeable difference between the ionospheric and the plasmaspheric TECs is the local time variation, which is far more distinctive in the ionosphere than in the plasmasphere. The local time variation in the ionosphere is mainly due to the solar controlled production, which is maximized at around noon and gradually decreased on both sides of noon local time. The local time variation in the plasmasphere is mainly driven by the coupling to the ionosphere. The electron density in the plasmasphere is enhanced during the day by the plasma flowing up from the underlying ionosphere under geomagnetically quiet condition. On the other hand, there is almost no recombination to deplete the plasma density in the plasmasphere. The main loss of the plasmaspheric density at night is the downward plasma transport back to the nighttime ionosphere. *Belehaki et al.* [2004] and *Jee et al.* [2010] estimated the plasmaspheric densities from the differences between ground-based GPS TECs (iTEC+ plasmaspheric TEC) and iTECs measured from TOPEX and Jason satellites. The estimated plasmaspheric densities showed the maximum in the evening sector, which is different from our result. As suggested by *Jee et al.* [2010], this is probably related with the limitations of the GPS global ionosphere maps developed from the measurements of ground receivers over the globe.

[10] It is important to note that ionospheric O^+ acts as both a source of plasmaspheric H^+ and as a porous barrier through which the H^+ must diffuse. H^+ ions begin to diffuse to higher altitudes when the O^+ density decreases below approximately $5 \times 10^{10}\,m^{-3}$, which happens in the topside ionosphere above approximately 500 km altitude depending on diurnal and solar cycle factors. If the plasmasphere is depleted, any ions produced above this altitude level can flow to higher altitudes. The upward flow depends mainly on the neutral hydrogen density and the O^+ scale height in the topside ionosphere. If the flux tubes are severely depleted, H^+ may even flow upward at night from H^+ production aided by larger neutral H densities. For relatively full flux tubes, the decrease in O^+ density and plasma temperatures at night reduces the pressure and allows H^+ to settle back into the topside ionosphere where it can charge exchange with neutral O to supply ionization to help maintain the ionosphere. In this case, the ionospheric O^+ provides a barrier to the H^+ down flow. In the morning, the plasma temperatures rise rapidly because of the low electron density and H^+ is expelled from the topside ionosphere back into the plasmasphere. Thus, the O^+ barrier to H^+ diffusion may help explain why changes in the plasmasphere density, such as the local time variation, are much less than in the ionosphere during magnetically undisturbed periods [*Richards et al.*, 2000].

[11] As for the latitudinal variations, they appear to be similar in both regions in the sense that the maximum plasma density over the magnetic equator decreases at higher latitudes especially during the daytime, except that no equatorial anomaly is seen in the plasmasphere. However, this similarity actually comes from completely different reasons for the ionosphere and the plasmasphere: the latitudinal variation in the plasmasphere is related to the geometry of the geomagnetic flux tubes (see Figure 1) while it results from the solar zenith angle effect on the ion production in the ionosphere.

4. Seasonal Variations

[12] Seasonal variations in the ionospheric density are mostly caused by seasonal changes in the neutral composition and dynamics [*Rishbeth*, 1998; *Richards*, 2001; *Jee et al.*, 2004]. However, there is little solar production of ions and little neutral atmosphere in the plasmasphere. Therefore, seasonal variations in the plasmasphere during quiet times should be related to the coupling to the ionosphere. The differences of seasonal variations between iTEC and pTEC can be easily found in the global TEC maps in Figure 3. First of all, the plasmasphere shows the lowest TEC in June solstice for all conditions, which resembles the annual anomaly in the ionosphere. Furthermore, it turns out that this annual variation is closely related to longitudinal variations, which will be further discussed in the next section.

[13] Another seasonal feature of the plasmaspheric density is the hemispheric asymmetry. Although it is not as evident as in the ionosphere, the hemispheric asymmetry in the plasmasphere seems to exist during solstices especially for high solar activity (see Figure 3b). Overall, the plasmaspheric density in the summer hemisphere is larger than in the winter

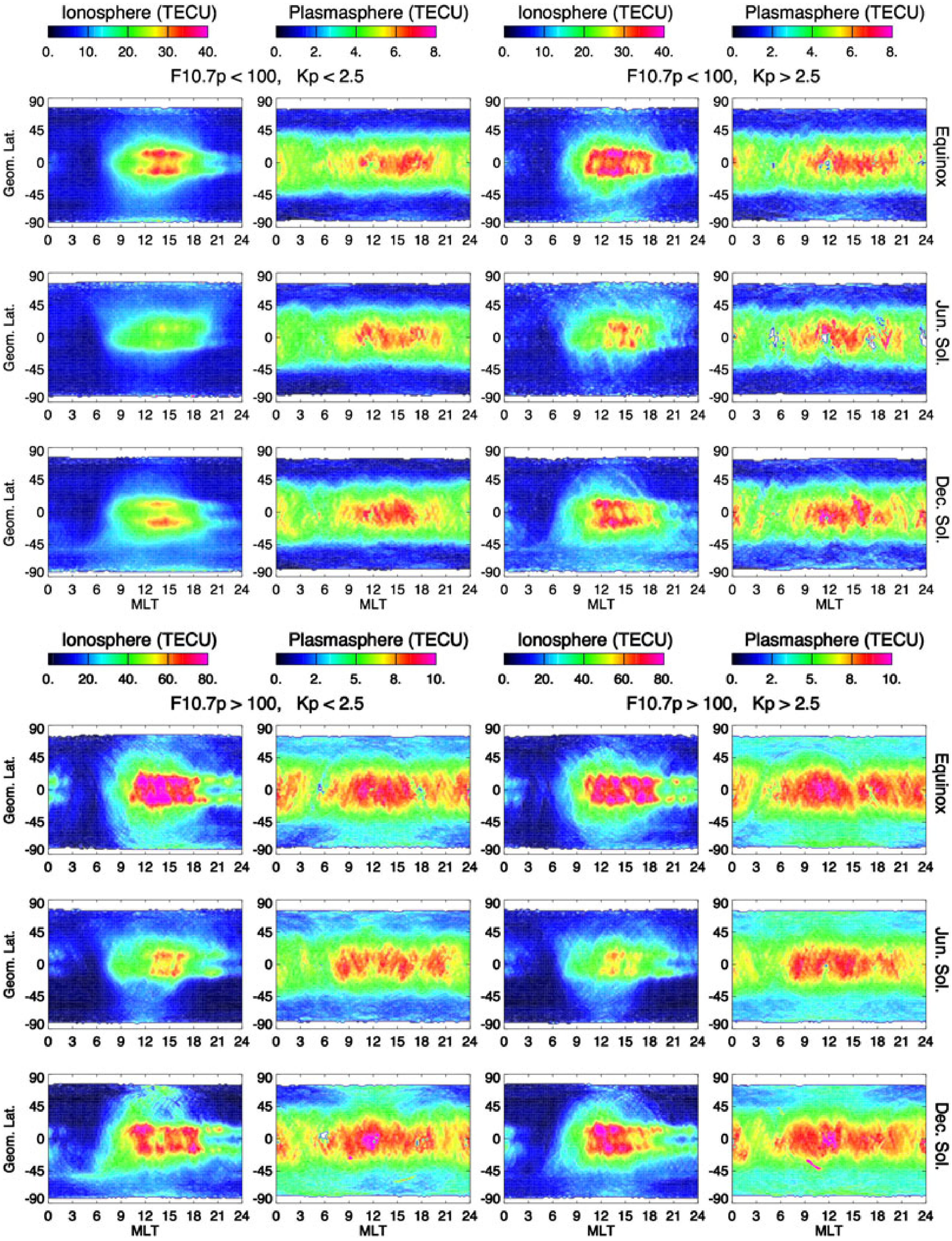

Figure 3. (a) Global ionospheric and plasmaspheric TEC maps for low ($K_p < 2.5$; left two columns) and high ($K_p > 2.5$; right) magnetic activities during low solar activity (F10.7p < 100). Each column of TEC maps shows three seasonal cases for equinox, June, and December solstices as indicated. (b) Same as Figure 3a but for high solar activity (F10.7p > 100).

hemisphere, which is similar to the asymmetry in the ionosphere. For the December solstice, however, the winter hemisphere during the day, at around noon, shows larger plasma density than in the summer hemisphere. This <?A3B2 twb.?>so-called winter anomaly appears in both the ionosphere and the plasmasphere. As for the semiannual anomaly (equinox > solstice), it is hardly noticeable in the plasmasphere while clearly evident in the daytime equatorial ionosphere. Both the annual and the semiannual anomalies in the plasmasphere are present in the empirical model of the plasmasphere that was developed by *Carpenter and Anderson* [1992], based on the measurements of electron density profiles within the region of approximately $2.25 < L < 8$ by the ISEE-1 satellite and Whistler observations at $L \sim 2.5$. Our result seems to indicate that the semiannual anomaly may not be as prominent as the annual anomaly in the plasmasphere, which does not appear in the integrated quantity over the extended region of the plasmasphere such as TEC.

[14] Global daily mean TECs in Figure 4 also show these seasonal variations. The TEC data are averaged over a 24 h period along the satellite orbit, which produces diurnally and globally averaged TECs. These TECs are displayed with day of year for the entire observation period from 2002 to 2009 together with the solar F10.7 cm flux (bottom). Both the mean iTEC and pTEC are consistently reduced as solar activity decreases in the declining phase of solar cycle 23. During the periods of 2002 and 2007–2009, pTEC shows

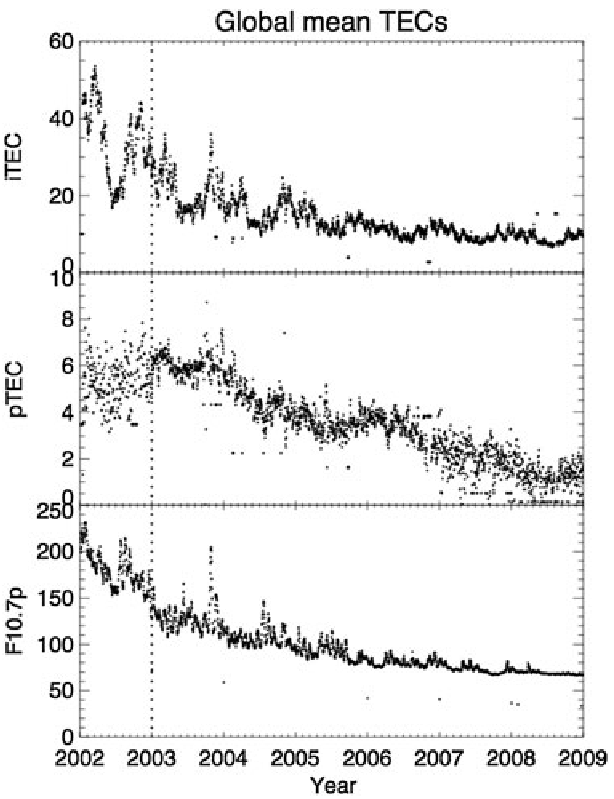

Figure 4. Global mean ionospheric and plasmaspheric TECs and solar F10.7 flux for the period from 2002 to 2010. The pTECs during 2002, left part of the dotted line, are from the very small, limited amount of data, and therefore it may not represent the plasmaspheric TEC during the period.

fairly large scatter due to the limited amount of data for the periods (e.g., see Figure 2). Nonetheless, the plasmaspheric TEC is clearly declining with decreasing solar F10.7 cm flux. Apart from the variation with solar activity, iTEC evidently shows the annual (December > June) and semiannual (equinox > solstice) anomalies in Figure 4, but only the annual variation is barely noticeable in pTEC.

5. Longitudinal Variations

[15] The seasonal variations in the plasmasphere have been discussed in a number of studies, in particular, in relation to the longitudinal variations [*Clilverd et al.*, 1988; *Guiter et al.*, 1995; *Richards et al.*, 2000; *Clilverd et al.*, 2007; *Menk et al.*, 2012]. All these studies suggest that the annual variation in the plasmasphere is strongest in the American sector and the ratio of December to June is approximately 1–3, depending on L value and solar activity. The ratio is larger for smaller L value and for lower solar activity. The mid-latitude ionosphere shows strong longitudinal variations such as the Weddell Sea Anomaly occurring mainly due to the effects of geomagnetic field and the neutral atmosphere [*Jee et al.*, 2009, and references therein]. This part of the ionosphere is dynamically interacting with the plasmasphere along the magnetic flux tubes. The existence of longitudinal variations in the ionosphere therefore gives an initial idea about the possibility of similar longitudinal variations in the plasmasphere.

[16] To investigate longitudinal variations in the plasmasphere in comparison with the ionosphere, we compared the equatorial plasmasphere (within $\pm 15°$ in magnetic latitude) with the mid-latitude ionosphere (20°S–60°S in magnetic latitude) in the southern hemisphere. The mid-latitude ionosphere is directly coupled to the plasmasphere within $1.21 < L < 4.17$ along the geomagnetic field lines (see Figure 7). We are comparing the southern mid-latitude ionosphere with the equatorial plasmasphere only because the iTEC data from Jason are poorly distributed in the northern hemisphere due to the large land area. Figure 5 shows the mean equatorial pTECs and mid-latitude iTECs during the daytime (10–16 MLT) and nighttime (22–04 MLT) for low (F10.7p < 100) and high (F10.7p > 100) solar activities. Each plot shows the longitudinal TEC variations for equinox and December and June solstices. There is an additional line in pTECs for the difference between December and June as indicated in Figure 5. The mid-latitude ionosphere shows strong longitudinal variations for both solar activities and for both day and night. The longitudinal variations in the ionosphere are fairly similar for low and high solar activities while they are completely different for day and night. As discussed in previous section, it is evident in Figure 5 that the annual anomaly (December > June) in the ionosphere almost always exists regardless of longitude. On the other hand, the plasmaspheric density shows moderate variations with longitude, but the annual variation is noticeable only in American sector ($-100°$ to $-30°$ in longitude) where the maximum density occurs in December and the minimum in June. In the remaining longitude sectors, the annual variations are barely noticeable or even reversed (i.e., June > December) at around 180° longitude. The maximum density differences between December and June are approximately 3–4 TECU in American sector, as shown in Figure 5, and the December-to-June ratio is approximately 1.5–2.0. Although the

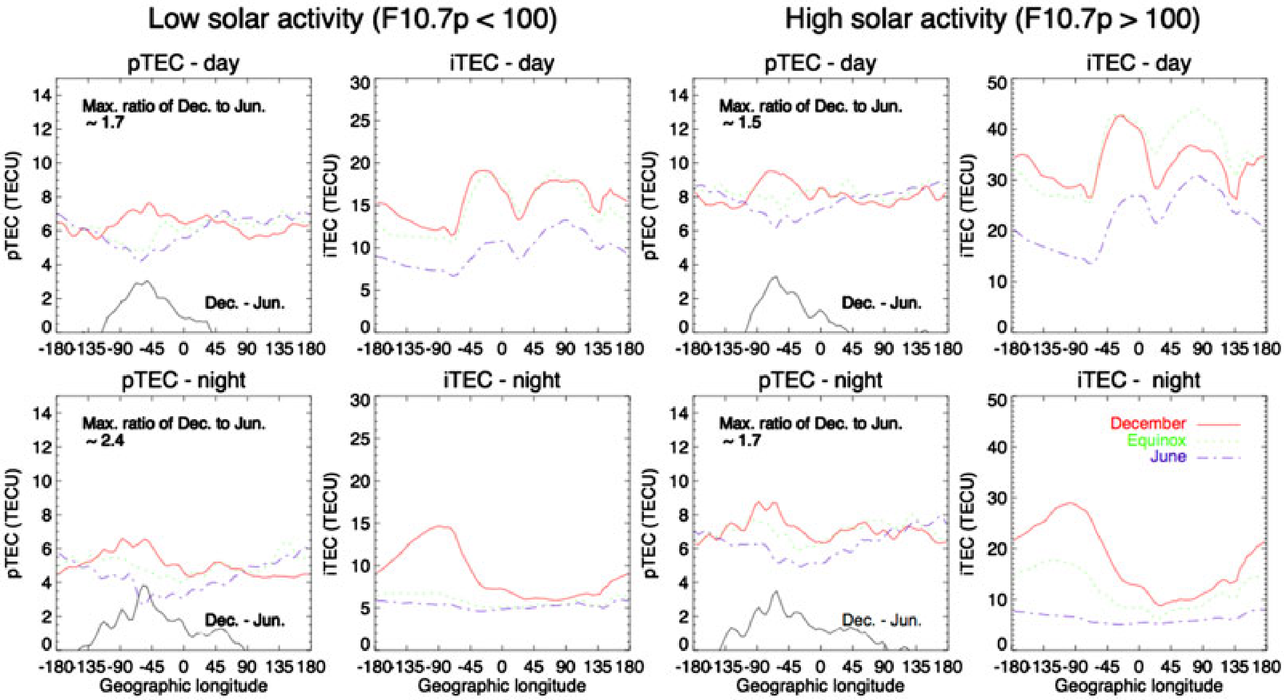

Figure 5. Longitudinal variations of the equatorial pTEC and mid-latitude iTEC during the day (10-16 MLT; top panels) and night (22-04 MLT; bottom panels) for low (left) and high (right) solar activities. Each panel shows the mean TECs for three seasonal cases, and the differences between December and June are additionally presented in pTEC. Also denoted are the maximum ratios of December to June solstices for each pTEC.

difference is not large, it is clear in Figure 5 that the ratio is larger at night than during the day and also larger for low solar activity than for high solar activity. For equinox, the longitudinal variations are almost negligible in the plasmasphere. Figure 5 also confirms that the semiannual variations (equinox solstices) are almost nonexistent both in the equatorial plasmasphere and in the mid-latitude ionosphere.

[17] From the above comparisons, one of the most noticeable differences between the plasmasphere and the ionosphere is that the annual variation in the plasmasphere appears only in American sector while the ionospheric variations appear regardless of longitude. This difference seems to suggest that there is almost no correlation between the annual variations of the ionosphere and the plasmasphere or there is an additional factor to counterbalance the effect of the ionospheric annual variations in the American sector. *Richards et al.* [2000] asserted that the principle cause of the plasmaspheric annual variation is not directly related to the ionospheric density variations but rather related to the high electron temperature in the topside ionosphere and plasmasphere. The largest offset of the geomagnetic equator from the geographic equator in the American sector causes a large asymmetry in the solar illumination of the ionosphere. This asymmetry may distinguish the American sector from the rest of longitude to maintain the larger electron density in December but the smaller in June throughout the day and night in the plasmasphere.

6. Variations With Solar and Geomagnetic Activities

[18] Figure 6 shows the global mean TEC variations with solar F10.7 flux and geomagnetic K_p index for the period 2002–2009. As also mentioned earlier with Figure 4, both iTEC and pTEC increase with solar F10.7 flux, but there is a clear difference in their behaviors in Figure 6: for instance, the iTEC increases almost linearly with increasing solar activity, but the plasmaspheric TEC increases nearly logarithmically with F10.7p. Note that the almost flat variation of pTEC for high solar activity ($F10.7 > 150$) may not be real because there are only a few data with very large scatters in 2002 (see Figure 4). The result of pTEC variations with F10.7 is rather unexpected because there were no observations to report this behavior of the plasmaspheric density. This result was also implied in Figure 4 in which the variations of iTEC and pTEC with solar cycle appear to be different: pTEC steadily increases from less than approximately 2 up to 4 TECU when F10.7 increases from approximately 70 to 100 during relatively low solar activity period from 2009 to 2005. During this period, on the other hand, the iTEC variation is negligibly small. It appears in Figure 6 as an initial steep increase in pTEC but a steady linear increase in iTEC. The behavior of the global mean plasmaspheric density with solar activity may suggest that once the plasmaspheric density enhances to a certain level as solar activity increases from the minimum, the plasma in the ionosphere does not keep flowing up to the plasmasphere although the ionospheric density continues to increase.

[19] In addition to the production-driven plasma density variations with solar activity, the plasma density at a fixed height can also vary with solar activity because the whole ionosphere and plasmasphere contracts or expands with solar activity variations [*Marinov et al.*, 2004; *Heelis et al.*, 2009]. For example, as solar activity decreases, the ionosphere

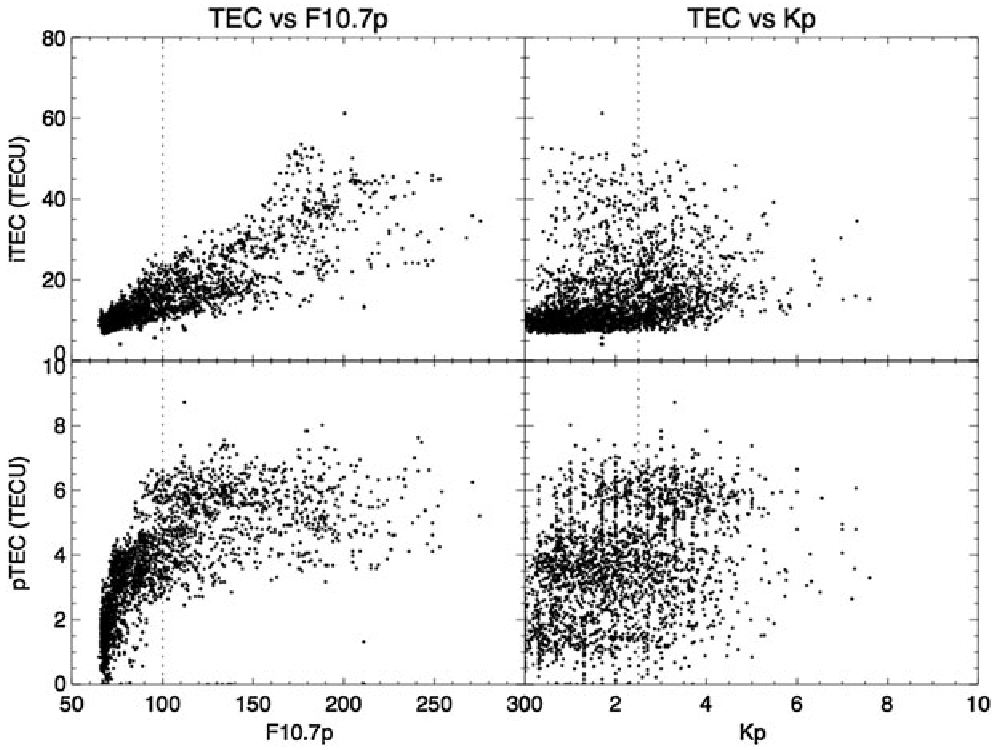

Figure 6. Scatterplots of iTEC (top) and pTEC (bottom) versus solar F10.7 cm flux (left) and K_p index (right). The dotted lines indicate the reference values of F10.7p and K_p for low and high activities.

and plasmasphere settles down to the lower altitude region and then the Jason iTEC tends to be larger than the theoretically defined iTEC due to the light ions from the plasmasphere. On the other hand, the Jason pTEC tends to be smaller than the defined plasmaspheric TEC because the lower part of the plasmasphere will be below the Jason-1 satellite altitude. In particular, this effect should be more important for the plasmaspheric TEC because the lower part the plasmasphere contributes the most to the plasmaspheric TEC whereas the contribution of the light ions from the plasmasphere is relatively small to the iTEC.

[20] The plasmasphere is filled with ions and electrons flowing up from the underlying ionosphere during magnetically quiet periods. But magnetic storms can peel off the outer layers of the plasmasphere, which is known to significantly deplete the plasmaspheric density. In addition, significant plasma depletion can occur in the region interior to the shrinking plasmapause probably by the drainage of the plasma into the nighttime ionosphere [*Spasojevic and Sandel*, 2010]. Then it begins to be refilled during recovery phase of the storms by plasma flow from the underlying ionosphere [*Kersley and Klobuchar*, 1980; *Spasojevic et al.*, 2003; *Dent et al.*, 2006]. According to this well-known theory of the plasmaspheric depletion and refilling, it can be expected for pTEC to decrease with increasing K_p. However, our data do not support this theory because Figure 6 shows almost no correlation between pTEC and K_p. For low solar activity, the daytime equatorial pTEC seems to be even enhanced as K_p increases, probably because the corresponding mid-latitude iTEC increases with increasing K_p as shown in Figure 3a. The pTEC used in this study is the vertical TEC within the altitude region of Jason to GPS satellites (see Figure 1). Although the plasmasphere may shrink down to $L < 3$ when there are severe magnetic storms [*Dent et al.*, 2006], however, most of magnetic storms for $K_p > 3$, which is categorized into the high magnetic activity in this study, may not be strong enough to appreciably move the plasmapause to the inner region of GPS satellite orbit and to deplete the plasma density within the region of $L = 1.2$ and $L = 4.17$ (i.e., pTEC). Furthermore, the plasmasphere density decreases with altitude (i.e., L value), and the contribution to pTEC would also decrease with L value.

[21] One other possibility of enhancing or at least compensating for the storm-induced depletion of plasmaspheric density is the contribution from the ExB upward plasma drift in the equatorial ionosphere, which is responsible for the equatorial ionospheric anomaly. The ExB plasma drift can be strong enough to raise the equatorial ionospheric plasma above the Jason satellite orbit altitude during severe magnetic storms and to expand the equatorial anomaly peaks from their normal position of around 10°–15° magnetic latitude up to approximately 30° [*Mannucci et al.*, 2005]. The elevated ionospheric plasma, of course, does not stay in the plasmasphere but quickly diffuses down to the ionosphere along the magnetic field lines to form the anomaly peaks. Although the elevated plasma density should be distinguished from the one diffused up by the plasma transport along the field lines from the mid-latitude ionosphere, it can certainly contribute to the pTECs representing the plasmaspheric density in this study. However, it should be noted that severe storms that can cause this strong vertical plasma drift are not very common and should have only a limited effect on the plasmasphere.

7. Implication for the Ionosphere-Plasmasphere Coupling: Plasmaspheric Flux

7.1. Plasmaspheric Flux

[22] An upward plasma flow from the ionosphere fills plasmaspheric flux tubes mainly during the day when the ionospheric density and temperature are high enough to produce a negative pressure gradient of the O^+ density with altitude. The negative pressure gradient competes with downward gravitational force and causes the upward plasma flow to achieve a diffusive equilibrium. At night, however, the ionospheric density and temperature are significantly lower due to recombination and reduction in plasma heating, respectively, and then the magnitude of pressure gradient decreases to reverse the plasma flow downward back to the ionosphere, which can considerably contribute to the maintenance of the nighttime ionosphere [*Evans et al.*, 1978; *Standley and Williams*, 1984; *Richards et al.*, 2000; *Jee et al.*, 2005]. In this regard, the plasmaspheric flux flowing between the ionosphere and the plasmasphere plays a crucial role in maintaining the daytime plasmasphere and the nighttime ionosphere.

[23] The plasmaspheric flux is one of the least known parameters in the ionospheric modeling [*Jee et al.*, 2005]. The governing equations for ions and electrons in the ionospheric models can be solved along the magnetic flux tubes or along the vertical height coordinate. The ionosphere models solving the equations along the vertical height coordinate, such as TIGCMs [Thermosphere-Ionosphere Global Circulation Models; *Roble et al.*, 1988] and IFM [Ionosphere Forecast Model; *Schunk et al.*, 2004], require numerical information for the plasmaspheric flux as a top boundary condition. The plasmaspheric flux varies with season, solar activity, and magnetic activity, which are uncertain. The ionosphere models such as SAMI2 [another model of the ionosphere; *Huba et al.*, 2000], ionosphere-plasmasphere model (*Schunk et al.*, 2004), and field line interhemispheric plasma model (*Richards et al.*, 2000), on the other hand, self-consistently take account of the flux by solving the equations along the magnetic flux tubes. However, this type of ionospheric models also has a limitation to realistically simulate the flux. The magnetic flux tubes beyond approximately L = 3 are eroded in response to magnetic storms and refilled over a period of several days during geomagnetically quiet times. Thus, the outer plasmasphere is constantly experiencing the repeated processes of erosion and refilling of the plasma: in other words, the flux tubes are usually in a partially filled state, which makes it difficult to simulate the plasma density and temperature all along the magnetic flux tube. These limitations of the ionospheric models regarding the plasmaspheric flux can be a significant source of uncertainties in the model results, in particular, for the nighttime ionosphere. For instance, *Jee et al.* [2005] reported in their modeling study that the plasmaspheric flux is as important as the neutral winds for maintaining the nighttime ionosphere. However, the plasmaspheric flux has not been well recognized as a source of substantial uncertainty in the ionosphere modeling compared with other physical parameters such as neutral winds and composition, electric fields, and temperatures. The simultaneous observations for the ionospheric and plasmaspheric TECs will be beneficial to understand how the plasmaspheric flux varies with season, solar activity, and magnetic activity.

7.2. Comparison Between the Equatorial Plasmasphere and the Mid-latitude Ionosphere

[24] Figure 7 shows a schematic diagram for the plasmaspheric flux between the ionosphere and the plasmasphere along the geomagnetic field lines below the GPS satellite orbit. It is clearly shown that the plasmasphere between Jason (1336 km, L = 1.21) and GPS (20,200 km, L = 4.17) satellites are coupled to the mid-latitude ionosphere via plasmaspheric flux. Assuming the ionospheric *F* region peak altitude of approximately 300 km, the magnetic field lines at the altitudes of Jason and GPS satellite orbits over the magnetic equator are connected to the *F* region peak altitude at the magnetic latitudes of approximately 20° and 60°, respectively, in geomagnetic latitude, according to the centered dipole magnetic field model. In other words, pTECs should be directly connected to the iTECs within 20°–60° magnetic latitudes in both the northern and the southern hemispheres. For the comparison between the plasmasphere and the mid-latitude ionosphere, we calculated mean equatorial pTECs (within ±15° in magnetic latitude) as the representative plasmaspheric densities and mean mid-latitude iTECs in the southern latitude region of 20°S–60°S. The mean pTECs and iTECs are displayed with magnetic local time for different season, solar activity, and magnetic activity in Figure 8. It seems that when the mid-latitude iTEC is enhanced with increasing solar activity, more plasma from the ionosphere flows up to the plasmasphere; that is, the upward plasmaspheric flux increases with increasing solar activity. However, although the daytime mid-latitude iTEC is enhanced almost twice from low to high solar activity, the equatorial plasmaspheric TEC increases only approximately 30%, which suggests that the plasmaspheric density does not linearly depend on the mid-latitude ionospheric

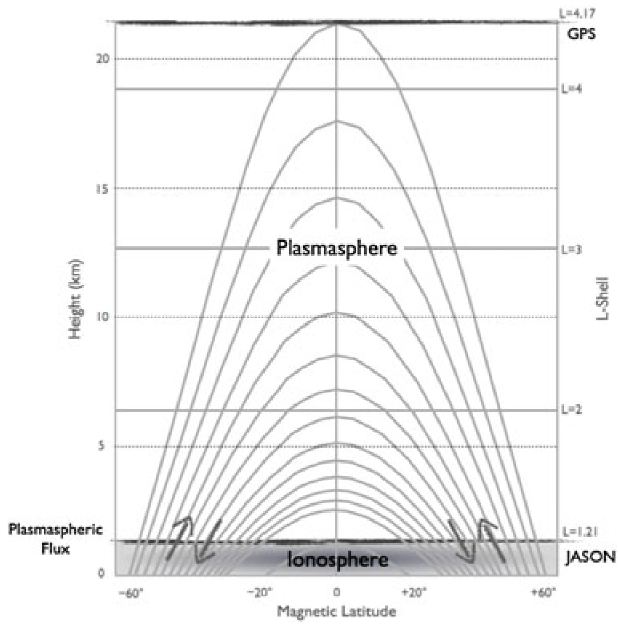

Figure 7. Geomagnetic flux tubes in the ionosphere and plasmasphere. The ionosphere and plasmasphere are coupled via plasmaspheric flux along the magnetic field lines and the coupling occurs in the mid-latitude region of approximately 20° to 60° in both hemispheres.

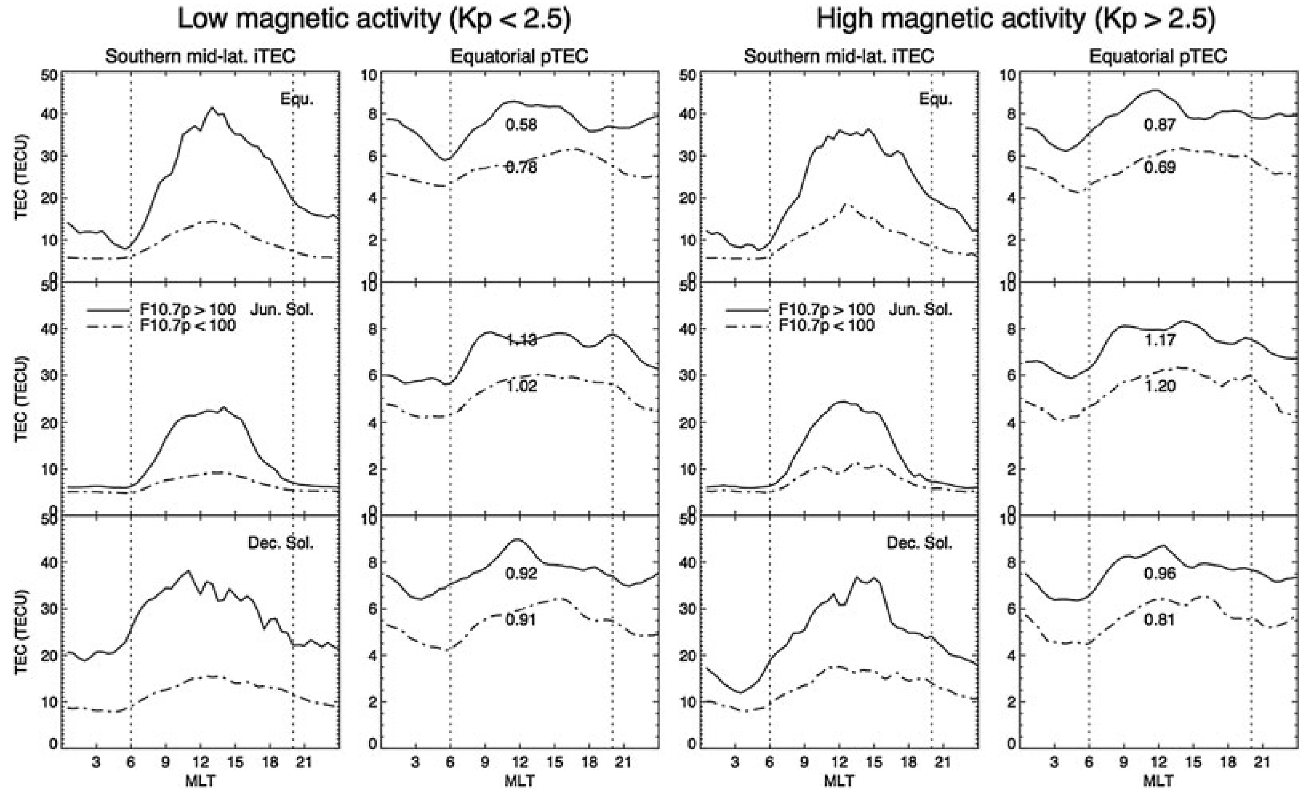

Figure 8. Local time variations of the mean mid-latitude ionospheric and equatorial plasmaspheric TECs for low (left) and high (right) magnetic activities. Each panel displays the mean TECs for low (dotted) and high (solid) solar activities for equinox (top), June solstice (middle), and December solstice (bottom). Two vertical lines in each panel indicate day-night boundaries in the mid-latitude ionosphere.

density even during geomagnetically quiet condition. In other words, the upward plasmaspheric flux filling the plasmasphere does not linearly increase with increasing ionospheric density. It is because the plasmaspheric flux is dependent not only on the ionospheric O^+ density but also on several other parameters such as neutral hydrogen density and neutral and plasma temperatures in the topside ionosphere where the O^+ density becomes low enough for H^+ to diffuse upwards [*Richards and Torr*, 1985].

[25] As described in section 3, the low density at night in the plasmasphere is due to the downward plasmaspheric flux to the mid-latitude ionosphere. By observing the differences between the daytime and the nighttime plasmaspheric densities, one may be able to see how much plasma flow back to the ionosphere and how the downward plasmaspheric flux vary with season and solar activity. But note that it is only an indirect way of observing the plasmaspheric flux between the plasmasphere and the ionosphere. For this purpose, we calculated the mean day-night differences of the equatorial plasmaspheric TEC as denoted at the center of each line plot for pTEC in Figure 8. Two vertical dotted lines in each panel of Figure 8 indicate day-night boundaries in the mid-latitude ionosphere. The day-night boundaries should be different for summer and winter hemispheres in the mid-latitude ionosphere. However, although we show the ionosphere only in the southern hemisphere, the equatorial plasmasphere is coupled to both summer and winter hemispheres simultaneously, and therefore it is more reasonable to use the same mean boundaries for all seasonal cases for the equatorial plasmasphere. The mean day-night differences of pTEC range from 0.58 TECU to 1.20 TECU, depending on season and solar activity, which corresponds to approximately 10% to 15% of reduction from the daytime density to the nighttime density in the equatorial plasmasphere. This amount of TEC also corresponds to approximately 5% to 25% of the nighttime ionospheric density, which may imply that the downward plasmaspheric flux on average contributes to the maintenance of the nighttime ionosphere by this amount. The differences are largest for June solstice and smallest for equinox. Assuming that the day-night differences represent the downward plasmaspheric flux to the ionosphere, this result may be interpreted that the plasmaspheric contribution to the nighttime ionosphere is largest for June solstice and smallest for equinox. With regard to the solar activity variations of plasmaspheric flux, the changes of the day-night difference with solar activity are almost negligible. However, this may suggest that the relative contribution to the nighttime ionosphere may actually be decreasing as solar activity increases because the nighttime ionospheric densities are greatly enhanced with increasing solar activity for most of seasons except for June solstice. Note that the nighttime iTECs in June are not enhanced much with solar activity. The solar activity variations of the nighttime ionosphere in June need to be further studied in more details.

8. Summary and Conclusion

[26] Simultaneous and independent observations for the ionosphere and the plasmasphere from the Jason-1 satellite provide a unique opportunity to directly compare the electron densities in both regions during the declining phase of solar cycle 23 from 2002 to 2009. Because the ionospheric density is nearly the only source of plasmaspheric electron density, the direct comparison between them would be beneficial to better understand the plasmasphere. On the other hand, the nighttime ionosphere is considerably influenced by the plasma flow from the plasmasphere (i.e., plasmaspheric flux), and therefore the comparison may be able to show some important aspects of the plasmaspheric contribution to the maintenance of the nighttime ionosphere.

[27] The results of the comparison revealed that the plasmaspheric TEC structures show significant differences from the ionosphere. First of all, the diurnal variation of plasmaspheric TEC is much weaker than that in the iTEC, although they are in phase (maximum at around 12-16 LT and minimum at around 03-06 LT). The hemispheric asymmetry for solstices exists, but it is barely noticeable for high solar activity. The plasmaspheric densities at mid and higher latitudes are overall smaller in the winter hemisphere than those in the summer hemisphere, which is similar to the hemispheric asymmetry in the ionosphere (see Figure 3). For December solstice, however, the winter hemisphere has a larger TEC during the day, around at noon, than the summer hemisphere, which is reminiscent of the winter anomaly in the ionosphere. The semiannual anomaly is hardly noticeable in the plasmasphere while it clearly exits in the ionosphere. These differences may suggest that the plasmaspheric flux between the ionosphere and plasmasphere, which determines the plasmaspheric density during quiet periods, is not only the function of the ionospheric density but also depends on other parameters such as the plasma and neutral temperatures.

[28] In agreement with the previous studies, there is an annual variation (i.e., December > June) in the plasmasphere maximizing in American sector ($-100°$ to $-30°$ in geographic longitude) unlike the annual variation in the ionosphere, which exists regardless of longitude (see Figure 5). The ratio of December to June in the equatorial plasmaspheric TEC is approximately 1.5 to 2.0, depending on local time and solar activity; it is larger at night and for low solar activity than during the day and for high solar activity, respectively.

[29] The global mean iTEC increases almost linearly with increasing solar activity, but the global mean plasmaspheric TEC increases nearly logarithmically with F10.7p. The behavior of the plasmaspheric density with solar activity may suggest that once the plasmaspheric density enhances to a certain level as solar activity increases from the minimum, the plasma in the ionosphere does not keep flowing up to the plasmasphere although the ionospheric density continues to increase.

[30] The Jason pTEC variations with K_p index do not support the well-known idea that magnetic storms are the major cause of plasmaspheric density depletion. The result of this study shows that the global mean pTEC does not have any correlation to K_p index (see Figure 6). It is probably because most of magnetic storms for $K_p > 3$ are not strong enough to affect the region of the plasmasphere within the GPS satellite orbit to decrease pTEC. And also note that the bulk of pTEC is mostly within $L < 2.5$.

[31] Finally, we took advantage of the simultaneous multi-year observations for the ionosphere and the plasmasphere to study certain aspects of their interaction by comparing the equatorial plasmaspheric TEC with the directly coupled mid-latitude iTEC. The result of the comparison shows that the relative plasmaspheric contributions to the nighttime ionosphere (via downward plasmaspheric flux) mostly decreases with an increasing solar activity, and the largest contribution occurs during June solstice for low solar activity when the downward plasmaspheric flux is largest while the nighttime ionospheric density is smallest.

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