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The Causes and Consequences of the Extended Solar Minimum between Solar Cycles 23 and 24

Key Points:
- The comparison between the global ionospheric TECs during the last two solar minima was performed
- The daily mean TECs show negligible differences between the two solar minima
- The global TEC maps show large differences with systematic variations

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Global ionospheric total electron contents (TECs) during the last two solar minimum periods

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Abstract The last solar minimum period was anomalously extended and low in EUV irradiance compared with previous solar minima. It can readily be expected that the thermosphere and the ionosphere must be correspondingly affected by this low solar activity. While there have been unanimous reports on the thermospheric changes, being cooler and lower in its density as expected, the ionospheric responses to low solar activity in previous studies were not consistent with each other, probably due to the limited ionospheric observations used for them. In this study, we utilized the measurements of total electron content (TEC) from TOPEX and JASON-1 satellites during the periods of 1992 to 2010, which includes both the last two solar minimum periods, in order to investigate how the ionosphere responded to the extremely low solar activity during the last solar minimum compared with previous solar minimum. Although the global daily mean TECs show negligible differences between the two solar minimum periods, the global TEC maps reveal that there are significant systematic differences ranging from about −30% to +50% depending on local time, latitude, and season. The systematic variations of the ionospheric responses seem to mainly result from the relative effects of reduced solar EUV production and reduced recombination rate due to thermospheric changes during the last solar minimum period.

1. Introduction

The last solar minimum period between the solar cycles 23 and 24 was extremely low and extended compared with the previous solar minimum periods. The declining phase of the solar cycle 23 was anomalously longer than predicted at the NOAA Space Weather Prediction Center. In March 2007, they anticipated it to reach a minimum in March 2008 (±6 months) due to the absence of expected signatures of minimum-like conditions on the Sun at the time of the panel meeting (www.swpc.noaa.gov). However, the solar cycle continued to decline further until it finally begins to rise back in 2009 (see Figure 1). During this extended period of solar minimum, the level of solar EUV was not only extremely low (about 10~15% lower compared with the previous minimum of solar cycle 22/23), but the duration of low solar activity was also unusually long, which may cause significant and unexpected impacts on the upper atmosphere. There have been a number of studies of the effects on the upper atmosphere such as *Gibson et al*. [2009], *Heelis et al*. [2009], *Coley et al*. [2010], *Emmert et al*. [2010], *Solomon et al*. [2010, 2011, 2013], *Lühr and Xiong* [2010], *Liu et al*. [2011, 2012], *Chen et al*. [2011], *Araujo-Pradere et al*. [2011], *Deng et al*. [2012], and *Yue et al*. [2013]. They investigated how this unusually low solar activity affected the thermosphere and the ionosphere using various measurements and model simulations on a local or global scale.

The thermosphere seemed to globally respond to the low solar activity by being cooler and thiner than the previous solar minimum [*Emmert et al*., 2010; *Solomon et al*., 2010; *Solomon et al*., 2011; *Solomon et al*., 2013]. However, most of the previous studies on the ionospheric response were relatively limited in terms of spatial and temporal coverages due to the lack of a single global observation that continuously observed the last two consecutive solar minimum periods for comparison. *Heelis et al*. [2009] and *Coley et al*. [2010], using ionospheric measurements during the 2008 solar minimum from the Coupled Ion-Neutral Dynamics Investigation on board the Communication/Navigation Outage Forecast System satellite, reported that the ionosphere was much thinner with lower transition height of O^+/H^+ and also cooler than expected by the 10.7 cm radio flux, and the ionospheric dynamics may also be significantly modified during this low solar activity. *Klenzing et al*. [2011], also using the measurements from the same satellite, found that the equatorial ionosphere was overall contracted relative to the International Reference Ionosphere (IRI) expectations, but

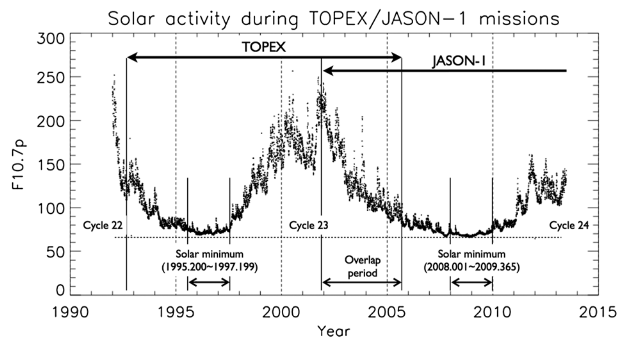


Figure 1. The periods of the TOPEX (1992.8~2005.10) and JASON-1 (2001.12~) satellite observations for the global ionospheric TECs with solar $F_{10.7}$ cm index during the periods. The overlap period of the two missions is about 4 years from 2001.12 to 2005.10. The last two solar minimums are also denoted by 2 year periods.

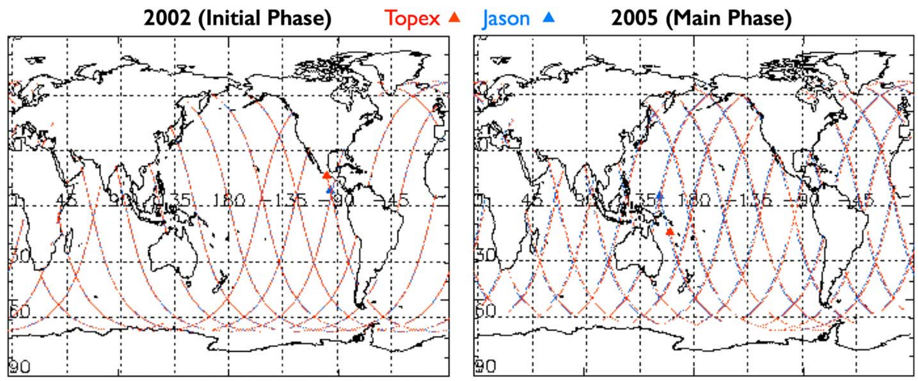
the extent was a strong function of altitude and local time. *Liu et al*. [2011] analyzed nearly global ionosonde data and the Jet Propulsion Laboratory (JPL) GPS total electron content (TEC) during the last solar minimum period and compared them with the corresponding ionospheric data during the previous solar minimum period, which showed about 10~18% lower daytime f_oF_2 over all latitudes in the last minimum. However, the comparison with the global TECs could not be made because the JPL TEC maps were not available during the previous solar minimum period of cycle 22/23. *Araujo-Pradere et al*. [2011] reported from their analysis of the ionospheric observations at limited locations that while the ionospheric TEC showed a consistent modest decrease of the mean value, the behavior of *F* region peak density was less clear and sometimes even higher than the previous minimum period. *Lean et al*. [2011] reported a statistically significant positive trend of 0.6 ± 0.3 TEC unit (TECU) per decade from the multiple GPS observations between 1995 and 2010, which is contrary to the expected ionospheric responses from the reduced solar EUV irradiance.

All these seemingly inconsistent ionospheric responses only indicate that further systematic study is necessary, for instance, by using a single observation for the global ionosphere encompassing the last two solar minimum periods in order to investigate the responses of the ionosphere to the extremely low solar activity during the last solar minimum compared with the previous minimum period. However, such a global ionospheric observation has not been available. Even the global ionosphere maps (GIMs) derived from the TEC data collected at hundreds of GPS ground stations worldwide have been available only from 1998, which do not include the previous solar minimum period occurring in around 1996. Furthermore, the GPS TEC measurements include not only the ionosphere but also the almost entire plasmasphere in which the plasma density can be nearly comparable to the ionosphere at night in terms of TEC, and the density variation with solar activity has not been well understood [*Lee et al*., 2013]. Therefore, the GPS TEC may not be ideal for the study of the ionospheric response to the low solar activity. The other possible observation for the global ionosphere is the vertical TEC measurements from altimetry missions such as TOPEX/Poseidon and JASON-1. The TOPEX and JASON-1 satellite observations may be currently the only available observations for the study of the global ionosphere during the last two consecutive solar minimum periods. For the usage of the measurements for current study, however, it should be confirmed that the two TEC measurements can be considered as a single type of measurement. In the following sections, the TEC measurements from TOPEX and JASON-1 satellites will carefully be compared with each other for the period of simultaneous observations and then a comparison of the global ionosphere between the two solar minimum periods will be performed.

2. Total Electron Contents Measured From the TOPEX and JASON-1 Satellites

2.1. TOPEX and JASON-1 Satellite Missions

The total electron content of the ionosphere is a widely used parameter for the representation of ionospheric morphology. In particular, the GPS TEC data has revolutionized ionospheric research in its spatial and temporal coverage of the ionosphere; networks of GPS receivers are capable of providing TEC measurements in near-real time on global and regional scales, which make it possible to produce global ionosphere maps for near-real time snapshots of the global ionosphere [e.g., *Jee et al*., 2010, and references therein]. Unfortunately, however, the GIMs were not available until 1998, when the solar cycle 23 had already begun. Another observation of the global ionospheric TEC comes from satellite altimetry missions such as TOPEX/Poseidon and JASON-1 and JASON-2, which have the primary mission to measure the global sea surface height with unprecedented accuracy. The accurate measurement of sea surface height requires the removal of the ionospheric delay imposed on the altimeter, resulting in TEC measurements between the sea surface and the satellite orbit altitude as a by-product of the satellite mission [*Fu et al*., 1994; *Codrescu et al*., 1999].



JASON-1 vs. TOPEX	Initial phase (Cycle 1 ~ 22)	Main phase (Cycle 24 ~)
Spatial difference	4° lat. & 1.5° lon. near the equator	20° lat. & 9° lon. near the equator
Temporal difference	about 70 sec apart each other	about 270 sec (4.6 min.) apart each other
Satellite orbit	JASON-1 follows TOPEX's orbit	TOPEX shifts its orbit and JASON-1 takes TOPEX's orbit

Figure 2. Spatial discrepancies between the TOPEX (red filled Δ) and JASON-1 (blue filled Δ) satellite orbits for (left) initial calibaration phase and (right) main phase of the JASON-1 satellie mission. The red (TOPEX) and blue (JASON-1) dotted lines are the ground tracks of the satellite orbits. The table below the maps shows the differences between the two satellite orbits for the initial and main phases.

The TOPEX satellite continuously produced TEC data along its orbit, with a 1 Hz sampling rate, from its launch in August 1992 through the end of the mission in October 2005, lasting for more than a full solar cycle, as shown in Figure 1. This highly successful mission was followed by the JASON-1 satellite, which was launched in December 2001 in order to continue measurements over the identical satellite orbit as its predecessor. The TECs from these satellites are the vertical total electron contents within the altitude region from the ocean surface to the satellite orbiting at about 1336 km altitude. The data have been extensively utilized not only for ionospheric studies [*Codrescu et al.*, 1999; *Codrescu et al.*, 2001; *Horvath and Essex*, 2003; *Jee et al.*, 2004; *Horvath*, 2006; *Scherliess et al.*, 2008; *Jee et al.*, 2009] but also for validating various ionosphere models and other independent measurements [*Mannucci et al.*, 1998; *Jee et al.*, 2005; Scherliess et al., 2006; *Jee et al.*, 2010; *Yasyukevich et al.*, 2010]. It should be kept in mind that the TOPEX/JASON-1 TEC data are obtained only over the global ocean, which is heavily biased toward the southern hemisphere, and the data in the northern hemisphere are limited to the northern Pacific and Atlantic oceans (see Figure 2).

The TOPEX and JASON-1 satellite missions have been collecting the global ionospheric TEC data for nearly two consecutive solar cycles, which consequently include both the last two solar minimum periods. The minimum solar activity between the cycles 22 and 23 occurred in 1996, and the minimum solar activity between the cycles 23 and 24 occurred in 2008. The TOPEX/JASON-1 TEC data are the only measurements available for the global ionosphere during these two solar minimums by a single type of observation so that a direct comparison between the two minimums is possible. However, although the two satellite observations are supposed to produce the identical TEC measurements without any biases between the two, this assumption should be carefully checked by comparing the measurements during the simultaneous observation period before any application.

2.2. Comparison Between TOPEX and JASON-1 TEC Measurements

There was about a 4 year overlap period between the two satellite missions from December 2001 to October 2005 (see Figure 1). During this overlap period of simultaneous satellite operations, the JASON-1 satellite was initially flying along the same ground track as the TOPEX satellite with approximately 70 s apart each other (with a spatial distance of ~4° latitude and ~1.5° longitude near the equator) until the JASON-1 finally took the TOPEX orbit on 21 August 2002 (23 August 2002, 10 day cycle) to start main phase of the mission. In other words, the initial calibration period of JASON-1 lasted about 8 months until the transition to the main phase occurred. Once the JASON-1 satellite began its main phase, the TOPEX satellite shifted its orbit to between the JASON orbits with a larger spatial distance of ~20° latitude and ~9° longitude near the equator (approximately 4.6 min apart) from the JASON-1 as shown in Figure 2. This figure shows the ground tracks of the two satellites during the (left) initial and (right) main phases with the locations of the satellites at a certain instance of time. As can be seen in the table in Figure 2 (bottom), the spatial and temporal discrepancies between the two satellites at a given time are much larger during the main phase than during the initial phase.

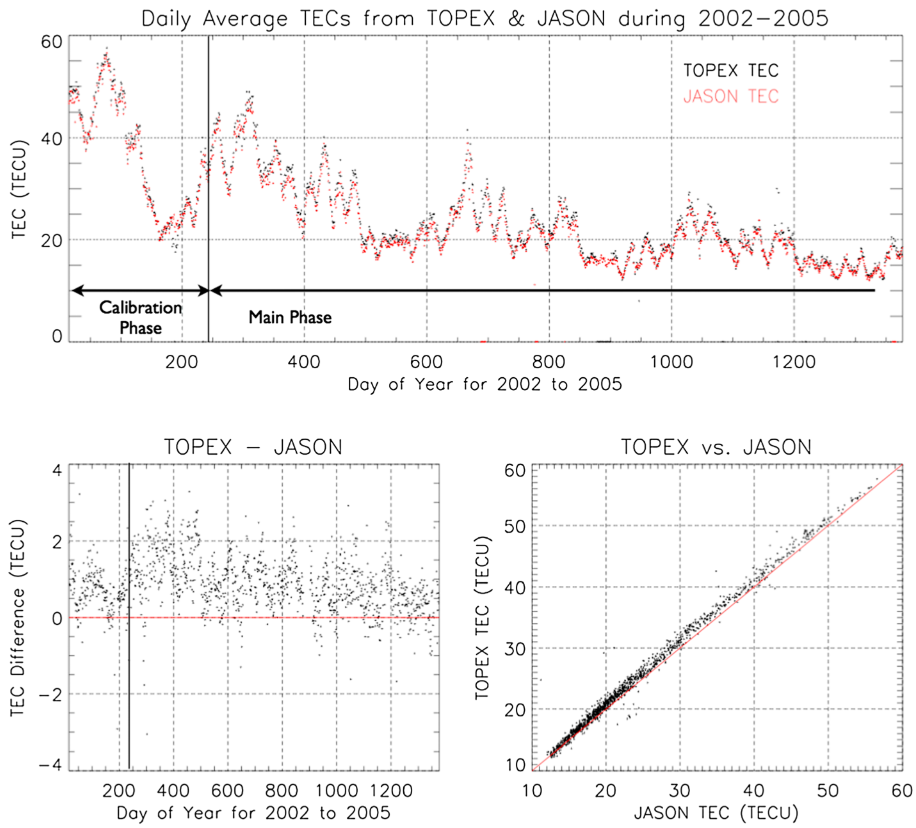


Figure 3. The daily mean TECs versus the day of year for the overlap period of the two satellite missions from 2002 to 2005. (bottom left) The differences between the two TECs are also displayed. (bottom right) TOPEX TEC versus JASON TEC in TECU are shown.

As an initial and quick comparison between the two TEC measurements, the daily mean TECs were calculated along the satellite ground track during the overlap periods, which are displayed in Figure 3 with their differences in the bottom panels of the figure. The daily mean TEC shows that the TOPEX TECs seem to be mostly larger than the JASON-1 TECs. Note that the difference is enhanced when the JASON-1 satellite orbit had transitioned to the main phase from the initial phase, and the spatial discrepancy between the two satellites increased as in Figure 1. This indicates that the spatial (probably temporal) discrepancy also contributed to the TEC differences in Figure 3. Therefore, the first comparison between the two satellite TEC measurements should be performed during the initial calibration phase when the spatial discrepancy is relatively small. In this period, the TEC differences are 0~2 TECU, which corresponds to about 0~4% smaller JASON-1 TEC than TOPEX TEC. Also note that the enhanced TEC differences during the main phase are decreasing with solar activity, being less than 1 TECU when the solar activity approaches to the minimum in 2005, which indicates that the differences should be negligibly small during the solar minimum periods.

For more detailed comparison, Figure 4 shows the global maps of the (top) TOPEX and (middle) JASON-1 TECs and (bottom) their differences for (first column) a 10 day cycle and for (second column) a 90 day period (or 90 day cycles) during the initial phase of the JASON-1 satellite mission. All the TEC maps in this figure are presented in TECU. As mentioned earlier, the satellite orbits around the Earth at least for 10 days to cover the whole globe, which however spans only for 1.333 h in local time for a 10 day period (i.e., the satellite orbits are close to Sun-synchronous, advancing only by 2°/d). Therefore, it takes about 90 days to monitor a full day as in Figure 4. The TEC maps show that the TECs appear to be almost identical but with a mean difference of 1.68 TECU over the globe for this period. This again indicates that the TOPEX TECs are consistently larger than the JASON-1 TECs by up to about 5 TECU, as can be seen in the difference map of the figure. Note that the differences are almost uniform over the globe and do not seem to reflect the morphology of the global ionosphere such as day-night differences, latitudinal variations, and the equatorial anomaly peak structure.

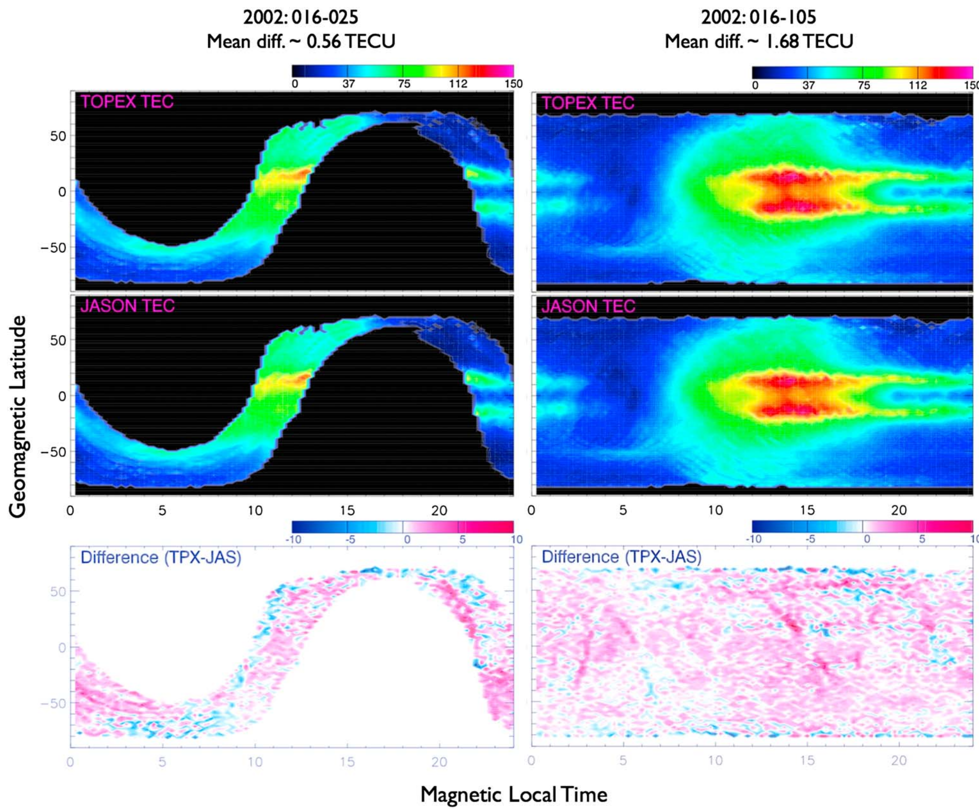


Figure 4. The TOPEX and JASON-1 TEC maps and their differences map in the geomagnetic latitude and local time coordinate for (first column) a 10 day cycle and (second column) a 90 day period in 2002. It takes about 90 days to cover a full 24 h of local time. Each column presents the TEC maps from (top row) TOPEX, (middle row) JASON, and their difference (TOPEX TEC – JASON TEC, bottom). The color scale ranges from 0 to 150 TECU for TEC maps and −10 to 10 TECU for difference map.

The decreasing TEC difference with solar activity in Figure 3 can also be found in the global TEC maps for the same 90 day periods of each year from 2002 to 2005 in Figure 5. Each TEC map has exactly the same format as in Figure 4 (second column). Note that the color scales for TEC maps for each year are different: 0~150 TECU for 2002, 0~100 TECU for 2003, and 0~80 TECU for 2004 and 2005, but the color scales for difference maps are all the same: −10~10 TECU. The difference maps in Figure 5 reveal that the overall positive differences gradually decrease from 2002 to 2005 especially at higher latitudes and finally become negative in 2005. The global mean difference therefore gradually decreases from 1.68 TECU in 2002 to −0.35 TECU in 2005. However, it is hard to see any correlation between the differences and the magnitude of TEC over the globe: the differences seem to decrease with declining solar activity but do not necessarily follow the global ionospheric TEC morphology that shows significant density variations with latitude and local time. From this comparison between the TOPEX and JASON-1 TECs, it can be concluded that the TECs obtained from the two satellites are almost identical within ±5 TECU (or within 10%), which is not statistically very meaningful. This conclusion also agrees with previous comparison studies. *Ping et al*. [2004] made a direct comparison between the TECs from TOPEX and JASON and also an indirect comparison by using the JPL global ionosphere map for the initial 2 year period of JASON-1, which estimated the bias of about 1.4 TECU, indicating a larger TOPEX TEC than JASON-1 TEC by this amount. But they considered it to be statistically insignificant. *Yasyukevich et al*. [2010] also compared the two TECs by using the mean global TECs (i.e., the mean TEC around the globe along the satellite orbit for a day) and concluded that they are practically identical.

3. Comparisons of TECs During the Last Two Solar Minima

3.1. Daily Mean TECs

For the study of the characteristics of global ionospheric TECs during the last solar minimum period and their comparison with the previous solar minimum period, the TOPEX and JASON-1 TEC data were selected for a

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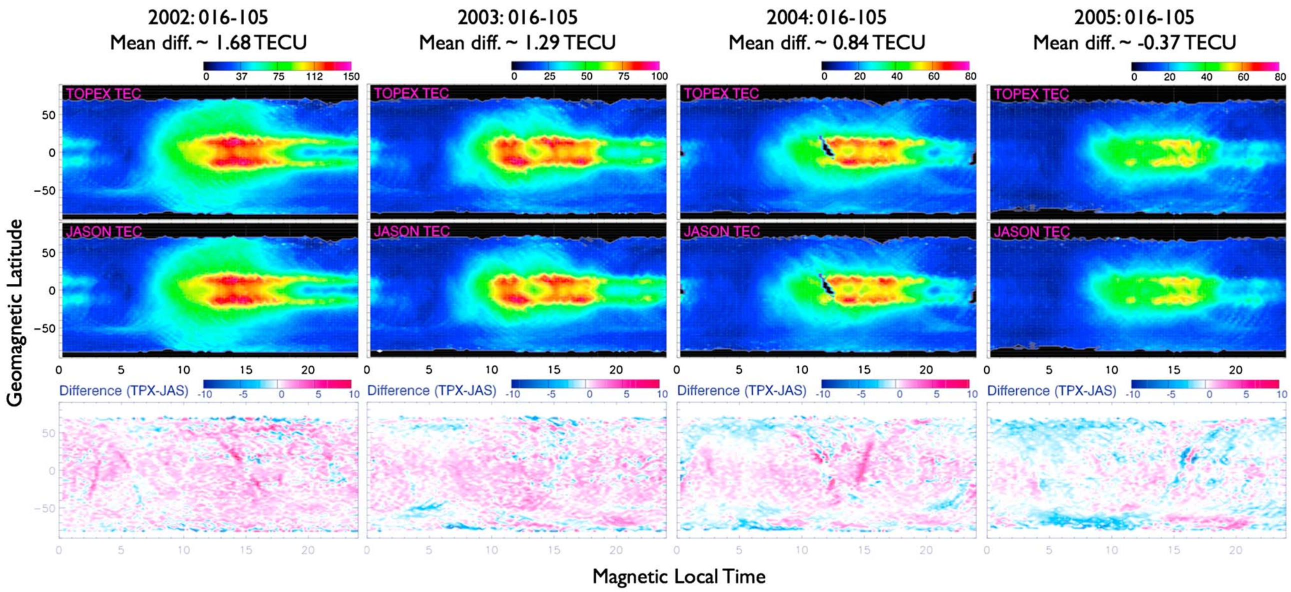

Figure 5. The global ionospheric TEC maps for each 90 day period between (left to right) 2002 and 2005 in the same format in Figure 4 (second column). Note that the color scales for the TEC maps are different for each year; 0~150 TECU for 2002, 0~100 TECU for 2003, and 0~80 TECU for 2004 and 2005. But the color scales for difference maps are all the same, −10~10 TECU.

2 year period in each solar minimum of cycle 22/23 and cycle 23/24 when the solar $F_{10.7}$ indices were the lowest as indicated in Figure 1. The TEC data for the last solar minimum (2008.001~2009.365) was obtained from the JASON-1 satellite, but for the previous solar minimum (1995.200~1997.199), it was obtained from the TOPEX satellite. For an initial and overall comparisons, the daily mean TECs were calculated from the 2 year TEC data for each minimum period and displayed with the day of year to show seasonal variations of TEC in Figure 6 (left). Also displayed in Figure 6 (right) are the mean solar $F_{10.7}$ cm index, $F_{10.7}$ $p = (F_{10.7} + F_{10.7}\,a)/2$, and the daily mean *Kp* index for each 2 year period. Not only the solar $F_{10.7}$ index but also the *Kp* index was lower during the last solar minimum period (red) than during the previous solar minimum (black), which indicates that the magnetic activity was also quieter as reported by *Deng et al.* [2012]. The daily mean TEC shows that there seem to be negligible differences between the last two solar minimum periods, which is rather unexpected. Also note that the semiannual variation is almost nonexistent during the last solar minimum, but it is perceptible during previous minimum. The annual variation exists in both the minimum periods.

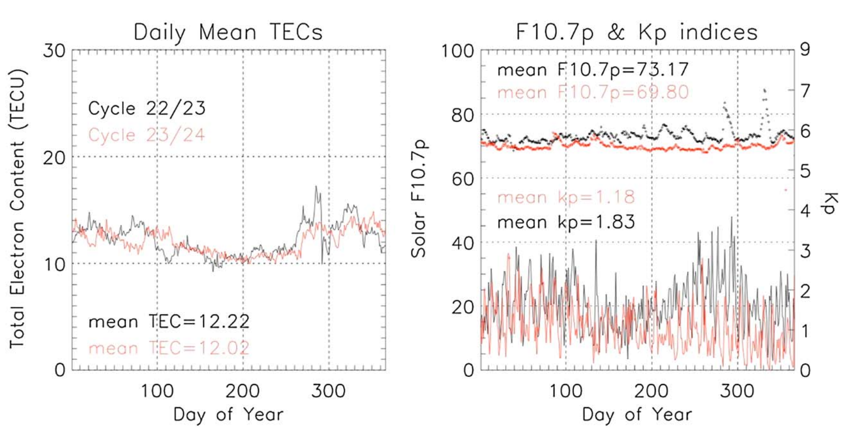

Figure 6. The (left) daily mean TECs and the (right) solar $F_{10.7}$ and *Kp* indices are presented with the day of year for the last solar minimum periods as indicated with different colors; black for previous minimum (solar cycle 22/23) and red for last minimum (solar cycle 23/24). The mean values are also denoted for each case.

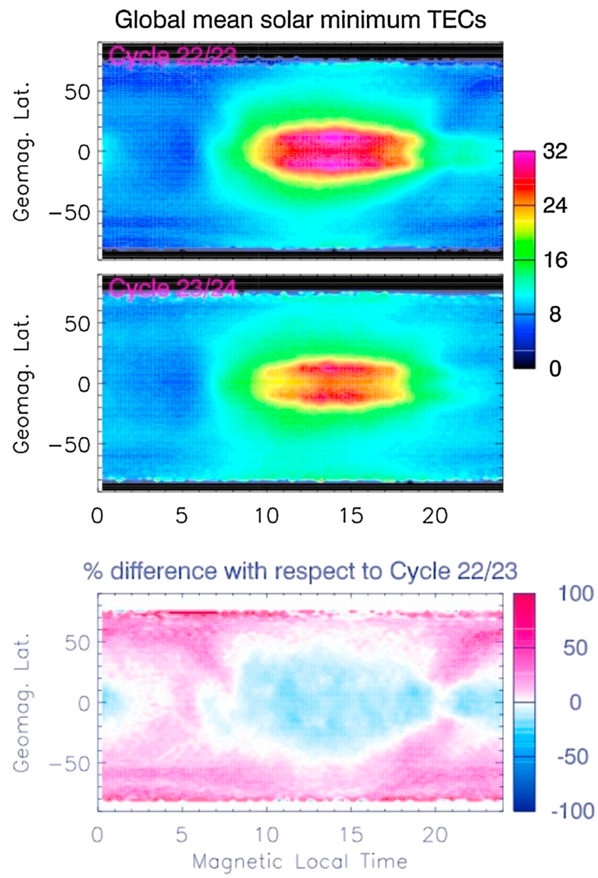

Figure 7. The global TEC maps for each solar minimum period of (top) cycle 22/23 and (middle) cycle 23/24 and (bottom) their difference map in the geomagnetic latitude and local time coordinate. The TEC maps are in TECU, but the difference map is in percentage (%) with respect to the previous solar minimum (cycle 22/23).

The solar EUV radiation is the principal energy source for determining most of the structures in the upper atmosphere. *Solomon et al.* [2010, 2011] showed that the level of solar EUV irradiance during the last minimum was substantially lower than during the previous solar minimum of cycle 22/23 by about 4% to 15% depending on indices used for solar EUV. Although the $F_{10.7}$ index, the most commonly used index for solar EUV level, showed only about 4% decrease as shown in Figure 6, they, based on other solar proxy and measurements of solar EUV flux, estimated at least about 10% decrease of EUV from the cycle 22/23 minimum to the cycle 23/24 minimum. When compared with other solar indices or direct observations for solar EUV irradiance, the $F_{10.7}$ index significantly underestimates the difference between the two minimum periods: that is, it does not correctly represent true solar EUV level when the solar activity becomes extremely low as in the last solar minimum period [*Chen et al.*, 2011; *Chen et al.*, 2012]. Note that it has been reported in a number of studies that the $F_{10.7}$ index does not well represent the solar EUV level when $F_{10.7}$ index is greater than about 200 [*Richards et al.*, 1994; *Balan et al.*, 1994; *Liu et al.*, 2006]. Therefore, the anomalously low solar activity during the last solar minimum revealed that the $F_{10.7}$ index has a fundamental limitation as a proxy for solar EUV level, not only at high solar activity but also at very low solar activity.

Under this extremely low solar EUV level during the last solar minimum, it is readily expected that the overall level of the ionospheric density should be lower than any other periods. The daily (also global) mean TEC in Figure 6 however shows almost negligible differences between the last two minimum periods, and this result seems to be consistent with some of previous studies such as *Lean et al.* [2011] and *Araujo-Pradere et al.* [2011]. On the other hand, there are other previous studies based on limited ground-based observations, indicating a significant decrease in the electron densities during the last minimum [*Chen et al.*, 2011; *Chen et al.*, 2012; *Liu et al.*, 2011; *Liu et al.*, 2012]. In order to further investigate the inconsistent responses of the ionosphere to the low solar activity during the last solar minimum, the global ionospheric TEC maps for the last two minimum periods are produced and compared with each other.

3.2. Global TEC Maps

Figure 7 shows the global TEC maps during both the 2 year solar minimum periods of (top) cycle 22/23 and (middle) cycle 23/24 and the percentage difference of cycle 23/24 TEC from (bottom) cycle 22/23 TEC. At first glance, there are significant differences between the two solar minimum TECs, ranging from about −30% to +50%, unlike the daily mean TECs in Figure 6. This amount of difference is significantly larger than the ionospheric changes reported in previous studies [e.g., *Araujo-Pradere et al.*, 2011; *Solomon et al.*, 2013]. Furthermore, the differences show systematic variations with latitude and local time. In the difference map, the negative indicates smaller TEC during the last solar minimum than the previous minimum, which is easily expected from the reduced EUV level during the last minimum. However, there are also significant positive differences, indicating the enhanced TEC during the last solar minimum compared with the previous solar minimum. The result of the TEC enhancement is very surprising. Its spatial extent is even larger than the negative, occurring at high latitudes during daytime and at most of latitudes at night except for the equatorial region.

The positive and negative differences over the globe are comparable with each other in terms of the overall magnitude of TEC differences, and it may explain the negligible difference of the global mean TEC in Figure 6. *Lean et al*. [2011] utilized the International Global Navigation Satellite Systems Service GPS TEC maps to calculate the daily averaged global TECs and found no corresponding TEC decrease to the reduced EUV irradiance from cycle 22/23 to cycle 23/24, which agrees with our result in Figure 6. *Araujo-Pradere et al*. [2011] found inconsistent responses of the ionosphere during the last solar minimum period from their analysis of the GPS TEC and ionosonde NmF_2 data collected at midlatitudes: while the midlatitude TECs showed modest decreases from cycle 22/23 to cycle 23/24, the midlatitude NmF_2 did not show consistent behavior, which are merely marginal with respect to the geophysical variability. The modest or negligible changes in the midlatitude ionosphere seem to be plausible in the latitudinal variation of the difference in Figure 7. The last solar minimum TECs at low latitudes were mostly smaller by up to 30% than the previous minimum TECs, but it becomes larger at higher latitudes. In the midlatitude region, therefore, the difference is relatively small in the transition from negative changes at low latitude to positive at high latitude. This is especially true during daytime, but at night, the difference tends to be positive, in particular, during the early morning around 05:00 magnetic local time.

The plasma density in the ionosphere is basically determined by the balance between production and loss of the ions and electrons with the additional effects of plasma transports. Apart from the transport effects, the change of solar EUV irradiance can directly affect the production rate and also the recombination rate via the changes of neutral composition in the thermosphere. Specifically speaking, during the last solar minimum period, the lower solar EUV irradiance must have reduced the production rate, which reduces the ionospheric density when the solar zenith angle is less than 90° as in the daytime at low and middle latitudes or in the summer polar region. The lower solar EUV irradiance must also have affected the neutral composition by cooling and lowering the thermosphere, which in turn affects the recombination rate especially when the solar zenith angle is greater than 90° as in the nighttime or in the winter polar region. The global morphology of the difference map in Figure 7 clearly shows these two aspects of the lowered solar EUV effects on the ionosphere. The daytime negative TEC differences obviously result from the reduced production due to the low solar EUV irradiance. At night however when the solar EUV production ceases, the recombination with neutral molecules controls the ionosphere. As reported by *Emmert et al*. [2010] from their analysis of satellite drag data and *Solomon et al*. [2010, 2011] from their numerical model simulations, the thermospheric density was anomalously low over the whole globe, and the lowered density in the thermosphere seemed to change the composition to reduce the recombination rate, which resulted in the increase of the nighttime ionospheric density during the last solar minimum period. The daytime ionosphere should also be affected by the changed neutral composition, but the reduced solar EUV production dominates the ionospheric density over the recombination effects.

However, the daytime high-latitude and nighttime equatorial ionospheric TEC differences in Figure 7 do not follow the above theory. At high latitudes, the solar zenith angle is large, and the reduced EUV effect on the production seems to be overwhelmed by the effects of the reduced recombination rate especially during summer, as will be discussed in the next section. The equatorial ionospheric TEC remained negative even after sunset until the early morning just before sunrise. This may indicate that the strength of the equatorial anomaly (i.e., vertical plasma drift) was weaker during the last minimum period than during the previous minimum period, which was also indicated by *Lühr and Xiong* [2010] and *Heelis et al*. [2009]. In particular, *Lühr and Xiong* [2010], in their comparison between the IRI-2007 model prediction and the satellite observations for the ionospheric density at about 400 km altitude during the last solar minimum, reported that the largest differences appear at low latitudes during daytime (i.e., model > observations), and the model prediction is somewhat larger than the observations even after sunset at low latitudes as in our result. The larger equatorial density of the IRI model implies that the equatorial vertical plasma drift is too strong in the IRI; in other words, it was smaller during the last solar minimum period than during the previous solar minimum periods.

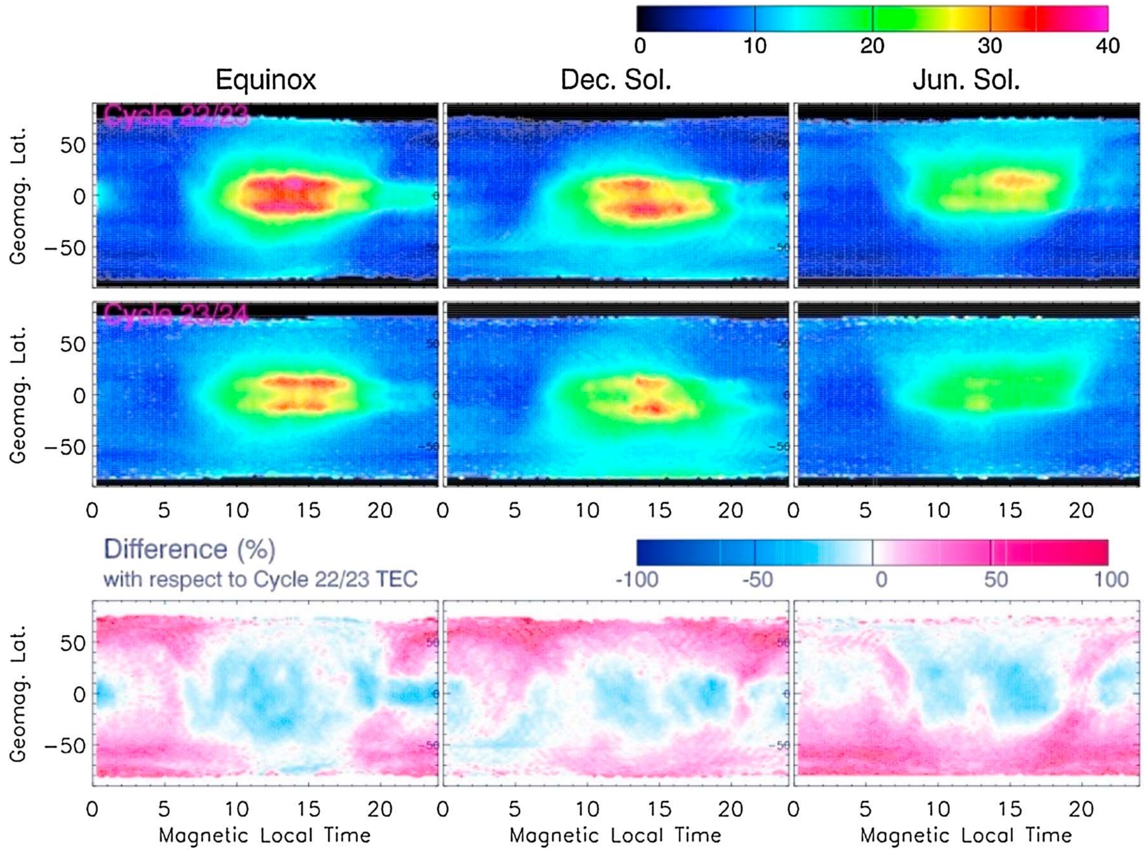

Figure 8. Same as the TEC maps as in Figure 7 but for three seasonal cases as (left) equinox, (middle) December solstice, and (right) June solstice.

3.3. Seasonal Variations of the TEC Differences

In order to investigate the seasonal variations of the ionospheric responses to the low solar activity, the seasonally averaged TECs in Figure 7 are divided into three different seasonal cases as shown in Figure 8: equinox (day of year: 50–110 and 234–294), December solstice (day of year: 1–50 and 295–366), and June solstice (day of year: 111–233). The TEC maps for each season are represented in the same format as in Figure 7 but with different color scale. The most noticeable seasonal characteristics in the difference TEC maps in Figure 8 are the day-night discrepancy in equinox and the hemispheric asymmetry in solstice. The distinctive day-night discrepancy in equinox (except for nighttime equatorial region) is the most apparent results of the reduced EUV production during daytime and the reduced recombination at night.

This simple and clear result of the reduced EUV irradiance however becomes complicated during solstices. While the TEC differences are largely symmetric around the magnetic equator in equinox, the differences in solstices show strong hemispheric asymmetry, being positive in winter but negative in summer at higher latitudes. The equatorial ionospheric TECs in solstices mostly show negative differences during daytime as in equinox. The hemispheric asymmetry in solstices implies that the ionospheric responses to the reduced EUV irradiance during the last solar minimum were different in the summer and winter hemispheres each other. In the winter hemisphere, the effects of the reduced EUV irradiance on the production seemed to be overwhelmed by recombination effects induced by changed neutral composition even during daytime due to large solar zenith angle. In the summer hemisphere, on the other hand, the reduced production seemed to dominantly affect the ionosphere throughout the day and even at night due to small solar zenith angle. Furthermore, the solstitial interhemispheric neutral circulations during the two solar minimum periods may have been different each other, which might have further affected the hemispheric asymmetry of the difference TEC maps in Figure 8. Systematic numerical experimentations with an ionosphere-thermosphere coupled model will be required to investigate the specific role of thermospheric changes in the ionospheric responses to the extremely low solar activity.

4. Summary and Conclusion

The ionospheric TEC measurements from TOPEX and its follow-on mission, JASON-1, are compared with each other during the overlap period of the two satellite missions to confirm that they can be considered as a single observation within ±5 TECU for global ionosphere. Using this global TEC observation, the global ionospheric responses to the extremely low solar activity during the last solar minimum period were investigated by comparing with the previous solar minimum period. The results of the comparison between the two solar minimum periods can be summarized as follows:

1. The differences in the global daily mean TECs are negligibly small unlike what was expected from the unusually low EUV level.
2. However, the global TEC maps reveal that there are significant differences, and the differences show systematic variations with latitude, local time, and season.
3. Daytime ionospheric TECs were reduced by up to 30% as expected, but the nighttime ionospheric TECs were unexpectedly enhanced by up to 50% from the previous minimum period. But the reduced daytime equatorial TEC continues to exist even after sunset until the early morning just before sunrise.
4. The negative (i.e., reduced) TECs at low latitudes during the last solar minimum become positive (i.e., enhanced) at higher latitudes and the midlatitude differences are relatively small.
5. The ionospheric responses to the extremely low solar activity show remarkable differences between the summer and winter hemispheres.

These results explain why previous studies on the ionosphere during the last solar minimum reported different and inconsistent ionospheric responses unlike the consistent results on the thermosphere. While the effects of the anomalously low solar EUV irradiance on the thermosphere were relatively uniform, the ionospheric responses show systematic variations with latitude, local time, and season since the thermospheric changes in composition and possibly in global neutral circulation may also strongly affect the ionospheric density changes in addition to the direct solar EUV effect on the ion production. The relative magnitude of the effects of these two factors varies with local time, latitude, and season, which result in the corresponding variations of the TEC differences between the last two solar minimum periods. For more specific roles of the thermospheric changes in the ionospheric density changes during the last solar minimum period, a numerical simulation study would be required by using an ionosphere-thermosphere coupled model.

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