The ionospheric anomalies prior to the M9.0 Tohoku-Oki earthquake

Huijun Le a,b,⇑, Libo Liu a,b, Jann-Yeng Liu c, Biqiang Zhao a,b, Yiding Chen a,b, Weixing Wan a,b

a Key Laboratory of Ionospheric Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
b Beijing National Observatory of Space Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
c Institute of Space Science, National Central University, Chung-Li, Taiwan

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ABSTRACT

The GPS total electron content (TEC) data were used to investigate the ionospheric abnormal behaviors prior to the 2011 Tohoku-Oki earthquake. The observations show a significant enhancement in TEC on March 8, 2011, and during the same period the solar activity also has a large increase. Both an empirical model and a theoretical model were used to check whether the TEC anomalies were entirely contributed by the increase in solar radiation. The comparison between the observations and the simulation results shows that only the solar radiation enhancement was not enough to produce the observed significant TEC enhancement. It means that some additional mechanisms, such as the per-earthquake ionospheric disturbance or the geomagnetic activities, may play a significant role in the significant TEC enhancement on March 8. The temporal–spatial distribution of the extreme TEC enhancement within 30 days before the earthquake was particularly pursued. It is found that the extreme enhancement was persistently located in the region adjacent to the epicenter and the magnetic conjugate point for a long time of 16 h. In addition, a geomagnetic disturbance with $Kp = 4$ occurred on March 7. Therefore, the significant TEC enhancement on March 8 might be related to the M9.0 Tohoku-Oki earthquake and the geomagnetic disturbance.

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1. Introduction

A huge earthquake with magnitude 9.0 hit Japan at 05:46 UT on March 11, 2011 and induced subsequently a great tsunami which caused the huge disaster. The epicenter (38.1°N, 142.37°E) locates near the east coast of Japan with the source depth of 32 km and the magnitude reaches as high as 9.0. It is officially named as the Tohoku District Off-the-Pacific-Coast earthquake, and is abbreviated as the Tohoku-Oki earthquake. The study of the ionospheric state prior to the occurrence of large earthquakes has attracted geophysicists’ attention for many years and it has also been one of important tasks of modern geophysics and radio physics due to the massive destruction of the great earthquakes like the 2008 Wenchuan and the 2010 Haiti earthquake.

Until now, researchers have paid much attention to the Tohoku-Oki earthquake. Several studies focus on the ionospheric disturbances after as well as before the great earthquake. For co-seismic disturbances, Tsugawa et al. (2011) firstly reported the detailed ionospheric disturbances following the 2011 Tohoku-Oki earthquake on the basis of the high-resolution GPS total electron content observation in Japan. By using dense GPS data in Japan, Rolland et al. (2011) analyzed the ionosphere response and found three different types of waves in the TEC signal over Japan. Liu et al. (2011b) studied seismo-traveling ionospheric disturbances triggered by seismic and tsunami waves of the Tohoku-Oki earthquake. Hao et al. (2012) provided the evidence of quake-excited infrasonic waves by Doppler shift measurements as well as by GPS TEC. For pre-seismic anomalies, Heki (2011) reported a very interesting and important result. He found clear precursory positive anomaly of ionospheric total TEC around the focal region. It started ~40 min before the earthquake and reached nearly 10% of the background TEC. Furthermore, similar preseismic TEC anomalies were seen in other great earthquakes including the 2010 Chile earthquake (M8.8), the 2004 Sumatra–Andaman (M9.2) and the 1994 Hokkaido-Toho-Oki (M8.3).

Although there are many reports on the pre-earthquake ionospheric anomalies for some special earthquake events from the 1970s, it is not sufficient to draw the conclusion that these anomalies are really related to the forthcoming earthquake because the ionospheric F2 layer has significant day-to-day variation (Forbes et al., 2000; Rishbeth and Mendillo, 2001; Mendillo et al., 2002) and it might also link with the lower atmosphere. Thus there are still the debates or doubts about pre-earthquake ionospheric anomaly (e.g. Afraimovich et al., 2004; Kamogawa, 2006; Rishbeth, 2006a,b; Dautermann et al., 2007; Thomas et al., 2012). Afraimovich et al. (2004) suggested that the TEC increase identified before the Hector Mine earthquake occurrence was not associated with the process of earthquake preparation but more controlled by local time and...
geomagnetic activity. Thomas et al. (2012) found that the abnormal TEC variation identified by Pulinets et al. (2007) as being related to the Hector Mine earthquake was not actually anomalous; it is just part of normal global-scale TEC variation. Based on the statistically analysis for 79 earthquakes in Southern California during 2004–2005, Dautermann et al. (2007) did not find significant correlation between TEC perturbations and these earthquakes in temporal or spatial variation. In the last decade, seismo-ionospheric anomalies of the TEC derived from ground-based receivers of GPS before large earthquakes have been intensively studied (e.g., Pulinets, 1998; Pulinets et al., 2003, 2007; Zhao et al., 2008, 2010; Lin, 2010, 2011; Liu et al., 2001, 2004, 2009; Xu et al., 2010, 2011; Zakharenkova et al., 2007). In order to try to answer the questions or respond these debates, Le et al. (2011) studied statistically the pre-earthquake ionospheric anomaly by using the GPS TEC data for total number of 736 earthquakes with magnitude greater or equal to 6 in years 2002–2010 around the world. The results show the occurrence rate of anomaly within several days before the earthquakes is overall larger than that during the background days, especially for the large magnitude and low depth earthquakes. These results indicate that those anomalous behavior of TEC within just a few days before the earthquakes are related with the forthcoming earthquakes in high probability.

In addition, electron temperature anomaly before large earthquakes was also studied recently. Based on the data from HINOTORI satellite developed by Japan, Oyama et al. (2008) found that electron temperature around the epicenters significantly decreases in the afternoon periods within 5 days before and after three earthquakes over Philippine. It is found that the TEC over a forthcoming epicenter region significantly decreases or increases in the afternoon and/or evening period of 1–6 days before the earthquake occurrence (Liu et al., 2004). Taking the Haiti earthquake as an example, there was a successive long time enhancement in TEC (nearly 24 h) 1 day before the earthquake and the TEC enhancement anomaly appears specifically and persistently in a small region of the northern epicenter area; these two factors suggest that the enhancement anomaly on 11 January 2010 is highly related to the Haiti earthquake (for details please see Liu et al. (2011a)). Comparing the observations and the simulations with the modified electric field, they proposed that seismo-electromagnetic environments could be modified around the epicenter, where the generated seismo-electric fields might penetrate into the ionosphere and perturb the TEC within it during the earthquake preparation period.

In this study, the GPS TEC derived from Jet Propulsion Laboratory (JPL) global ionosphere map (GIM) was used to investigate

Fig. 1. The temporal variation of TEC at the epicenter (38.1°N, 142.37°E) extracted from JPL GIM (a) during August 2, 2011–December 3, 2011. The 30-day median (dashed line) is also shown in the corresponding panel. Solar activity level (F10.7p index) is plotted in panel (b). Geomagnetic activity index (Dst and Kp) and the z component of IMF are plotted in panel (c–e).
the ionospheric behaviors before the Tohoku-Oki earthquake and find possible seismo-ionospheric anomalies in the region adjacent to the epicenter. The solar activity was just much enhanced before the earthquake. Both an empirical model and a theoretical model were employed to check whether the TEC anomalies were entirely contributed by the increase in solar radiation. Furthermore, we checked whether these anomalies might be associated with the forthcoming earthquake by an analysis on the temporal–spatial distribution of the extreme enhancement. Some geomagnetic disturbances occurred before the earthquake. The geomagnetic activity effect before the earthquake was also discussed.

2. Data source

The data of JPL TEC map are utilized here to investigate the ionospheric variations before the Tohoku-Oki earthquake during background days (ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex). The JPL TEC maps with 2-h time resolution covering ±87.5° latitude and ±180° longitude ranges with spatial resolutions of 2.5° and 5°, respectively. The TEC is generated by mapping the slant path delay of the dual frequency L band (1.545 GHz and 1.226 GHz) signal (code group delay and phase advance) observed by the global distributed international GPS service (IGS) stations. Vertical TEC (VTEC) is converted form slant TEC (STEC) using single or multi-layer assumption and mapping functions. Data from over more than 100 continuously operating GPS receivers in a global network are being used to produce GIM of the TEC. The error of their products is around several TEC Units (TECU, 1 TECU = 10¹⁶ - electrons/m²).

To identify whether the anomaly in TEC would be really related to the earthquake, we need to know the solar and geomagnetic activity condition during the anomaly days. The solar activity condition is indicated by 10.7 cm solar radio flux (F10.7) in units of 10⁻²² W m⁻² Hz⁻¹ (http://spidr.ngdc.noaa.gov/spidr/). In this study, F10.7p = (F10.7 + F10.7a)/2 is used as the solar activity proxy. Here F10.7 is the 10.7 cm solar flux index on the current day and F10.7a is the 81-day average of F10.7 centered on the current day. It was indicated by Liu et al. (2006) that F10.7p, which was adopted by Hinteregger et al. (1981) and Richards et al. (1994), can better represent the intensities of solar extreme ultraviolet (EUV) fluxes than F10.7. The z-component of interplanetary magnetic field (IMF) Bz (http://spidr.ngdc.noaa.gov/spidr/), the geomagnetic Dst and Kp indices (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/) are used to monitor the geomagnetic activity condition.

3. Observations and analysis

To study the TEC anomaly before the Tohoku-Oki earthquake, the temporal variation in TEC above the epicenter several days before the earthquake is needed and the reference value is also needed. Thus we plotted the temporal variation in TEC from February 8 to March 12 at the grid point (40°N, 140°E) closest to the epicenter in Fig. 1a. The 30-day running median is also shown in the figure. The results show long-time significant enhancements in TEC during period of March 3–12. The daily peak TEC increases from the lowest value of 16.2 TECU on February 25 to the highest value of 35.2 TECU on March 8. To check possible effect of the solar activity and geomagnetic activity on the ionospheric behaviors, the F10.7p index, Dst index, Kp index and Bz are illustrated in Fig. 2.

![Fig. 2](image-url) The latitude–time-TEC plots extracted from the JPL TEC along 142.37°E from November 2, 2011 to December 3, 2011. The solid and open start symbols are the epicenter and corresponding conjugate point of the Tohoku-Oki earthquake, respectively. The three white lines from the top to down denote the location of the epicenter, magnetic equator, and the magnetic conjugate point of the epicenter, respectively.
Fig. 1b–e, respectively. As shown in Fig. 1b–e, the solar activity and geomagnetic activity is not quiet during the period, but just disturbed a lot. Fig. 1b shows a significant increase of F10.7p index from ~88 on February 25 to ~122 on March 8. Comparing Fig. 1b and a, one can find the similar temporal evolution between the TEC and the F10.7p index, which suggests that the solar activity enhancement should be the primary source for the significant TEC enhancement from the low values on February 24–26 to the high values on March 8–10. In addition, there are also some significant geomagnetic disturbances on February 14–15, February 18–19, March 2–3, and March 10–12, respectively, which then cause the corresponding abnormal increases in TEC as shown in Fig. 1a.

As it is known, the ionospheric anomaly before an earthquake occurred not only above the epicenter, but also occurred at the other adjacent region (Zhao et al., 2008; Liu et al., 2010), or even occurred in the region adjacent to the magnetic conjugate point. Furthermore, the stronger the earthquake magnitude, the larger the possible coverage is. The Tohoku-Oki earthquake’s magnitude reaches M9.0. To further illustrate TEC variation at the other latitude region along the earthquake meridian plane; we plotted the Latitude–Local Time TEC map extracted from the JPL GIM along the longitude of 142.37°E during period of February 11–March 12 in Fig. 2. The results show the significant enhancements in TEC about 1 week before the earthquake with the peak enhancement occurring on March 8.

As shown in Fig. 1b, the solar activity has a significant increase around March 6–10 and reaches a peak on March 8. Thus the solar activity enhancement should be one of the main driving sources for the significant increase in TEC. Fig. 1b–e shows that solar activity level is almost the same on March 7–9, and the geomagnetic activity is relatively quiet on the 3 days except a moderate disturbance of Kp = 4 – on March 7. However, seeing from Fig. 2, one can find the enhancement in the TEC on March 8 is much stronger than that on March 7 and 9. The results also show that the increase in TEC not only occurred near the epicenter, but also occurred in the whole middle-low latitude region. Furthermore, the peak enhancement did not occur above the epicenter, but at the 10–20° south of the epicenter. The greater the earthquake’s magnitude is, the larger the area of the earthquake preparation zone becomes (Dobrovolsky et al., 1979), which results in the larger disturbing region in the ionospheric height. Liu et al. (2009) reported the abnormal changes of TEC occurring in the places more than 20° away from the epicenter before the M8.0 Wenchuan earthquake. Thus, for the great M9.0 Tohoku-Oki earthquake, the large radius of the earthquake preparation zone may result in the disturbances even far away from the epicenter, as shown in Fig. 2.

The GIM TEC is not the real observation from the GPS receiver stations. Thus, to further cross-check the accuracy and reliability of the GIM, we compared the raw TEC data from the four GPS stations (usud, tskb, ccjm, and mcil) with the corresponding TEC from JPL GIM. The usud and tskb stations locate around the epicenter and the ccjm and mcil stations locate about 10–15° south of the epicenter. Fig. 3 shows the TEC series at the four stations and the JPL GIM at the corresponding locations. The comparison among
these data shows that the JPL TEC is well consistent with the TEC derived from the single station. Seeing from Fig. 3, one can find the significant enhancement in the TEC on March 8 from both the single stations and JPL GIM. The percentage enhancements on March 8 compared to March 7 are 16.2, 23.2, 39.2, and 43.1, for stations usud, tskb, ccjm, and mcil, respectively. As for the results from JPL GIM, the corresponding enhancements are 17.6, 17.8, 28.1, and 20.4, respectively. Both the JPL GIM and single station measurements show the anomaly on March 8 is more significant at the southern side of the epicenter than at the epicenter. Furthermore, the raw measurements from the single stations show more significant anomaly on March 8.

4. Check solar activity effect

As illustrated in Figs. 1–3, there are some significant enhancements in TEC about 1 week before the great M9.0 earthquake particularly on March 8, 2011. At the same time, we also noticed that the solar activity and geomagnetic activity is much disturbed; especially there are large enhancements in solar irradiation. Fig. 1 shows the solar activity F10.7p index increases from ~88 on February 25 to ~122 on March 8. Fig. 2 depicts that the significant increase in TEC about 1 week before the earthquake seems to be a large-scale phenomenon, rather than a very local enhancement. As mentioned above, the large-coverage enhancement may result from the increase of solar activity or some other driving forces. To verify this idea, it is needed to know to what extent the solar radiation enhancement can cause the TEC to increase.

To check the solar activity effect on the ionosphere, we first used NeQuick model (Hochegger et al., 2000; Radicella and Leitinger, 2001) to simulate the TEC variation along the longitude 142.37°E for different solar radiation flux: F10.7 = 88 on February 25 and F10.7 = 122 on March 8. NeQuick is an ionospheric electron concentration model able to give the electron density distribution on both the bottomside and topside of the ionosphere. It has also been adopted by the International Telecommunication Union, Radio Communication Sector (ITU-R) as a suitable method for TEC modeling.

We first plotted the temporal evolution of JPL TEC along 142.37°E on February 25 and March 8 in Fig. 4. The results on February 25 represent the reference situation with low solar activity (F10.7p = 88) and the results on March 8 represent the anomaly situation with higher solar activity (F10.7p = 122). Then we plotted the NeQuick simulated TEC with the solar activity input of F10.7p = 88 and F10.7p = 122, respectively. As shown in Fig. 4, the NeQuick model reproduces the main characteristic of JPL TEC on February 25 by using the same solar activity of F10.7p = 88 although the NeQuick model has the more distinguished equatorial ionization anomaly (EIA) structure. The JPL GIM results show the TEC values are much higher on March 8 than on February 25. However, with F10.7p index increasing from 88 on February 25 to 122 on March 8, the NeQuick does not give as high as the significant enhancement on March 8 as JPL GIM observed. Comparison of JPL TEC along 142.37°E with the corresponding NeQuick results shows again that not all of enhancements on March 8 come from the increase in solar activity, while part of the enhancement might come from the other factors like the earthquake effect or other effects.

Except the empirical ionospheric model NeQuick, we also used a theoretical ionospheric model, TIME-IGGCAS (Yue et al., 2008), to cross check the ability of TEC enhancement from F10.7p = 88 to F10.7p = 122. The model solves the 2-D coupled equations of the mass continuity, momentum, and energy for three dominant ions.
O⁺, H⁺ and He⁺. It also calculates values of concentrations of three minor ions N₂⁺, O₂⁺ and NO⁺ in the E- and F-region under the assumption of photochemical equilibrium. The neutral temperature and densities are taken from the NRLMSIS-00 model (Picone et al., 2002), and the NO concentration is calculated from an empirical model developed by Titheridge (1997). The neutral winds are supplied by the HWM-93 model (Hedin et al., 1996). The photoelectron heating effect is similar to that of Millward et al. (1996). At low altitudes (below 300 km), the photoelectron heat is distributed locally. At higher altitudes (above 300 km), the photoelectron heat comes from local and also from sources in the other hemisphere.

We modeled the middle-low latitude ionospheric behaviors along 142.37°E with F10.7p = 88 on February 25 and F10.7p = 122 on March 8, respectively. The TEC value was calculated by integrating the electron content from 130 km to 1500 km. The absolute change of TEC (ΔTEC) and the percentage change of TEC (rTEC) between the two simulated results were calculated and shown in Fig. 5a and b. The corresponding ΔTEC and rTEC from JPL GIM are plotted in Fig. 5c and d. The observations from JPL GIM show a significant enhancement for both ΔTEC and rTEC. However, neither the simulated ΔTEC nor the simulated rTEC reached the same magnitude as JPL GIM results show. Comparisons of the observed results with the simulated results show again the significant increase in TEC on March 8 comes not only from the solar radiation enhancement but also from other factors. In addition, the absolute change of JPL TEC show the peak enhancement did not occurred above the epicenter (∼38°N) but at the southern side of the epicenter. Furthermore, from the percentage change, one can find the increase in TEC in northern hemisphere is much higher than that in southern hemisphere.

5. Discussion

5.1. Temporal–spatial variations

As discussed above, through checking solar activity effect via an empirical model and a theoretical model, we found that the solar radiation enhancement was not enough to produce the significant enhancement in TEC on March 8. Thus, there should be some other factor like pre-earthquake effect or other effects together with solar activity enhancement to contribute to such a significant increase.

The TEC derived from the JPL GIM can be ideally used to observe the temporal and spatial variations simultaneously. The GIM TEC covers ±87.5° latitude and ±180° longitude ranges with spatial resolutions of 2.5° and 5°, respectively. Therefore, each TEC map consists of 5183 (=71×73) grid points. Each day has 13 maps from 00UT to 24UT with a 2-h interval. In order to further compare the TEC variation on March 8 with that on the other days and find its abnormal behavior, an analysis on the temporal and spatial

![Diagram](image-url)
distribution of extreme enhancement within 30 days before the earthquake was conducted. Firstly, for each grid at a given UT time of a given day, we calculated the difference of TEC on the given day from the reference value, the median of 30 days before. Such a calculation was done for total of 30 days before the earthquake (from February 19 to March 10). Secondly, for each grid at each UT time, we checked whether its extreme enhancement of the 30 days before the earthquake appeared on March 8. Finally, we can get the spatial distribution of 30-day extreme enhancement at the given UT time that appeared on March 8. Fig. 6 illustrates such a spatial distribution at various UT times from 00UT to 22UT, respectively.

Considered the great magnitude (M9.0) of the earthquake, the earthquake preparation area of lithosphere should be very large, which may result in the abnormal ionospheric variation even far away from the epicenter. From Fig. 6, one can see that most of grids of the extreme enhancement from 04 UT to 20 UT occurred in the adjacent regions of the epicenter and its magnetic conjugate point. Liu et al. (2010) also reported abnormal changes of TEC over large area for 2004 Sumatra–Andaman earthquake. It has been reported that seismo-ionospheric TEC anomalies often repeatedly and persistently appear near the epicenters for 8–12 h on the anomalous days before large earthquakes (Liu et al., 2000, 2004, 2009, 2010). To further see if the TEC enhancement anomalies specifically appear in the earthquake adjacent region for a long duration, Fig. 7 plots the spatial distribution of the 30 day extreme enhancement that appeared repeatedly at various time points on March 8. The results show the grids with 7, 8, 9, and more repeating times appear mainly in the adjacent region of epicenter and the magnetic conjugate areas. The extreme enhancement persistently located around the adjacent region of epicenter and the magnetic conjugate point for as long as 16 h, which indicate that these anomalies might be related to Tohoku-Oki earthquake. Liu et al. (2011a) also reported a longer time (nearly the entire day) of extreme enhancement locating the epicenter on January 11, 2010, 1 day before 2010 Haiti earthquake.

In addition, the results also show these grids of extreme enhancement did not lie above the epicenter but mainly lay above two crests of EIA and equatorial regions. Such a characteristic of the distribution of extreme enhancement shows that the electric field disturbance may be one of the factors producing the abnormal enhancement in TEC, because it can cause the anomaly of both the epicenter and its magnetic conjugate point. Liu et al. (2011a) suggested that the TEC enhancement anomaly 1 day before the 2010 Haiti earthquake might be derived from the change of dynamoelectric field of the ionospheric plasma fountain by seismo-electric signals generated around the epicenter during the earthquake preparation period.

5.2. Effects of geomagnetic disturbances

Although the discussion above shows that the local and long duration anomaly on March 8, 2011 implies that this anomaly may be related to the subsequent earthquake on March 11, 2011, the anomaly may also result from other driving forces like geomagnetic disturbances. As mentioned in Section 3, a geomagnetic disturbance with Kp = 4 – occurred on March 7, 2011. There are several geomagnetic disturbance events occurring 1 month before the earthquake, such as $\text{Dst} = -39$ nT, $\text{Dst} = -32$ nT, $\text{Dst} = -68$ nT, $\text{Dst} = -25$ nT, and $\text{Dst} = -98$ nT on February 14, February 18, March 1, March 7, and March 12, respectively. The event on March 7 is the smallest one among these geomagnetic disturbance events. However, there is the largest ionospheric variation with the

![Fig. 6](image.jpg) The spatial distribution of extreme enhancement based on JPL GIM at various UT times (from 00 UT to 22 UT) of the 30 days before the earthquake that appeared on March 8, 2011. The color denotes the difference of the TEC observed on March 8, 2011 from the associated median. The solid and open star symbols denote the epicenter and its magnetic conjugate point.
enhancement of about six TECU after the event on March 7. In addition, we do not find similar TEC anomalies localized around the epicenter for long time for other events. Thus, we initially considered that the anomaly on March 8 was not mainly associated with the geomagnetic disturbance on March 7. But the geomagnetic disturbance effect cannot be excluded based on the data used in this study. The enhancements in TEC on March 8 might be induced mainly by the pre-earthquake effect and partly by the geomagnetic disturbance.

6. Summary

As illustrated in Figs. 1–3, the global TEC maps derived from JPL show some significant enhancements occurred on March 8, 3 days before the great Tohoku-Oki earthquake. In addition, the variation of F10.7p index also shows large increase in solar radiation in the same period. To check whether total of the enhancements in TEC were contributed by the increase in solar radiation; we used both the empirical model NeQuick and the theoretical model TIME-IGGCAS to model the TEC changes from low solar activity of F10.7p = 88 to a higher solar activity of F10.7 = 122. The simulations from both NeQuick and TIME-IGGCAS show that the solar radiation enhancement was not enough to produce the significant enhancement in TEC on March 8, which means there should be some other factors contributing to the significant enhancement. In order to further compare the TEC variation on March 8, 2011 with that on the other days and find its abnormal behavior, an analysis on the temporal and spatial distribution of extreme enhancement within 30 days before the earthquake was conducted. The results show that most of grids of the extreme enhancement on March 8 occurred at the adjacent regions of the epicenter and its magnetic conjugate point. Furthermore, we also calculated the spatial distribution of the 30 day extreme enhancement that appeared repeatedly at various time points on March 8, 2011. The color represents the repeat times. The places with repeat times less than 4 are not shown. The solid and open star symbols denote the epicenter and its magnetic conjugate point.

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