The TEC Enhancement Before Seismic Events Is an Artifact

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Key Points:

- VTEC residuals for several stations depend highly on selected time window
- VTEC residuals for station LYAR vary significantly for choice of polynomial fit
- TEC enhancement as an earthquake precursor is an artifact

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The TEC Enhancement Before Seismic Events Is an Artifact

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Abstract Since 2011 there has been an ongoing debate about the possibility of short-term earthquake prediction using total electron content (TEC) ionospheric monitoring by the Global Navigation Satellite System (GNSS). Heki (2011), https://doi.org/10.1029/2011gl047908 initiated this debate when he published results for the 2011 Tohoku event reporting a TEC enhancement 40 min before the earthquake; several later papers by Heki and coworkers have made similar claims for other earthquakes. If correct, Heki's methods might contribute to short-term earthquake prediction. However, Heki's claims have been strongly criticized as being due to a decrease in the background TEC after earthquakes–the so called ionospheric hole–rather than an enhancement before. Depending on the choice of reference curve to be subtracted from the raw data to infer the "anomaly," the data analysis can produce either a hole or an enhancement. We show that the choice of reference curve -calculated by Heki with a polynomial fit-is strongly affected by the degree of the polynomial, as well as by the selection of the time window. We also show using synthetic examples that even if there is actually no signal before the event, Heki's methods can lead to spurious precursory signals (i.e., signals with non-zero amplitude before the event) after the reference curve is subtracted. It thus appears likely that the reported TEC enhancements are artifacts.

Plain Language Summary The present seismological consensus is that short-term earthquake prediction is not possible. In 2011, Heki argued against this view, suggesting that it was possible to make short-term earthquake predictions by measuring total electron content (TEC) in the atmosphere. He reported that data for the 2011 Tohoku earthquake showed a TEC "enhancement" 40 min before the event. This report has been strongly criticized: it has been suggested that the observed data instead were due to a decrease of the TEC after the earthquake, the so-called ionospheric "hole." The key point is the selection of the reference curve to be subtracted from the data to reveal either the hole or the enhancement. We show that the reference curve is highly sensitive to the degree of the polynomial and the selected time window. Thus, the claimed TEC enhancement could simply be an artifact that can be obtained by subjectively "tuning" the reference curve. We further support this conclusion by conducting synthetic tests that show the likely artificial nature of the enhancement.

1. Introduction

The possibility of making short-term earthquake predictions has been investigated for over one hundred years by seismologists. Here, we follow standard seismological usage by defining short-term earthquake predictions as deterministic statements that a large earthquake is imminent within sufficiently narrow bounds in magnitude, location and time, and with enough reliability and accuracy, to justify issuing alarms to the public. Throughout the history of seismology, with the exception of the early 1970s, the consensus of the seismological community was that short-term earthquake prediction, as defined above, is not possible (e.g., Geller et al., 1997; Jordan et al., 2011; Macelwane, 1946; Wood & Gutenberg, 1935). Scholz et al. (1973) claimed to have observed temporal changes in in-situ seismic wave velocities that could be used to make short-term earthquake predictions. That optimism dissipated after further research failed to reproduce such results, suggesting they were artifacts. A review by Geller (1997) gives an overview of earthquake prediction research, with emphasis on the 1970s. An on-line debate on Nature's home page considered earthquake prediction research, with opinions divided on whether it was worthy of further funding, but with general agreement that it was not possible at that time (Main, 1999).

Claims to have observed earthquake precursors have been extensively published in the last 50 or more years. After a large earthquake occurs, retrospective searches can find "anomalies" of all sorts, e.g., electromagnetic, geochemical anomalies, seismic quiescence, etc., that occurred before the earthquake. However, there are no known causal and quantitative physical mechanisms for attributing the "anomalies" to hypothetical preparatory processes of earthquakes. It is often difficult to rule out non-earthquake-related mechanisms that might have generated the signals; the statistical evidence is weak, and there are no objectively testable hypotheses for how to use the alleged anomalies to make quantitative prediction going forward in real-time (Geller, 1997).

Seismological pessimism notwithstanding, some workers are continuing to pursue the search for electromagnetic anomalies (Uyeda et al., 2009) and atmospheric-ionospheric anomalies (e.g., Kamogawa, 2006; Liu et al., 2004). They propose that, during the nucleation process of the earthquake, the fault acts as an electromagnetic dipole, producing electromagnetic perturbations, detectable near the source, and locally perturbing the ionosphere, but there is no quantitative physical mechanism that can be tested. Several authors have attempted to make statistical studies of the correlation of ionospheric anomalies with earthquakes (Hayakawa et al., 2010; Le et al., 2011; Liu et al., 2006). The ionospheric anomalies seem to appear randomly in the days or even weeks before the seismic events. The ionosphere is a strongly active and dynamic medium: consequently, it is difficult to find a quantitative physical explanation for a causal relation between the presumed anomalies and earthquakes. Strong arguments have been raised against the existence of ionospheric precursors (e.g., Kamogawa, 2007; Rodger & Clilverd, 2007). The reported anomalies are also thought to be related to other disturbances such as geomagnetic storms (Rishbeth, 2007).

2. TEC Observations After Earthquakes

The total electron content (TEC)—a derived product of GNSS data, useful for removing the ionospheric delay—represents the integral of the electron density along the ray-path between the satellite and the station (Mannucci et al., 1993, 1998). TEC observations are usually located at the ionospheric piercing points (IPPs), using the approximation that the ionization is fully concentrated within a thin layer. This approximation is related to the ionospheric structure: the highest ionization is generally located at 300 km with a sharp decrease above and below. The IPPs are, in essence, located at the intersection of the station-satellite ray-path with the thin layer at the altitude of the highest ionization. Due to the ionospheric structure and observation geometry, the TEC follows a natural U-shape and is usually converted to vertical TEC (vTEC = TEC cos ϕ, where ϕ is the elevation angle) to reduce the effect of the geometry or to differential TEC (dTEC) to highlight the perturbation instead of the background (Figure 1).

TEC measurements are today commonly used to study ionospheric dynamics, space weather, and to explore the post-seismic effect of earthquakes and tsunamis in the ionosphere, called ionospheric seismology (e.g., Occhipinti, 2015, and references therein). The first detection of a post-seismic signal using TEC was presented by Calais and Minster (1995) following the Northridge, California, earthquake (17 January 1994). It is today broadly accepted that the vertical displacement at the epicentral area induced by the seismic rupture produces acoustic-gravity waves (AGW_{epi}) that propagate into the atmosphere (e.g., Occhipinti et al., 2013). The AGW_{epi} is strongly amplified during upward propagation due to the effect of the conservation of the kinetic energy ρv^2(in the adiabatic approximation of the atmosphere) and the decreasing density ρ of the atmosphere. Arriving at ionospheric altitude, the AGW_{epi} induces a strong perturbation in the plasma density visible in TEC observations by GNSS and is useful for tsunami risk estimation (e.g., Manta et al., 2020). Similar ionospheric signatures are also produced by the propagation of the Rayleigh wave ($AW_{Rayleigh}$), tsunamis (IGW_{tsuna}), and volcanic explosions ($AGW_{Volcano}$). Observation by ionospheric monitoring is now systematically (Occhipinti et al., 2013; Rolland et al., 2010). The validity of these signals has also been confirmed by numerical modeling (Occhipinti et al., 2006, 2008, 2011; Rolland et al., 2011), and they can be used to estimate the earthquake magnitude (Occhipinti et al., 2010). For a complete description of the AGW_{epi}, IGW_{tsuna}, and $AW_{Rayleigh}$ see Occhipinti (2015). The $AGW_{volcano}$ is detailed by Manta et al. (2021).

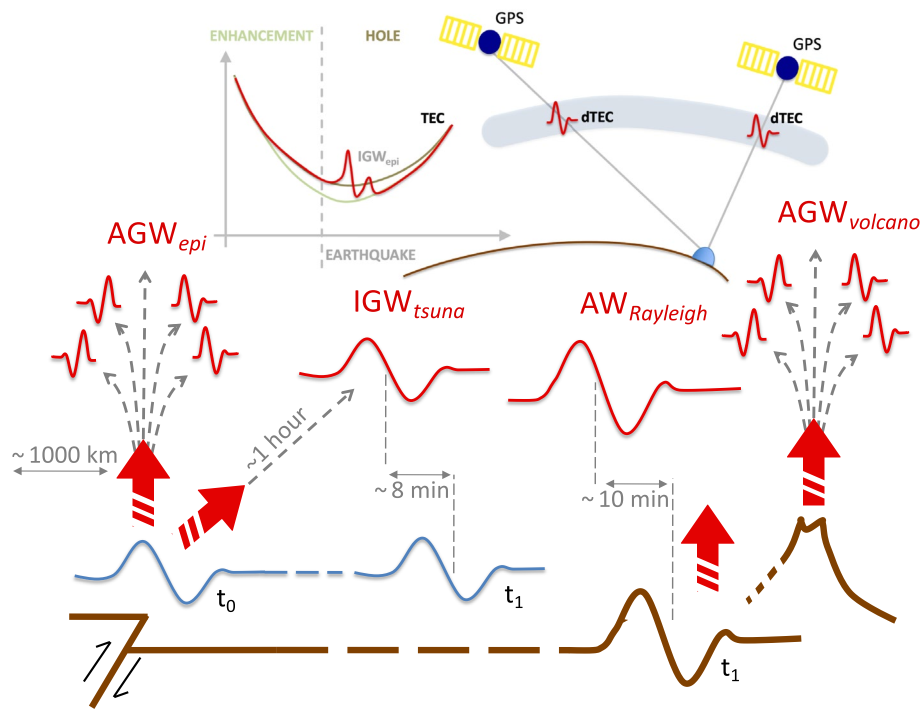

Figure 1. Atmospheric/ionospheric waves generated by earthquakes, tsunamis, and volcanic eruptions (bottom, adapted from Occhipinti, 2015): the vertical displacement in the epicentral area or at teleseismic distances (induced by tsunamis and Rayleigh waves) produces, in the near-field, an acoustic-gravity wave coupled with the uplift at the source (AGW_{epi}, and; in the far-field, an internal gravity wave coupled with the tsunami (IGW_{tsuna}), and a pure acoustic wave coupled with the Rayleigh wave ($AW_{Rayleigh}$). A volcanic eruption also generates an acoustic-gravity wave ($AGW_{volcano}$) that appears in the proximity of the explosion. During the upward propagation, the AGW_{epi}, IGW_{tsuna}, $AW_{Rayleigh}$, and $AGW_{volcano}$ are strongly amplified by the effect of the exponential decrease of the air density. The interaction of the AGW_{epi}, IGW_{tsuna}, $AW_{Rayleigh}$, and $AGW_{volcano}$ with the ionosphere produces strong variations in the plasma density observable by ionospheric sounding techniques (upper-right) and nominally here by GNSS measurements of the total electron content (TEC) and its variation (dTEC). The TEC background has a natural U-shaped behavior; depending on the selection of the unperturbed TEC background reference curve either, either a (post-seismic) hole or a (precursory) enhancement in the TEC (upper-left) can be produced.

2.1. Hole Versus Enhancement Debate

The existence of post-seismic oscillatory disturbances in the atmosphere is uncontested. However, following the catastrophic tsunamigenic seismic event in Tohoku (M_w 9.1), Japan, on 11 March 2011, Heki (2011) claimed to have found a total electron content (TEC) "enhancement" 40 min before the earthquake (which he attributed to a hypothetical electromagnetic dipole behavior of the fault during the nucleation process). He suggested that such signals might be useful for making short-term earthquake predictions. Heki (2011) also made similar analyses that suggested precursory signals for three other events: Sumatra (M_w 9.3, 2004), Hokkaido-Toho-Oki (M_w 8.2, 1994), and Chile (M_w 8.8, 2010).

Heki initiated an ongoing debate on whether or not this and similar claims of precursory signals should be accepted. The opposite side of the debate is the view that there was not an (precursory) enhancement before the earthquake, but rather a slow feedback of the ionization called the (postseismic) hole-to return to the normal condition of the ionosphere after the AGW_{epi} passed following the seismic event (Figure 1). The conclusion of the debate rests on the details of the signal processing methods used to isolate the "anomaly." We review these methods below.

Heki (2011) calculates a reference curve and subtracts it from the observed time series to obtain the anomaly, called differential TEC. The reference curve is a polynomial of some particular degree, fit to the data excluding a particular time window; for the 2011 Tohoku earthquake, Heki excluded the window from 40 min before the earthquake to 20 min after the earthquake. He then found the polynomial of the particular degree, which best fit the remainder of the observed data and subtracted it from the entire time series to obtain the differential TEC. In this case, the above approach produced the residual (differential TEC) that Heki (2011) claims as showing an enhancement starting 40 min before the Tohoku earthquake, which he argues, could have been used to predict the earthquake.

Heki (2011)'s selection of the excluded time window to compute the best polynomial fit (in the Tohoku earthquake the excluded time window was 5:12–6:00 UT, with the event occurring at 5:45 UT) that serves as the reference curve is based on the hypothesis that the ionosphere is not perturbed by the seismic event more than 40 min before and more than 20 min after the earthquake. This hypothesis is pure speculation. The degree of the polynomial used for the reference curve is also purely arbitrary. One other point that should be stressed is that Heki (2011)'s methods require determination of the reference curve from TEC data, which can only be done after the earthquake has already occurred. This makes it impossible to use these methods in operational real-time prediction of earthquakes even if an enhancement exists.

In the electronic supplement of Heki (2011), he claims that he can demonstrate that the positive anomalies are not artifacts coming from coseismic TEC decrease in three different ways. With regard to these three points, taken in opposite order: (3) It was shown by Astafyeva et al., (2013) that the ionospheric hole after the event reaches well into Korea and therefore the stations in Northern Japan used by Heki were affected. (2) Heki claims that stations in Northern Japan show an enhancement without being affected by the ionospheric hole after the earthquake, but a recent study of Tozzi et al., (2020) shows that the method on which this claim was based is inappropriate. (1) Heki argued that linear extrapolation after the onset of the precursor showed that the coseismic TEC decreases bring back the enhanced TEC to the state before the anomaly. However, Masci et al. (2015) considered tests of data fitting using only data before the earthquake; they clearly showed that for this case, no precursor is detectable and that claims for the detection of an enhancement depended on the choice of the time window for the fitting and the method used to fit the data.

2.2. The Ongoing Debate, 2011-Present

The claims of Heki (2011) triggered a debate which is still ongoing. Some other authors (Kakinami et al., 2012; Kamogawa & Kakinami, 2013; Utada & Shimizu, 2014) interpreted the TEC data differently: they pointed out that TEC does not recover to the normal state after the AGW_{epi} reaches the ionosphere. Consequently, these critics speculated about the effect of the giant tsunami on the ionosphere, noting that it produces what authors call an ionospheric hole: a wide depletion of TEC that can spatially extend up to several hundred kilometers and that lasts for a few tens of minutes, hypothetically due to the high recombination of plasma in the lower thermosphere through chemical processes. The formation of an ionospheric hole has also been observed for seismic events on land, for which tsunamis are not generated (Astafyeva et al., 2013). Thus, it seems that an ionospheric hole is mainly induced by the propagation of the AGW_{epi} (Matsumura et al., 2011) and not by the IGW_{tsuna}, which theoretically is only visible in the ionosphere 40 min after the tsunami genesis (Occhipinti, 2008)

Other authors made analyses of the data used by Heki (2011) but using other algorithms. Instead of a polynomial fit, Kamogawa and Kakinami (2013) used each of the 3 days before and the 3 days after the earthquakes of Tohoku, Sumatra, Hokkaido-Toho-Oki, and Chile (i.e., for the same events used by Heki, 2011) to define the unperturbed TEC: their results support the hypothesis of an ionospheric hole. As the mean-daily value of the TEC is strongly affected by solar radiation, they compared the TEC observed during the day of the seismic events with the TEC for the surrounding days by shifting them to the same level as at the time of the rupture. This approach is also subjective because it excludes the possibility of an enhancement before the earthquake.

Masci et al. (2015) used a more objective approach by comparing the slant TEC of the day of the Tohoku earthquake to the mean level of the 30 surrounding days. They show that the variations on the day of the earthquake lie within one standard variation of the surrounding 30 days and that therefore neither a TEC enhancement nor a hole can be distinguished from the normal fluctuations of the TEC. They also analyzed the effects of several choices of the excluded time window (5:12–6:00, 5:12–8:00, and 5:12–9:00) on the computation of the polynomial fit to define the reference curve for TEC. Additionally, they computed the polynomial fit for the entire TEC curve (without excluding any time window). They clearly show the dependence of the vTEC residuals on the choice of the time window used for the fitting of the data and the subjectivity of the approach of Heki (2011)

Heki and Enomoto (2013) investigated whether the finding of a TEC enhancement could be confirmed by using data from ionosondes and magnetometers. They argue that the simultaneous appearance of TEC enhancement, geomagnetic declination, and the critical frequency of the sporadic E layer is proof of the existence of a precursor. Utada and Shimizu (2014) on the other hand interpret the geomagnetic declination data differently after investigating its spatial dependence as well. They suggest that the changes in geomagnetic declination are instead due to acoustic disturbances caused by the tsunami which then affects ionospheric conductivity as also suggested by Kakinami et al. (2012).

In response to these criticisms, Heki and Enomoto (2015) propose a new approach to identify an enhancement by analyzing the abrupt increase of TEC rate (breaks) in absolute vTEC time series to avoid the computation of the reference curves. They show that during 3 weeks around the Tohoku event, seven breaks were detected, but only one corresponds to the Tohoku seismic event (Heki & Enomoto, 2015). This clearly proves that their proposed method for identifying an abrupt increase in TEC before seismic events is not suitable for warning purposes even if the hypothesis of the TEC enhancement were to be confirmed. Tozzi et al. (2020) clearly show that this method is not usable for issuing alarms of imminent large earthquakes.

Heki and Enomoto (2015) discuss the dependence of the pre-seismic enhancement on the magnitude M_w, claiming that larger and longer TEC enhancements appear for larger magnitudes. This would indicate that the size of an earthquake can be known before its occurrence, in contradiction to seismological evidence that small and large earthquakes start in the same way (Meier et al., 2016), which suggests that the duration and size of an earthquake cannot be known until the rupture stops. Thus, if Heki and Enomoto (2015) were correct in saying that pre-seismic enhancements existed and were dependent on M_w, this would revolutionize seismology. On the other hand, the enhancements might just be artifacts due to the way the reference curve is calculated and could be easy to explain as due to the effects of a hole after the earthquake; indeed, as already pointed out by Masci et al. (2015), larger earthquakes create larger co-seismic ionospheric disturbances, which can explain the relation between the earthquake magnitude and the amplitude of the artifact-enhancement. We consider this question below.

He and Heki (2016) focus on three earthquakes in South America: the 27 February 2010 Maule (M_w 8.8, 6:34 UTC), the 1 April 2014 Iquique (M_w 8.2, 23:46 UTC), and the 16 September 2015 Illapel (M_w 8.3, 22:54 UTC) events. They present, for the first time, their new theory of the pre-earthquake TEC anomaly: the enhancement of TEC observed by IPPs close to the epicenter becomes a TEC depletion (negative variation) of IPPs in the far field and following the direction of the magnetic field line. The idea behind those new analyses is that the source acts as a hypothetical electromagnetic dipole during the nucleation process, and consequently attracts the electrons of the ionospheric plasma to the dipole at the epicenter, thus creating the enhancement. The movement of the electrons along the magnetic line reduces the ionospheric plasma density (number of electrons) far away from the epicenter. Following this hypothesis, the enhancement of the TEC appears in the lower ionosphere (close to the epicenter) and the depletion of the TEC in the higher ionosphere (far from the epicenter). The problem with this theory is that it has no basis in physics. It describes phenomena supposedly occurring deep in the Earth (hypothetical preparatory processes of earthquakes, whose existence has never been shown) somehow creating ionospheric disturbances without any physically observable phenomena (e.g., seismic displacement) at the surface. He and Heki (2016, 2018) explored the geometrical distribution of the supposed enhancement. In any case, both the enhancement and the depletion are calculated by comparison with the unperturbed TEC background based on a reference curve determined by a polynomial fit, as discussed above.

He and Heki (2017) extend their analysis to moderate earthquakes ($7.0 < M_w < 8.5$); they report anomalies preceding the rupture for 8 out of 32 earthquakes, using a polynomial fit as the reference curve. In order to make their approach to compute the unperturbed TEC background by polynomial fit more robust, the authors use the so called L-curve method (Menke, 1989) to choose the degree of the polynomials. They showed two examples to highlight the variation of the vTEC residual depending on the degree of the polynomial fit. Whereas the TEC enhancement showed by the residual seems stable for the earthquake in New Zealand, it strongly depends on the choice of the polynomial degree for the earthquake in Papua New Guinea. They define the degree for which the RMS residual for the polynomial shows the largest decreases as the most appropriate.

2.3. 3D Theory of the Ionospheric Precursor

As mentioned above, He and Heki (2016) tried to expand the analysis of the earthquake precursor with a three dimensional approach. They used different altitudes for the calculation of the ionospheric piercing points (IPP) to try to localize the perturbations. By tuning the altitude of the IPP, they expect to find positive perturbations close to the epicenter at lower altitudes, and negative perturbations farther from the epicenter at higher altitudes.

In order to quantitatively fix the altitudes of the positive and negative anomalies, they minimize the angular standard deviations of the positive and negative perturbation groups. This leads to altitudes of ∼170 km for positive and ∼420 km for negative TEC anomalies.

To additionally support the idea that positive electron density anomalies (enhancements) are visible close to the epicenter, and at low altitude, and negative electron density anomalies appear further away from the epicenter at high altitudes; He and Heki (2018) perform a more robust 3-D tomography for the Illapel earthquake. The results of their tomographic approach support the results already obtained by He and Heki (2016). This is not surprising, as the TEC anomaly used as input for the tomography is the same used by He and Heki (2016), and it is obtained using the polynomial fit as the reference curve, which has been already criticized before by several studies (e.g., Kamogawa & Kakinami, 2013; Masci et al., 2015). In essence, He and Heki (2018) simply found another representation of the same results, but they did not reply to the criticisms cited above about the computation of the TEC reference curve using the polynomial fit.

The positive and negative anomalies found by He and Heki (2016) align along the geomagnetic field. As mentioned above, He and Heki (2016) suggested that positive charges from rocks under near-failure stress, possibly during a hypothetical earthquake nucleation stage, cause the ionospheric anomalies immediately before large earthquakes. This would mean that during the nucleation process, the fault acts as an electromagnetic dipole, producing electromagnetic perturbations which propagate into the ionosphere following the geomagnetic lines.

3. A Reevaluation of TEC Precursor Claims

Starting from the results of He and Heki (2016), we analyzed the same South American earthquakes to reproduce their results showing the pre-seismic enhancement. We demonstrate the subjective nature of their proposed polynomial fits. In this paper, we analyze TEC observations from the 2014 Iquique and 2010 Maule events. The processing of the TEC data was done using the SPECTRE code (Lognonné et al., 2006) as described by Eisenbeis et al. (2019). We show that the presence of a hole or an enhancement in the comparison between the TEC and the reference curve calculated using a polynomial fit strongly depends on the degree of the polynomial, as well as on the time window used to calculate it.

Figure 2 shows the results of our attempt to reproduce the reference curve of He and Heki (2016) for the LYAR station used in their study. We first used (upper left panel) the full time series (from 21 UTC to 5 UTC), excluding the time window from 40 min before until 20 min after the event (gray area in Figure 2), to compute the polynomial fit of third and fifth degree following the specifications of He and Heki (2016). The results, for both third and fifth degree, do not fit the TEC data well and do not show any enhancement. The best fit to the TEC data appears to be that using the polynomial fit of ninth degree (upper right panel), which does not conform to the specifications set by He and Heki (2016), but was used in their later papers (e.g., He & Heki, 2017). As shown in the upper right panel of Figure 2, despite the polynomial fit of ninth degree reproducing the TEC data well, no enhancement is visible but rather a hole after the earthquake. Using the full time series for this station, we find no evidence to support the existence of the TEC enhancement before the earthquake: the results clearly support the existence of an ionospheric hole forming after the earthquake.

He and Heki (2016) only show results for the time window of 1 h before and 1 h after the earthquake, the area indicated by the vertical dashed gray lines in Figures 2 and 3. As shown in Figure 2 using different

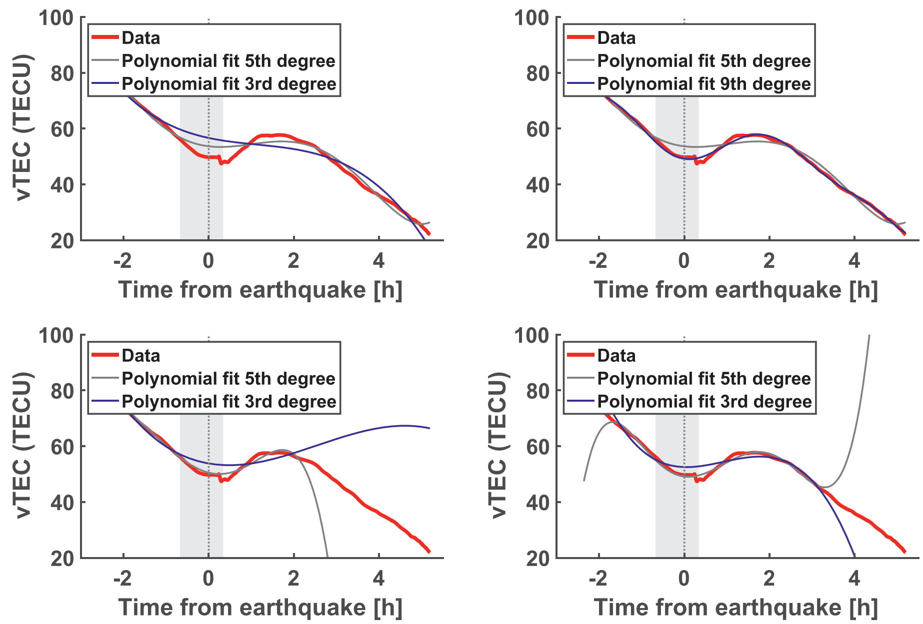

Figure 2. Vertical total electron content (vTEC) time series for station LYAR for the 2014 Iquique event. The gray area shows the time window excluded from fitting, following He and Heki (2016): from 40 min before to 20 min after the event. The vertical dotted gray line at 0 h shows the origin time of the earthquake, and the other two (at ±1 h) show the start and end of the time window shown in their paper. The red line is the observed vTEC time series, and the blue and gray lines show the polynomial fit of third and fifth degree, respectively (except for upper right panel which shows fifth and ninth degree curves). Dashed lines in the lower panels show the part of the signal excluded from computation of the polynomial fit. For the upper panels, the full length of the time series from 2.5 h before to 5 h after the event was used for the polynomial fitting.

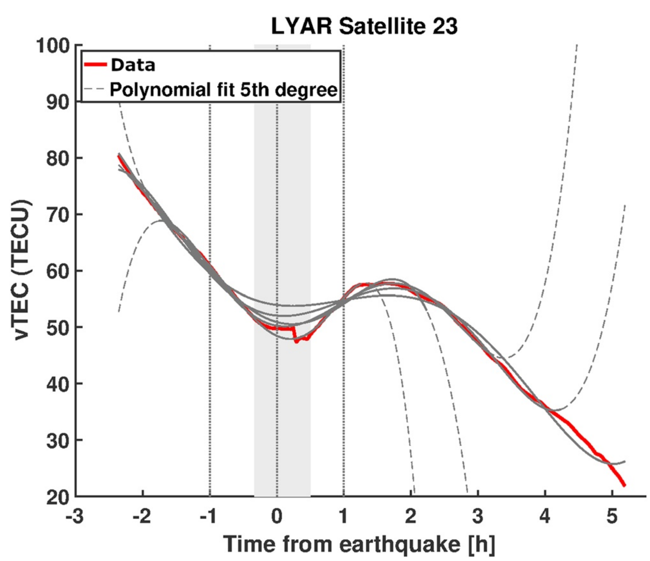

Figure 3. Same vertical total electron content (vTEC) time series as in Figure 1 for station LYAR. Red is the observed time series, and the curves of the polynomial fit of fifth degree using different time windows for the fitting are in gray. The part of the curves used for the fit is shown in full gray line, and the excluded parts are shown in dashed line. The gray area is again the time window excluded from the fitting from 20 min before to 30 min after the event following He and Heki (2016). The dashed vertical line at 0 is the origin time of the earthquake whereas the dashed vertical lines at ± 1 show the limits of the plot in He and Heki (2016) .

time windows (bottom left panel: 2.5 h before to 1 h 15 min after the earthquake and bottom right panel: 2 h before to 2 h 15 min after the earthquake), the polynomial fits of third and fifth degree lead to different conclusions: a hole appears for the polynomial fits of third degree with the shorter time-series (bottom left panel) and for the polynomial fits of fifth degree with the longer time-series (bottom right panel); an enhancement appears only using the polynomial fits of fifth degree with the shorter time-series (bottom left panel). The polynomial fits of third degree with the longer time-series (bottom right panel) do not fit the data well.

In summary, attempts to reproduce the enhancement presented by He and Heki (2016) using their specifications fail, thereby demonstrating the subjectivity and limitations of their methodology for defining the TEC reference curve to highlight the enhancement.

As an enhancement appears only using the polynomial fit of fifth degree (Figure 2, bottom left panel), we additionally explore in Figure 3 the effect of the length of the time window, using five different lengths for the fitting. For all the variations used, there is only one curve showing a pre-seismic enhancement; all other curves show either a hole after the earthquake or neither an enhancement nor a hole.

In order to generalize the analysis of the LYAR station for the Iquique event, we analyze a second station (AREQ) for the same event, and we also analyze an additional station (CHMZ) for the Maule event (Figure 4). All analyzed data are also shown in He and Heki (2016).

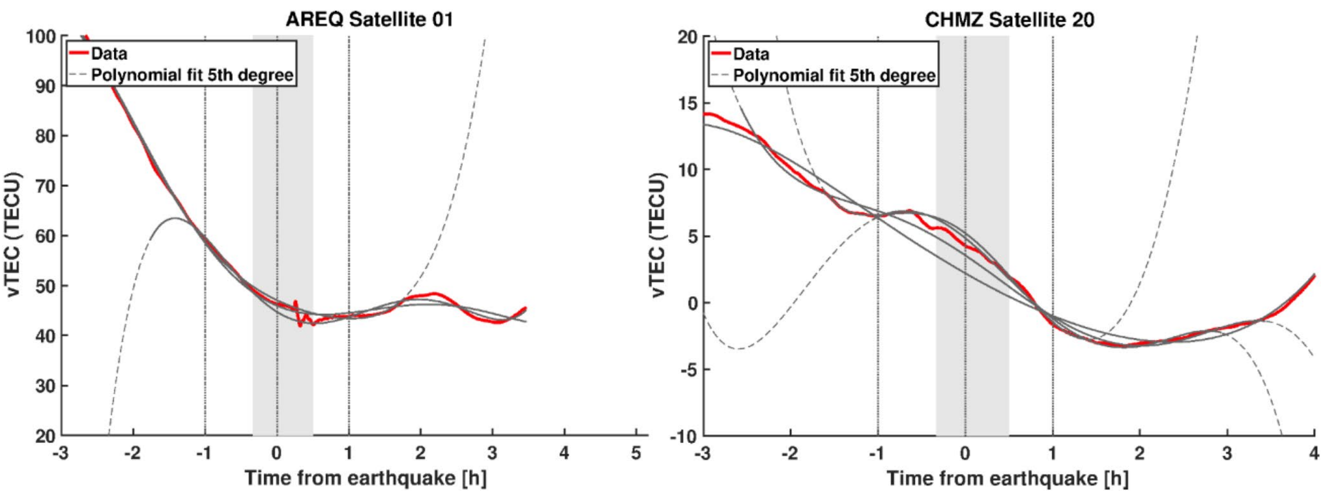

Figure 4. Vertical total electron content (vTEC) time series for station AREQ and satellite 1 for the Iquique event, and station CHMZ and satellite 20 for the Maule event. Red curve is the original observed time series, and gray curves are the polynomial fit of fifth degree using different time windows for the fitting. The part of the signals excluded from the fitting is shown by dashed gray lines. The gray area is the time window before and after the event excluded from the fitting as in He and Heki (2016). The dashed vertical line at 0 h is the time of the earthquake, and dashed gray lines at ± 1 h show the time window used by He and Heki (2016).

We show (Figure 4) only the fifth degree polynomial fits using three different time windows for AREQ and four different time windows for CHMZ. The time excluded before and after the earthquake is again shown with a gray box whereas the dashed line of the time series is used outside of the time window used for the fitting. The results for station AREQ (Figure 4, left panel) are similar to those for the LYAR station (Figures 2 and 3), where it is possible to fit the data in such a way to obtain either a hole after the earthquake or an enhancement before it just by changing the time window.

In order to fully explore He and Heki (2016)'s 3D theory, we also analyzed—for the case of the Maule event—the station CHMZ (Figure 4, right panel) that produces IPPs a bit further away from the epicenter and which is supposed to show a depletion (instead of an enhancement). Here, the nature of the signal makes it difficult to reproduce the data with a polynomial fit of fifth degree. We can only reproduce the depletion found by He and Heki (2016) with a shorter time window (comparable to the time window shown by He & Heki, 2016). The two additional examples of satellite station combinations shown in Figure 4 confirm the findings of our investigation, showing a strong dependence of the vTEC residual on the time window used for the polynomial fit.

4. Synthetic Data

In order to support the dipole effect theory to explain hypothetical TEC enhancements before seismic rupture, He and Heki (2017) presented a simple synthetic analysis to reply to criticisms about potential artifacts induced by their processing technique, which removes the part of the signal just before and just after the earthquake and models the remaining signal with a polynomial fit to obtain the unperturbed TEC background. They create a synthetic TEC response coupling the background (u-shape), the IGW_{epi} with a recovery to the ionospheric background (the hole), and the dipole effect producing the enhancement (inverted v-shape). They showed (Figure 5, top-panels) that with and without the dipole effect (inverted v-shape), the obtained reference curve using the polynomial fit is identical to the original background. Unfortunately, for their case, which we are reproducing here in Figure 5 (top-panels), they removed the part of the signal (just before and just after the earthquake) that contains both the enhancement and the hole. They also presented an extreme case of an infinite hole, an unrealistic case in which the ionosphere never recovers to the original background after the seismic event. He and Heki (2017) claim that only in this unrealistic case does the polynomial fit introduce an artificial enhancement compared to the signal (Figure 5, bottom-panels).

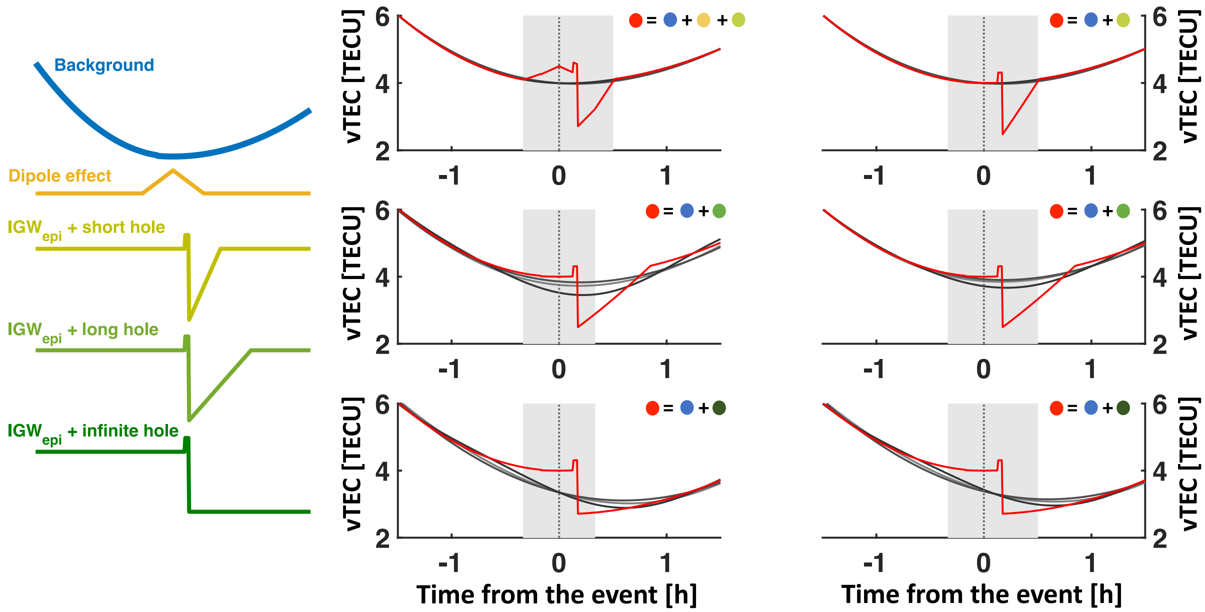

Figure 5. Synthetic tests to explore the hole versus enhancement debate. Each red synthetic curve is composed (following the dot radiolabeling) by the summation of the TEC background (blue), the dipole effect (yellow) and the IGW_{epi} with various holes (the three greens). The gray window around the seismic event (time zero represent the rupture) is removed from the synthetic (red) curve to compute the polynomial fit (gray lines). From lighter to darker gray the lines represent third, fifth, and ninth degree, respectively.

However, it is easy to show, with the same synthetic approach, that as soon as the duration of the hole is longer than the removed time window (Figure 5, middle panels), the polynomial fit creates an artificial enhancement, which is independent of the selected degree of the polynomial fit (we used polynomial fits of third, fifth and ninth degree in Figure 5). The results in Figure 5 also show that larger post-seismic disturbances, which create holes of longer duration, produce larger artificial enhancements before the earthquake. This fully explains the correlation between length-and-size of the enhancement and magnitude of the earthquake claimed by Heki and Enomoto (2015). We emphasize again that the theory of Heki and Enomoto (2015), which claims that it is possible to know the magnitude of an earthquake before the rupture, directly contradicts established paradigms in seismology (e.g., Meier et al., 2016), and thus should be accepted only with strong supporting data, which is virtually non-existent.

5. Conclusion

Heki (2011) initiated a debate about the possibility of pre-seismic total electron content (TEC) enhancements 20–40 min before earthquakes that could be used to make short-term predictions of earthquakes. This idea lead to the theory (e.g., Heki & Enomoto, 2015) that by observing ionospheric TEC enhancements, it is possible to predict the magnitude of an earthquake before the rupture begins. This theory contradicts prevalent paradigms in seismology. Several studies have already criticized the works by Heki and coworkers for the existence of the enhancement and proposed instead the presence of a depletion after the earthquake in the ionospheric electron density, the so called ionospheric hole. Such hole is visible in TEC observations after earthquakes (e.g., Kamogawa & Kakinami, 2013; Utada & Shimizu, 2014) and following the arrival of the acoustic-gravity wave generated at the epicentral area by the surface uplift related to the rupture (AGW_{epi}, Occhipinti et al., 2013).

Additional works (e.g., Masci et al., 2015) highlighted the impossibility of discriminating between a hole and an enhancement due to the variability and dynamic of the ionosphere, making it difficult to objectively define a TEC reference curve. Indeed, the so called "hole versus enhancement" debate focuses on the definition of the reference curve (the unperturbed TEC background) used to determine the enhancement and/or the hole by comparison with TEC observations. The method used to compute the umperturbed background proposed in several papers defending the enhancement theory (e.g., He & Heki, 2016) is based on a polynomial fit of the TEC observation close to the epicenter while removing the TEC data just before and just after the event from the fitting process. The removed part of the signal around the time of the event is the part of the TEC signal supposed to be perturbed by the hole and/or the enhancement. In our work, we take the case of the TEC observations presented by He and Heki (2016), related to the seismic events of Iquique (2014) and Maule (2010) to thoroughly prove that the enhancement appears only after "tuning" the polynomial fit involving several parameters: the duration of the analyzed TEC observations, the removed window around the earthquake, as well as the selected degree of the polynomial fit. Our results, supported by various observations and simple synthetic tests, prove that the pre-seismic enhancement debated in the last 10 years appears only after a subjective selection of parameters and that it is thus consequently an artifact.

Despite human dreams, earthquakes remain unpredictable.

Data Availability Statement

This work is entirely based on freely available GNSS data from the following web-resources: UNAVCO (www.unavco.org) using the Data Archiver Web Interface (https://www.unavco.org/data/gps-gnss/data-access-methods/dai2/app/dai2.html#), This research was supported by Program National de Télédétection Spatiale (PNTS, http://programmes.insu.cnrs.fr/pnts/) Grant No. PNTS-2020-16; by the CNES, granted project Global Ionospheric Seismology network & background; and by the Institut Universitaire de France (IUF). This is IPGP contribution 4191.

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