Ionospheric anomalies preceding the low-latitude earthquake that occurred on April 16, 2016 in Ecuador

Carlos Sotomayor-Beltran

Imaging Processing Research Laboratory (INTI-Lab), Universidad de Ciencias y Humanidades, Lima 39, Peru

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ABSTRACT

A catastrophic seismic event of $M_s$ 7.8 occurred on April 16, 2016 in Ecuador. As with some other major earthquakes, many human lives were lost. Thus in the last two decades, the search for seismo-ionospheric signatures has become an active field of research. In order to provide further insights into ionospheric precursors of earthquakes, Global Ionospheric Maps (GIMs) provided by the Center for Orbit Determination in Europe (CODE) were used to look for ionospheric anomalies prior to the earthquake in Ecuador. By producing differential Vertical Total Electron Content (VTEC) maps and using a statistical method, a negative ionospheric anomaly was observed 10 days before the incident. At different confidence levels the negative disturbance was permanently visible. This anomaly also is located within the earthquake preparation zone, defined by the Dobrovolsky equation. Additionally, due to the extreme low-latitude nature of the earthquake, the dynamics of the Equatorial Ionization Anomaly (EIA) shape were observed. A further confirmation of the ionospheric anomaly was provided by the dramatic change of the EIA 10 days before the earthquake with respect to a non-disturbed day. Due to the really quiet geomagnetic and solar conditions for April 6, 2016, the negative anomaly is considered to be a seismo-ionospheric signature.

1. Introduction

The search for earthquake precursors in the ionosphere is a very active field of research (e.g. Liu et al., 2004; Zakharenkova et al., 2006, 2008; Zhao et al., 2008; Mubarak et al., 2009; Zhu et al., 2010; Zou and Zhao, 2010; Yao et al., 2012; Zhu et al., 2013; Wang et al., 2014; Xinzhi et al., 2014; Li et al., 2015; Guo et al., 2015; Pundhir et al., 2015; Alcay, 2016). There are studies that for example concentrate on a particular earthquake and through the employment of different techniques, they are able to identify ionospheric anomalies that appear a few days before and which are associated to an earthquake. For instance, the $M_s$ 7.9 earthquake that happened in the county of Wenchuan, China (31.0°N 103.4°E) has drawn a lot of attention in regards to the observations of seismo-ionospheric signatures (Zhao et al., 2008; Li et al., 2009, 2015; Liu et al., 2009; Zhu et al., 2010; Ma and Wu, 2012). Initially, Zhou et al. (2009) detected 9, 6 and 3 days before this earthquake ionospheric disturbances considered as precursors of the incident. Such detections were possible by observing the time series Vertical Total Electron Content (VTEC) derived from a GPS station. Earlier, Zhao et al. (2008) were able to also observe the ionospheric anomaly 3 days before the earthquake by making use of Global Ionospheric Maps (GIMs) and using data from ionosondes as well. They indicated that this anomaly was a seismo-ionospheric signature. Intriguingly, for the rest of the days where ionospheric anomalies were observed by Zhou et al. (2009), Zhao et al. (2008) considered that they were product of considerable geomagnetic activity. The same year that Zhou et al. (2009) published their study, Liu et al. (2009) also published a work related to the same earthquake. Liu et al. (2009) came to the conclusion, using GIMs as well, that the only seismo-ionospheric signature was the one that occurred 3 days before the earthquake. Later, making use again of GIMs and looking carefully into the Kp geomagnetic index, only the ionospheric disturbance detected 3 days prior to the seis could be further confirmed to be product of the earthquake preparation (Zhu et al., 2010; Li et al., 2015).

In regards to low-latitude earthquakes when looking for ionospheric precursors, there are just a bunch of studies dedicated to analyze individually ionospheric disturbances (Zakharenkova et al., 2006, 2008; Mubarak et al., 2009; Zou and Zhao, 2010; Zhu et al., 2013; Liu et al., 2016; He and Heki, 2017; Akhoondzadeh et al., 2018). As expected, different techniques are also used to detect ionospheric precursors a few days prior to these seismic events. For instance, for the March 28, 2015 earthquake that occurred in Sumatra (2.07°N 97.1°E), Mubarak et al. (2009) looked only into the time series of the VTEC obtained from GIMs to observe anomalies related to the seis. On the other hand, a more sophisticated approach was used by Zou and Zhao (2010) and Zhu et al. (2013). The former investigated the August 15, 2007 seis that...
happened in Peru (13.38°S 76.60°W), while the latter studied an earlier earthquake that occurred in Sumatra on April 11, 2012 (2.31°N 93.06°E). By using GIMs, both studies were able to generate global differential VTEC maps, in this way facilitating the task of ionospheric disturbance detections. Due to the low-latitude nature of the earthquake that occurred on December 26, 2004 in Indonesia (3.32°N 95.86°E), Zakharenkova et al. (2006) looked for changes in the shape of the Equatorial Ionization Anomaly (EIA, McDonald et al., 2011) and were able to observe some ionospheric anomalies associated to the earthquake. In a similar fashion, as preparation to the September 26, 2005 earthquake in Peru (15.67°S 76.4°W), Zakharenkova et al. (2008) observed a few days before the incident changes in the EIA.

In the present work, GIMs from the Center for Orbit Determination in Europe (CODE) were used to report detections of ionospheric anomalies preceding one of the most very low-latitude earthquakes in the last decade.

2. The Pedernales earthquake

The April 16, 2016 seismic event, also known as the Pedernales earthquake (Nocquet et al., 2016; Ye et al., 2016), happened 27 km south-southeast of the coastal city of Muisne, Ecuador, as reported by the United States Geological Survey (USGS). The seismic, of moment magnitude ($M_w$) of 7.8, had its epicenter at 0.38°N 79.92°W (Fig. 1) and occurred during late daytime hours, at 18:58 (23:58 UT). As indicated by Nocquet et al. (2016) this incident was a product of the Ecuador-Colombia subduction zone. As in the past, with other large earthquakes that occurred in this zone, this seismic was a very dramatic natural catastrophe. According to the media≈270 people died and a bit more than 2500 were injured.

Two very recent studies (He and Heki, 2017; Akhoondzadeh et al., 2018) have already detected ionospheric anomalies prior to the Pedernales earthquake. He and Heki (2017) have identified these anomalies almost immediately (~17 min) before the onset of the earthquake through the use of the reference curve method. On the other hand, Akhoondzadeh et al. (2018) detected ionospheric disturbances between 7 and 12 days before the seismic event by using satellite and ground data. Additionally, GIMs were among the collected data of Akhoondzadeh et al. (2018), which only allowed them to identify a disturbance 1 day prior to the seismic, at 9:00 UT.

3. Data analysis

Publicly available GIMs were downloaded from CODE. GIMs are routinely produced every 1-h and they are available through the ftp site from CODE (ftp://ftp.aiub.unibe.ch/CODE/). The maps of VTEC have a resolution of 5° x 2.5°, in longitude and latitude, respectively. As GIMs come in daily IONosphere map EXchange format (IONEX) files (Schaer et al., 1998), a total of 26 IONEX files were downloaded for the period between April 1 and April 26, 2016. Due to the structure of the IONEX files, Python alongside its library NumPy were used to facilitate the handling of the VTEC data. 3D cubes per each IONEX files were generated containing only VTEC data.

In order to identify ionospheric anomalies related to the seismic event, an extensively used statistical method was applied (e.g. Liu et al., 2004; Zhou et al., 2009; Zou, 2010; Zhu et al., 2010; Hasbi et al., 2011; Yao et al., 2012; Zhu et al., 2013; Li et al., 2015; Alcay, 2016; Sharma et al., 2017). Assuming that the VTEC for a certain time for each day within a window of days follows a normal distribution, the mean $\mu$ and standard deviation $\sigma$ were calculated. Afterwards, the upper and lower bounds were defined ($\mu + \alpha \sigma$ and $\mu - \alpha \sigma$, respectively). According to the literature, when $\alpha$ is equal to 1.34 (e.g. Liu et al., 2004; Zou and Zhao, 2010; Hasbi et al., 2011; Li et al., 2015; Sharma et al., 2017) we can identify anomalies with a confidence level of 80–85%. On the other hand, if $\alpha$ is equal to 2 (e.g. Zhou et al., 2009; Zhu et al., 2010; Yao et al., 2012; Zhu et al., 2013; Alcay, 2016) the disturbances detected are identified with a 95% confidence level. Finally, VTEC maps were produced using the upper bound and lower bound definition for both confidence levels. There is a positive anomaly detection if the VTEC for a certain hour at a particular day falls above the upper bound; whereas, if the VTEC falls below the lower bound a negative anomaly is detected. For VTEC between the upper and lower bounds there are no ionospheric disturbance detections ($\Delta$VTEC = 0).

Because geomagnetic and solar activity also play an important role in generating ionospheric anomalies, data for the geomagnetic indices Dst and Kp and for the solar index F10.7 for the month of April 2016 were retrieved from the World Data Center for Geomagnetism in Kyoto (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html), the German Research Center for Geosciences (https://www.gfz-potsdam.de/en/kp-index/) and the OMNI database (https://omniweb.gsfc.nasa.gov/form/dx1.html), respectively (Fig. 2). According to the National Oceanic and Atmospheric Administration (NOAA) space weather service, geomagnetic storms can be classified as moderate and minor if Kp = 6 and Kp = 5, respectively. Hence, from Fig. 2 it can be observed that two minor storms occurred on April 2 and April 12–14, 2016 and a moderate storm happened on April 7–8, 2016. On the other hand, a classification by Loewe and Prölls (1997) indicates that moderate storms occur as well when $-100$ nT $<$ Dst $\leq 50$ nT. Hence, towards the last hours of April 16, 2016 (the day of the earthquake) it can be noticed in Fig. 2 that a moderate storm commences (Dst $\leq -50$ nT) and it develops throughout April 17, 2016. Additionally, Fig. 2 also shows the solar radio flux at 10.7 cm (F10.7 index). From Fig. 2 it can be seen that between April 1 and 9, 2018, the F10.7 index remained rather stable indicating low solar activity; however, between April 9 and 18, 2018, this index was higher than 100 which points to strong solar radiation.

4. Results and discussion

In order to define the earthquake preparation area of the lithosphere, the Dobrovolsky equation is used (Dobrovolsky et al., 1979):

$$R = 100.43M,$$  

where $M$ is the magnitude of an earthquake, and the radius ($R$) defines the preparation zone for the Pedernales earthquake. For this seismic event $R$ resulted in $\sim 2259$ km.

Afterwards, an inspection of the differential VTEC maps was undertaken. Due the considerable geomagnetic activity during the first half of the month, extremely large spatial structures were observed in several maps. For instance, in Fig. 3 and Fig. 4 it can be observed that on April 7, 2016 at 22:00 UT and at both confidence levels, 80–85% and 95%, the effects of significant geomagnetic activity can be clearly identified. In this case, the ionospheric anomalies seen are at a global scale. Moreover, looking into the geomagnetic indices for this day (Fig. 2), starting at approximately 18:00 UT onwards Kp ≥ 5 and at

![Fig. 1. The red circle shows the epicenter of the Pedernales earthquake.](image-url)
Fig. 2. Dst, Kp and F10.7 indices for the month of April 2016. The vertical red dashed line in the plots indicates the day that the seismic incident happened.

Fig. 3. Differential VTEC maps for April 6 and April 7 when the upper bound and lower bound are $\mu + 1.34\sigma$ and $\mu - 1.34\sigma$, respectively. The red dashed circle defines the earthquake preparation zone defined by $R$ (Dobrovolsky et al., 1979). The grey circle points to the location of the Pedernales earthquake.
around 20:00 UT forwards Dst \leq -50 \text{nT}, as previously indicated, the Kp index hints definitely to a moderate geomagnetic storm. Nevertheless, in Fig. 2 we can observe as well that there are two windows which are almost free from the influence of geomagnetic activity. For the range of days April 4–6 and April 9–11, 2016, Kp \leq 3 and Dst \geq -20 \text{nT}.

Through, once again, the inspection of the ΔVTEC maps at a confidence level of 80–85%, 10 days (May 6) before the earthquake a negative ionospheric anomaly was clearly identified to the north of the epicenter (Fig. 3). The anomaly is observable in the global ΔVTEC maps at 18:00 (when it started to appear), 20:00 and 22:00 UT. One can also notice that at 20:00 and 22:00 UT in the southern hemisphere where the magnetic conjugate region is located a negative anomaly occurred as well. The aforementioned was already observed in some previous studies for other earthquakes (e.g. Zhao et al., 2008; Yao et al., 2012; Zhu et al., 2013). It is important to indicate that the anomaly detected in the northern hemisphere falls, at almost all the times mentioned, well within the preparation earthquake zone. At 22:00 UT, however, it extends to the west partially outside the preparation region. At the most intense moment of this anomaly, at \sim 20:00 UT, the minimum ΔVTEC is of \sim -6.76 \text{TECU} (where 1 \text{TECU} = 10^{16} \text{electrons/m}^2). In order to confirm that this is an actual anomaly, the ΔVTEC maps at a confidence level of 95% were also observed (Fig. 4). The negative disturbance is still present; however, it can be detected starting at 20:00 UT, where its minimum ΔVTEC is of \sim -2.05 \text{TECU}. This detection also falls inside the preparation zone defined by R (Dobrovolsky et al., 1979). Afterwards, at 22:00 UT it can be seen how the anomaly moved west until it disappeared. As mentioned above during May 6, the geomagnetic conditions were quiet (Kp \leq 3 and Dst \geq -20 \text{nT}) as well as the solar activity (F10.7 index lower than 100); thus, it can be suggested that this negative anomaly is a seismo-ionospheric signature.

Due to the location of the Pedernales earthquake, nearly at the equator (latitude = 0°), another tool that helps to identify ionospheric anomalies is the observation of variations in the shape of the EIA. Pulinets and Legen’ka (2002) and Pulinets (2012) agree that the EIA under the influence of the preparation to an earthquake can suffer three major changes. The first is the enhancement of the EIA, the second is the vanishing of the crests of the EIA, and finally the last one is the displacement of the EIA. To analyze the dynamics of the EIA for the Pedernales earthquake, a strip along the 80°W meridian at a local time (LT) of 15:00 UT was selected (Fig. 4). In Fig. 2 it can be observed that for April 4, 5, and 6 at 20:00 UT the geomagnetic conditions remained rather quiet (Kp \leq 3 and Dst > -20 \text{nT}). However, for April 7 at \sim 20:00 UT Kp = 5 and Dst < -50 \text{nT}, which points to a moderate geomagnetic storm. This can be confirmed in Figs. 3 and 4, where global scale ionospheric anomalies are clearly seen at 22:00 UT in all their intensity. Fig. 5 shows that for April 4, 7 and 8 at 20:00 UT, the shape of the EIA is rather stable. During these daytime hours (20:00 UT), the EIA is expected to normally show a double-crest with a through structure. For April 7 at 20:00 UT the EIA is not affected by the considerable geomagnetic conditions. This can be confirmed by looking in Figs. 3 and 4 where there are no anomalies above the region of the EIA, even at their highest intensity (22:00 UT). The most striking
feature in Fig. 5 is the disappearance of the crests on April 6 (10 days before the seismic event). This vanishing of the crests is basically a consequence of decrement in the VTEC; which also corresponds to the negative anomaly observed at 20:00 UT in Figs. 3 and 4. On April 5, the disappearance of both crests can also be seen; however, this weakening of the VTEC did not show up in the ΔVTEC maps. This indicates that VTEC values for this day for this region at 20:00 UT are still above the lower bound at both confidence levels (80–85% and 95%); hence, it does not classify as an ionospheric anomaly for this study. The disappearance of the crests in this study is rather different to what Zakharenkova et al. (2006) have observed for another earthquake. They saw 2 days prior to the 2004 M9 earthquake in Indonesia that the shape of the EIA was dramatically enhanced, especially its southern crest during still daytime hours ~ 17:00–19:00 LT (10:00–12:00 UT). Later, Zakharenkova et al. (2008) observed also the drastic change of the EIA 2 and 3 days before the M7.5 earthquake that occurred during 2005 in Peru. However in their study, the change of the EIA happened only during night time hours, 21:00 LT (02:00 UT).

Very recently, Guo et al. (2015) have observed a negative ionospheric anomaly 15 days prior to the 2014 M8.2 earthquake in Chile. They suggested that this anomaly is associated to the earthquake preparation. The mechanism for this negative disturbance was explained by the air ionization due to natural ground radioactivity model proposed by Pulinets (2012). Depending on the levels of ionization, the air conductivity in the boundary layer of the atmosphere can increase or decrease, which in turn will result in the observation of negative or positive ionospheric anomalies, respectively. It is very likely that such a model is also at work for the negative ionospheric anomaly detected 10 days before the Pedernales earthquake. Nevertheless, it should be as well noticed that due to the closeness to the geomagnetic storm that happened on April 2, 2018 it might be possible as well that a westward disturbance electric field is contributing in inhibiting the formation of the crests for April 5 and 6, 2018 at 20:00 UT. The suppression of the crests was observed, for instance, during the geomagnetic storm of March 18, 2015 at the beginning of the recovery phase (Spogli et al., 2016).

5. Conclusions

Using GIMs from CODE, it was possible to generate differential VTEC maps to look for ionospheric disturbances before the day of the April 16, 2016 earthquake that happened in Ecuador. A negative ionospheric anomaly was clearly detected 10 days before this seismic event (also known as the Pedernales earthquake). The following points provide a summary as to why then this negative disturbance is considered to be a precursor of the Pedernales earthquake:

At confidence levels of 80–85% and 95% the ionospheric disturbance is visible in the ΔVTEC maps of April 6, 2016. At a confidence level of 80–85% also a negative disturbance occurs in the magnetic conjugate region.

The negative anomaly observed at both confidence levels falls well within the circle defined by the earthquake radius preparation, R ~ 2259 km.

The shape of the EIA during the daytime hours changed drastically. For April 4, 7 and 8, 2016, the EIA shows the expected double-crest with a trough shape (at 20:00 UT). However at 15:00 LT (20:00 UT), on April 6, 2016, the crests disappeared. The cause for the inhibition of both crests could be attributed to the level of air ionization product of natural radioactivity and also to a westward disturbance electric field product of the geomagnetic storm of April 2, 2018.

Finally but also rather important, during the whole April 6, 2016, the geomagnetic conditions remained very quiet (Kp ≤ 3 andDst ≥ -20 nT) and the solar activity was stable (F10.7 lower than 100). Hence, it can be suggested that the ionospheric negative anomaly is a precursor to the earthquake but a contribution of a westward disturbance electric field should not be ruled out.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jastp.2018.11.003.

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