Ionospheric Anomalies before the 2015 Deep Earthquake Doublet, M_w 7.5 and M_w 7.6, in Peru

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***Abstract*—Two major earthquakes separated by ∼5 minutes occurred in the same fault in Peru at depths of 606.2 and 620.6 km on November 24, 2015. By using Global Ionospheric Maps (GIMs) from the Center for Orbit Determination in Europe (CODE) and a broadly used statistical method, differential Vertical Total Electron Content (VTEC) maps were derived. Two positive ionospheric anomalies were clearly identified in the differential VTEC maps 2 and 1 day prior to the day of the earthquakes. These anomalies were located inside the earthquakes' preparation regions defined by the Dobrovolsky equation. On the other hand, due to the low-latitude nature of the seismic events, the Equatorial Ionization Anomaly (EIA) shape was also analyzed. A third positive disturbance was revealed between November 20 and 21, 2015. For the aforementioned anomaly and the one on November 22 (2 days before the earthquakes), an enhancement of the VTEC was observe through the considerable modification of the EIA shape into a well-defined double-crest with a trough. By looking into the Dst and Kp indices, the geomagnetic conditions starting on November 20 until the 24 were very quiet; thus, it is considered that the three detected anomalies are precursors to the earthquake doublet. Moreover, it is suggested that the mechanism at work that produced the positive disturbances is the air ionization through the release of radon from the Earth's crust.**

Keywords*—Ionospheric anomalies; earthquakes; total electron content

I. Introduction

Earthquakes can be the cause of major devastations depending on their intensity. Hence in the past years, the detection of seismo-ionospheric signatures has been taking increasingly attention [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. There are different methods to detect ionospheric anomalies before a strong earthquake. For instance, [18] and [15] observed ionospheric disturbances prior to earthquakes by looking into the time series of Vertical Total Electron Content (VTEC) derived from GPS stations. On the other hand, [11], [13] and [9], for example, used Global Ionospheric Maps (GIMs) in order to observe better the spatial distributions and dynamics of the anomalies. A third technique, is the observation of the modification of the Equatorial Ionization Anomaly (EIA) for earthquakes that occurred at low-latitudes [1], [2].

The majority of the aforementioned studies [1], [3], [4], [6], [9], [8], [13], [14], [16], that have detected ionospheric disturbance prior to a strong earthquakes, have detected these disturbances for earthquakes that had their origin in the Earth's crust (depth $\leq$ 70 km). Only quite a few studies [19], [12], [15] have looked for seismo-ionospheric signatures in earthquakes that had their origin deeper than the crust. [19] detected a ionospheric anomaly using two-dimensional component analysis one day before the July 7, 2017 earthquake near Papua New Guinea (depth ∼378 km). Once again [12], using the same method, detected for the February 27, 2015 earthquake in Indonesia (depth ∼547 km), a sesimo-ionospheric signature also one day before the incident. [15] detected, by looking into the time series of GPS stations, positive ionospheric anomalies hours before the October 26, 2015 earthquake in Afghanistan (depth ∼200 km).

In this study, global VTEC maps provided by the Center for Orbit Determination in Europe (CODE) were used to observe for ionospheric anomalies preceding the two strong deep earthquakes that happened in Peru on November 24, 2015. Additionally, the latitudinal shape of the EIA will be analyzed due to the low-latitude location of the earthquake doublet.

II. The Earthquake Doublet

Two major earthquakes occurred on November 24, 2015 near the Peru-Brazil border [20], [21]. The first one of magnitude M_w 7.5 happened at 22:45 UT (17:45 local time; LT) and the second one of magnitude M_w 7.6 at 22:50 UT (17:50 LT). The epicenter of the former was located at 10.54°S 70.94°W and of the latter at 10.06°S 71.02°W (Fig. 1). Because of the location of the earthquakes, deep in the Amazon, there were no casualties or infrastructure damage as reported by the media. According to the United States Geological Survey (USGS) the M_w 7.5 and M_w 7.6 earthquakes initiated at depths of 606.2 and 620.6 km, respectively. As indicated by [20] this doublet earthquake, as many that happened in the past in this region, is product of the subduction of the Nazca plate under the South American plate.

Using data from Global Navigation Satellite System (GNSS) receivers from the International GNSS Service (IGS), only a previous study by [15] have detected 12 and 5 days (November 12 and 19, 2015, respectively) before the earthquake doublet positive ionospheric anomalies. [15] detected these anomalies by looking into the VTEC time series of the three nearest GNSS stations to the seismic event. Only two stations, POVE and AREQ, relatively near to the epicenter were able to detect the ionospheric disturbances. The third one, because it was close to the border of the earthquake preparation zone, did not show a clear anomaly.

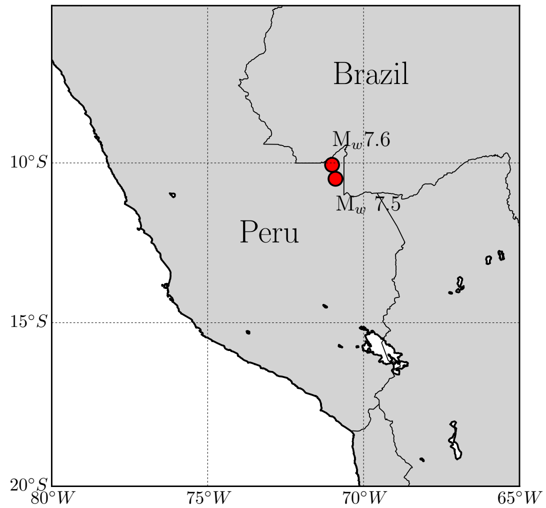

Fig. 1. The two red circles point to the epicenters where the two seismic events occurred on November 24, 2015

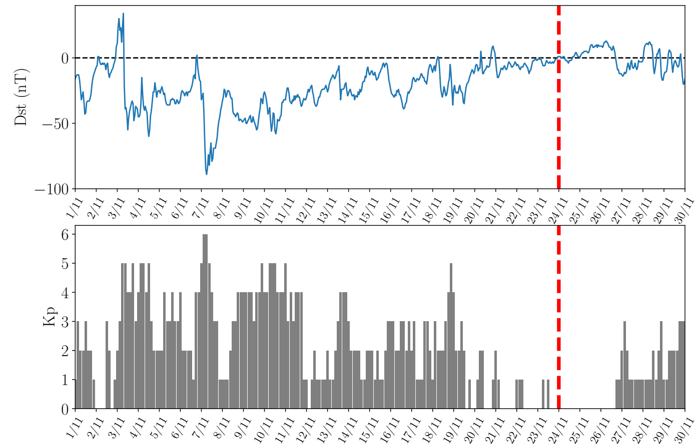

Fig. 2. Dst and Kp indices for November 2015. The vertical dashed red line in both plots indicates the day the two earthquakes happened.

III. Methods

A. Ionospheric Data

GIMs, that are generated on a daily basis through IONEX files [22], were retrieved via ftp (ftp://ftp.aiub.unibe.ch/CODE/). IONEX files in the range between 15 days (November 9, 2015) before and 11 days (December 5, 2015) after the day of the two incidents were downloaded. GIMs are being produced in the recent years every hour, and they consist basically of a 5° x 2.5° geographical grid in longitude and latitude, respectively, of VTEC values. All the GIMs in the selected range of days were stored in 3D cubes, where the three axes of these cubes are latitude, longitude and number of GIMs.

In order to identify the spatial distribution of the ionospheric anomalies, a broadly used statistical method was applied to the VTEC data [18], [4], [6], [9], [11], [14], [23]. To every grid point in the 3D cubes of GIMs, a sliding window was applied to calculate the mean (μ) and the standard deviation (σ). The VTEC for a specific grip point at any given hour on any day within this window is considered to follow a normal distribution. To identify ionospheric disturbances, the confidence level used in this study is higher than the one used by [15]. To detect anomalies with a confidence level of 95%, the upper and lower bounds (UB and LB) were chosen as follows:

$$UB = \mu + 2\sigma, \tag{1}$$

$$LB = \mu - 2\sigma. \tag{2}$$

If a VTEC value at a certain grid point on a particular time falls outside of these bounds, there is an anomaly. The ionospheric anomalies are positive and negative when the VTEC is higher than the UB and lower than the LB, respectively. In this way, differential VTEC (ΔVTEC) maps were generated.

B. Geomagnetic Conditions

To make sure that the detected anomalies are not a product of space weather conditions, the geomagnetic indices, Dst and Kp, for the month of November 2015 were observed. Data for the Dst index were obtained from the World Data Center for Geomagnetism in Kyoto (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html), and for the Kp index were retrieved from the German Research Center for Geosciences (https://www.gfz-potsdam.de/en/kp-index/). In Fig. 2, it can be seen that between November 3 and 11, the Kp index reached values greater than 4, meaning that there is significant geomagnetic activity. This is further confirmed when data for the Dst index was observed. Since November 3 until November 19, 2015, values of Dst < -20 nT are reached, which points to the existence of weak geomagnetic storms. Between November 20 and 28 the geomagnetic conditions are rather quiet (Dst > -20 nT and Kp $\leq$ 3).

The Earthquakes' Preparation Regions

As indicated by [24], precursors to earthquakes are expected to be observed within a circle defined by the preparation radius:

$$R = 10^{0.43M}[\text{km}], \tag{3}$$

where M is the moment magnitude of an earthquake. For the M_w 7.5 and M_w 7.6 earthquakes, their preparation radius are $\sim$1678 km and $\sim$1853 km, respectively.

IV. Results and Discussion

A. Differential VTEC Maps

After inspection of the ΔVTEC maps, extremely large ionospheric disturbances starting on November 18 at approximately 20:00 UT were observed and they disappeared at around 22:00 UT of the next day (November 19). In Fig. 3 one can see the full extent of these disturbances between 00:00 and 06:00 UT from November 19, 2015. From Fig. 2 it can be seen that towards the end of November 18, the Kp index reaches a

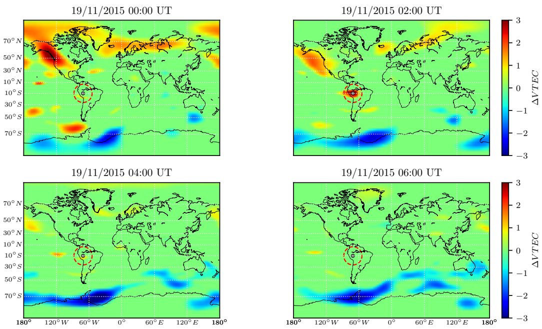

Fig. 3. Global spatial distribution of ΔVTEC for November 19, 2015 between 00:00 - 06:00 UT. The units for the ΔVTEC are TECU, where 1 TECU = 10^{16} electrons/m^2. The grey circles point to the location of the M$_w$ 7.6 earthquake and the dashed red circles define the earthquake preparation zone [24].

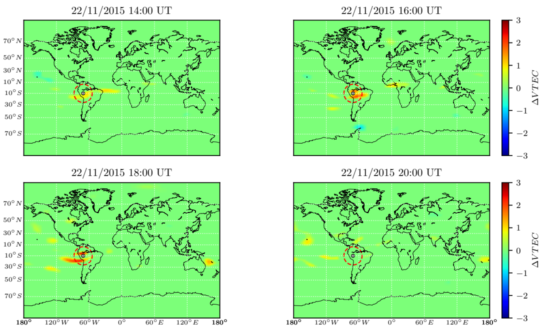

Fig. 4. Global spatial distribution of ΔVTEC for November 22, 2015 between 14:00 - 20:00 UT. The units for the ΔVTEC are TECU, where 1 TECU = 10^{16} electrons/m^2. The grey circles point to the location of the M$_w$ 7.6 earthquake and the dashed red circles define the earthquake preparation zone [24].

value of 5, whereas for these same hours and the early hours of November 19 the Dst index values point to the existence of a small intensity geomagnetic storm (-20 nT > Dst > - 50 nT). In addition, the spatial ionospheric disturbances, positive and negative ones, are clearly of a global scale; hence, it can be considered that these anomalies are very likely originated due to the weak geomagnetic conditions. However, it can not be entirely rule out the possibility that a component of the positive ionospheric anomaly observed right over the epicenters on November 19 at 02:00 UT might be due to the preparation for the seismic events; this due to the pronounced increment of VTEC at this time inside the earthquakes' preparation regions. Due to the size of the presented maps, only the earthquake preparation region (R ∼1853 km) for the M_w 7.6 earthquake is shown.

On November 22, 2015 (2 days prior to the two seismic events) a positive ionospheric anomaly appeared at ∼14:00 UT, and it remained above the location of both earthquakes until ∼20:00 UT, when this already moved to the west (Fig. 4). It is worth noticing that nowhere else in the maps shown in Fig. 4 there are permanent anomalies, only the one detected within the earthquakes preparation zone (R ∼1853 km).

In a similar fashion, one day before the earthquake doublet (November 23) another positive anomaly over the location of the epicenters was observed (Fig. 5). This one was present approximately between 08:00 UT and 10:00 UT (03:00-05:00 LT). At 12:00 UT the disturbance started to move westward until it disappeared. As with other studies [25], [5], [9], [13], [11] that observed ionospheric anomalies with their accompanying anomaly in the conjugate geomagnetic region, in Fig. 5 this can not be seen, and this is mainly due the time in which the anomaly was observed (03:00-05:00 LT). At these hours of the day the EIA is not yet above the Peruvian sky.

B. The EIA Shape

Due to the low-latitude location of the seismic incidents the sky above this geographic region is also subjected to the Equatorial Ionization Anomaly (EIA) [26]. [27] have indicated that the latitudinal shape of the EIA can undergo some variations before a strong earthquake. Three modifications were

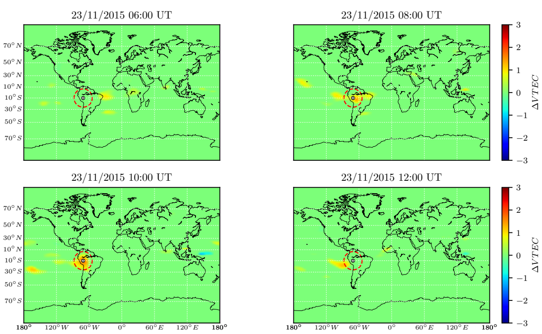

Fig. 5. Global spatial distribution of ΔVTEC for November 23, 2015 between 06:00 - 12:00 UT. The units for the ΔVTEC are TECU, where 1 TECU = 10^{16} electrons/m^2. The grey circles point to the location of the M$_w$ 7.6 earthquake and the dashed red circles define the earthquake preparation zone [24].

proposed by [27]: enhancement of the EIA, vanishing of the crests, and shifting of the EIA. In view of this, a meridian section at 71°W was selected for the period of days between November 19 and 24, 2015 at 18:00 UT (Fig. 6). This hour was chosen because at 18:00 UT (13:00 LT) on November 22, a positive ionospheric anomaly at its most intense moment was observed (Fig. 4).

In Fig. 6 it can be seen that for November 22 the EIA, which at this hour (18:00 UT) of the day is above the Peruvian sky, significantly increases showing a sharper definition of the double-crest with a trough shape. The rest of the selected days, November 19, 21, 23 and 24 remained in a non-disturbed state. However, on November 20 (4 days before the two earthquakes), it can be observed as well a considerable increase of the EIA. Thus, looking into the ΔVTEC maps for this day (Fig. 7), two positive anomalies can be observe appearing on November 20 at 20:00 UT and completely disappearing on November 21 at ∼08:00 UT. On November 21 at 00:00 UT, it can be observed that a negative ionospheric anomaly appears well-within the preparation region and in between both positive anomalies. Hence; it is clear that at this time, 00:00UT (19:00

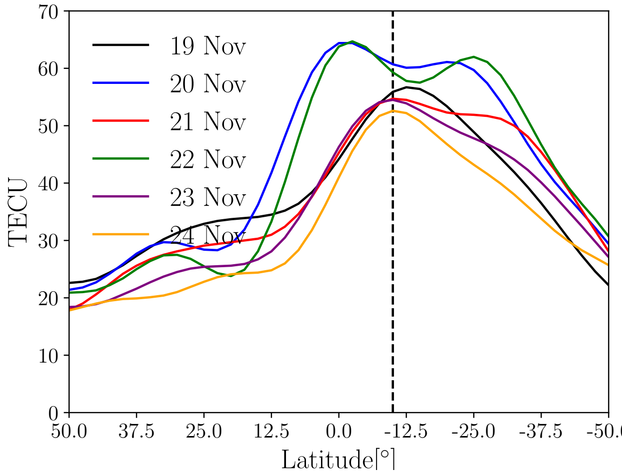

Fig. 6. Structure of the VTEC for the 71°W meridian at 18:00 UT between November 19 and 24, 2015. A relevant range of latitudes is shown, 50°N–50°S. The vertical dashed black line indicates the latitude 10°N, approximately where the two earthquakes took place.

LT), both positive anomalies and negative anomaly correspond actually to the modification of the EIA shape observed in Fig. 6 for November 20 at 18:00 UT, the double-crest with a trough shape. Authors in [2] have also observed a similar deformation of the EIA during night hours a few days before the September 26, 2005 earthquake in Peru. Another example of the modifications of the EIA during night and day time into a well defined double-crest with a trough occurred 1 and 2 days before the December 26, 2004 earthquake in Indonesia [1].

In Fig. 8 it can observed that the positive ionospheric anomaly observed in Fig. 5 on November 23 at 10:00 UT (05:00UT), before sunset, shows an increment of the VTEC. The other selected days, before and after (November 19, 20, 21, 22 and 24), remained stable.

C. Origin of the Seismo-Ionospheric Signatures

As indicated by [21], the M_w 7.5 and M_w 7.6 earthquakes occurred in the same fault. Hence, it is safe to assume that the days before in which seismo-ionospheric signatures were observed can be considered to be a product of the preparation to the two earthquakes. Looking at the geomagnetic activity (Fig. 2) between November 20, 2015 and the day the earthquakes happened (November 24, 2015), one can observe that this remained very quiet (Dst $>$ -20 nT and Kp $\leq$ 3). Thus, it can be suggested that the three observed positive ionospheric anomalies, November 20 (20:00 UT) - 21 (06:00 UT), November 22 (14:00-18:00 UT) and November 23 (08:00-12:00 UT), are precursors of the earthquakes.

In order to explain why an increment of VTEC is observed in these three days as a product of the earthquakes' preparation, a model that works with air ionization due to radon's release from the Earth's crust is considered [28], [29]. Radon emanating from the crust towards the Earth's surface and the air will cause the ionization from the latter. Afterwards, depending on the ionization levels in the lower atmosphere, the air conductivity will increase or decrease. When the air conductivity decreases, the ionosphere potential increases, and it is in this case when positive ionospheric anomalies can be observed. The concentration of radon has already been observed to increase many days before some major earthquakes [30], it would then remain to see if that is the case for the earthquake doublet.

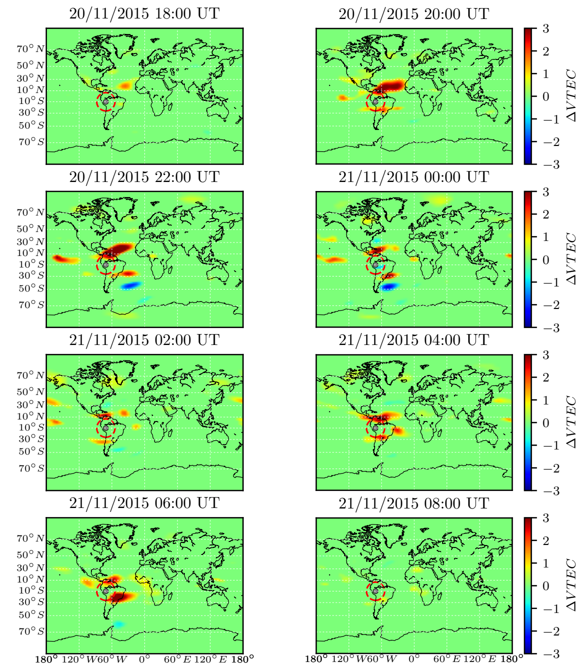

Fig. 7. Differential VTEC global maps for the period between November 11, 2015 at 18:00 UT and November 21, 2015 at 08:00 UT. The grey circles point to the location of the M_w 7.6 earthquake and the dashed red circles define the earthquake preparation zone [24].

V. Conclusions

Using GIMs provided by CODE, ionospheric anomalies were investigated prior the earthquake doublet that happened in Peru on November 24, 2015. First, by generating global differential VTEC maps, two ionospheric anomalies, at a confidence level of 95%, were observed 2 (November 22, 2015) and 1 (November 23, 2015) day prior to the seismic events. Both positives anomalies were observed to fall inside the earthquake preparation zone define by the Dobrovolsky equation [24]. Due to the low-latitude nature of the earthquakes, 10.54°S and 10.06°S, the shape of the equatorial ionization anomaly was also analyzed. By looking into the EIA, it was not only possible to confirm the ionospheric disturbance observe on November 22, 2015, but it was also possible to identify a third anomaly that occurred between November 20 (20:00 UT) and November 21 (06:00 UT). As for other major earthquakes previously studied at low-latitudes, in this case it was possible to observe as well how the EIA shape was modified, through the increase of the VTEC and a sharper definition of the

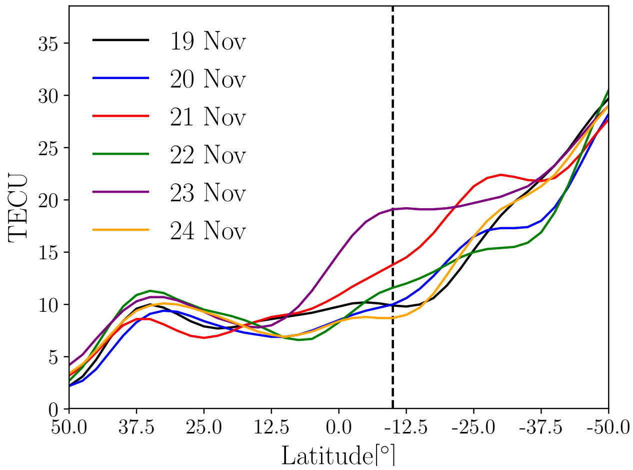

Fig. 8. Structure of the VTEC for the 71°W meridian at 10:00 UT between November 19 and 24, 2015. A relevant range of latitudes is shown, 50°N–50°S. The vertical dashed black line indicates the latitude 10°N, approximately where the two earthquakes took place.

double-crest with a trough shape, which is expected to be seen during daytime. These findings along with the fact that the geomagnetic conditions starting on November 20, 2015 remained very quite (Dst $>$ -20 nT and Kp $\leq$ 3), reveal that these three disturbances are seismo-ionospheric signatures to the earthquake doublet. It is very likely that air ionization due to the release of radon may be the originating mechanism for the observed positive ionospheric disturbances. Finally, the detection of these anomalies should provide a further insight in the detection of seismo-ionospheric signatures for very deep earthquakes.

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