Comments on the paper "Two independent real-time precursors of the 7.8 M earthquake in Ecuador based on radioactive and geodetic processes – Powerful tools for an early warning system" by Toulkeridis et al. (2019)

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Abstract

In the paper entitled "Two independent real-time precursors of the 7.8 M earthquake in Ecuador based on radioactive and geodetic processes – Powerful tools for an early warning system", Toulkeridis et al. (2019) claim that they found radiation and GPS signal anomalies before the April 16th 2016 Pedernales earthquake (Ecuador) and that their findings can be used to forecast earthquakes in the medium and short term in active continental margins. Using an extended data set that overlaps Toulkeridis et al. (2019) study period, we find: (1) the success rate of predicting earthquakes using radiation anomalies is 2.5%; (2) radiation anomalies, including the one recorded

during the hours before the M 7.8 earthquake, temporally correlate with local rainfall; (3) Toulkeridis et al. (2019) GPS results are physically unrealistic and inconsistent with previously published GPS and InSAR analysis; (4) there is no anomaly in the GPS time series before the earthquake. Therefore, Toulkeridis et al. (2019) results are not reliable evidence of precursors to the M 7.8 earthquake in 2016 in Ecuador, and their proposed method cannot be used to forecast earthquakes.

1. Introduction

After a major earthquake hits populated areas, there are often individuals, either scientists, emergency professionals or laypeople who look for precursory signals that could have been recognized and communicated prior to the event, thus avoiding the number of deaths and injuries. The 2009 L'Aquila earthquake is one of the most recent and notorious examples for this (Jordan et al, 2011), and the amateur prediction and its aftermath has the scientific community erring on the right side (Kolbert, 2015).

The scientific literature abounds with success stories about earthquake precursors being retrospectively identified after major earthquakes (Geller, 1997; Uyeda et al. 2009), but only a handful of examples exist for genuine short-term forecasts such as the M 7.3 earthquake in Haicheng, China, in 1975 (National Research Council, 2003). The search for diagnostic precursors has not yet produced a successful short-term prediction scheme (Jordan et al. 2011) and any proposed forecast/prediction methodology must follow a rigorous and transparent process of evaluation (Peresan et al. 2012).

In the paper "Two independent real-time precursors of the 7.8 M earthquake in Ecuador based on radioactive and geodetic processes – Powerful tools for an early warning system" Toulkeridis et al. (2019) compare gamma radiation time series from a single sensor installed in the Andes at Lasso (Lat.: S 0.7898°, Long.: W 78.6152°) with the occurrence of earthquakes. They claim that almost all earthquakes with magnitude M ≥ 5, and located up to 250 km from the sensor, occurred few hours after a significant positive radiation anomaly, including the M 7.8 earthquake on Abril 16th 2016 whose epicenter was about 200 km from the sensor. Toulkeridis et al. (2019) further claim that they observe a ~1 m transient displacement at all continuous GPS sites in Ecuador several minutes prior to the M 7.8 earthquake. They indicate that the whole GPS network recorded a northward instantaneous displacement exceeding 1 m at most GPS sites at the time of the earthquake. They conclude that real-time monitoring of radiation and of GPS displacement can be used to implement an early warning system for forecasting earthquakes in the medium and short terms.

Our comment includes the analysis of a 15 month-long radiation time series from the same sensor as Toulkeridis et al. (2019) that overlaps their study period. We show that the detection performance of earthquakes is very poor, while correlation with local rainfalls is high, as it is seen during the hours preceding the M 7.8 earthquake. When analyzing the GPS data, we find no transient displacement anomaly before the earthquake. We further show that their GPS results are: (1) inconsistent with the known physics of earthquakes; (2) of bad quality compared with the standard state-of-the-art of GPS analysis; and (3) inconsistent with independent estimates of displacements for the Ecuador earthquake.

2. Radiation precursors

2.1. Method, data availability, operating conditions and detection range

We solicited the time series to NOVACERO, the firm owning the Radiation Portal Monitor (RPM) used by Toulkeridis et al. (2019). We have been given about 15 months of radiation data overlapping their period of study. The LUDLUM model 4525 RPM used in this work is equipped with an EJ-200 plastic scintillator that reacts in the presence of gamma radiation and optionally to neutron emissions. It is designed to detect radioactive material in scrap metal for recycling purposes. Besides radioactive material, various natural processes can be the source of gamma rays such as thunderstorms, solar flares and cosmic rays (Marisaldi et al., 2013). Toulkeridis et al. (2019) claim that they detect radiation anomalies associated to earthquakes located up to 250 km away from the sensor. In Figure 4 of their paper, they show the radiation time series for four earthquakes to support their hypothesis (also in Figure C1). However, they do not provide neither a systematic statistical analysis for the whole time series nor a quantitative performance assessment of using radiation time series for earthquake forecast. Here we present two statistical analyses. The first compares the gamma radiation anomalies with the earthquake occurrences, and the second highlights a significant correlation between radiation anomalies and local rainfalls.

2.2. Gamma radiation anomalies prior to earthquakes

Statistical analysis is a must-do process when assessing the potential of seismic precursors (Chen et al. 2004; Uyeda et al. 2009), where all cases confirming or rejecting the studied hypothesis must be clearly presented. In order to assess whether radiation anomalies are reliable earthquakes precursors in Ecuador, we perform a statistical analysis of the temporal correlation between the radiation anomalies and earthquakes occurrence during the 15-month time window of radiation level provided by NOVACERO. This time window overlaps the period used in Toulkeridis et al. (2019) as indicated previously. Following Toulkeridis et al. (2019) method, we selected all earthquakes of magnitude $M \geq 5$ from the NEIC catalogue (https://earthquake.usgs.gov/earthquakes/search/) in a 250 km radius around the RPM, resulting in a list of 19 earthquakes (Table 1) which includes the four events, with $M \geq 5$, shown in Figure 4 of Toulkeridis et al. (2019).

In order to identify the gamma radiation anomalies, we first fill the gaps with median values using the entire time series. When we find more than one value for the same minute, we take their average. We filter the time series using a low-pass zero-shift filter, for periods larger than one hour, in order to identify only hours-long anomalies, as those shown by Toulkeridis et al. (2019). Then, we normalize this filtered time series with the largest amplitude and compute the square of it to enhance anomalies. With this final time series (second trace in Figure C2) we define the anomalies (third trace in Figure C2) as time series periods with amplitudes larger than their 98% percentile.

We find 162 anomalies, which includes all those presented in Toulkeridis et al. (2019). As an indicator of the temporal variability of the radiation time series, we note that choosing a 95% percentile results in 899 anomalies, while using percentiles equal or larger than 99% would not include all the anomalies presented in Toulkeridis et al. (2019). Finally, we decide to associate an earthquake to a radiation anomaly if the earthquake occurs either during the anomaly or within a 6-hour time window after the anomaly's final time. We select these association criteria because, in the cases presented by the authors, the earthquakes happen during the anomaly (Fig 4A) or up to three hours after the time of the anomaly (Fig. 4B).

Table 1. List of the earthquakes M ≥ 5 in a 250 km radius around NOVACERO sensor between January 2015 and May 2016 (source: https://earthquake.usgs.gov/earthquakes/search/)

Date (UTC-05:00)	Latitude	Longitude	Depth (km)	Magnitude (M)
2015-03-27 16:59	-1.201	-77.584	195.0	5.5
2015-04-28 06:19	-2.086	-79.623	89.0	5.4
2015-05-30 01:26	1.220	-79.570	13.0	5.3
2015-10-15 05:07	-2.502	-78.762	97.1	5.4
2016-03-05 19:54	-1.428	-80.401	10.0	5.1
2016-04-16 18:58	0.382	-79.922	20.6	7.8
2016-04-16 19:29	-0.265	-80.464	15.5	5.5
2016-04-17 02:14	-0.385	-80.201	23.9	5.8
2016-04-17 04:23	-0.234	-80.694	10.0	5.6
2016-04-19 17:22	0.578	-80.025	11.0	5.6
2016-04-20 03:33	0.639	-80.210	14.0	6.2
2016-04-20 03:35	0.708	-80.035	10.0	6.0
2016-04-21 22:03	-0.292	-80.504	10.0	6.0
2016-04-21 22:20	-0.281	-80.504	10.3	5.9
2016-04-21 23:31	-0.421	-80.543	10.0	5.0
2016-04-22 20:24	0.613	-80.252	10.0	5.7
2016-04-26 16:58	-0.194	-80.731	10.0	5.4
2016-05-18 02:57	0.426	-79.790	16.0	6.7
2016-05-18 11:46	0.495	-79.616	29.9	6.9

We only find 4 earthquakes, with magnitude M $\geq$ 5, being associated with radiation anomalies. Namely, two of them (M 5.4 on October 15th 2015 and M 7.8 on April 16th 2016) are shown in the Figure 4A and 4C of Toulkeridis et al. (2019), whereas the third is a M 5.5 aftershock occurring 30 minutes after the M 7.8 earthquake (Figure C1), which is associated with the same radiation anomaly, and is not presented by Toulkeridis et al. (2019). The fourth associated earthquake is the M 5.1, wrongly labeled 5.5M in Toulkeridis et al. (2019), that occurred on March 6th 2016 at 00:54:41 UTC. This event is shown after the second anomaly in Figure 4B from Toulkeridis et al. (2019) but the date on their figure is wrong. Two main flaws appear in Figure 4B: (1) the radiation time series is presented 24 hours ahead of its actual time: for instance, the first anomaly starts at the beginning of March 4th (at 00:12 Local Time, 05:12 UTC), when it actually occurs on March 5th at 05:12 UTC (Figure C1); (2) the earthquake after the first anomaly does not exist, it is actually a M 4.3 earthquake, which occurred on 4 March at 06:25 (Local Time, 11:25 UTC) without any precursory radiation anomaly (Figure C1).

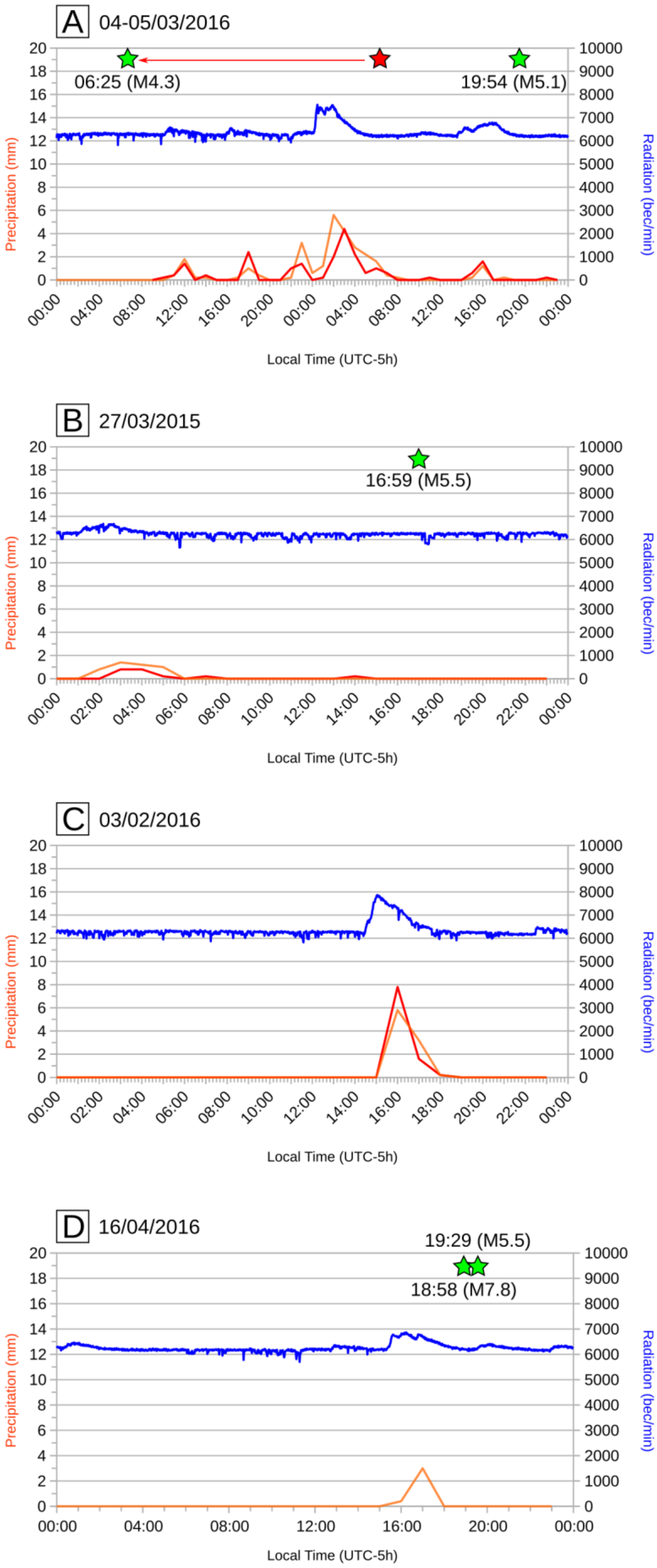

Figure C1. Examples showing relationship between rainfalls occurrence and radiation level measured in Lasso. A: corresponds to Figure 4B in Toulkeridis et al. (2019). Their Figure 4B misplaced the M 4.3 earthquake by approximately one day. The real span between the M 4.3 and M 5.1 earthquakes is 37 hours 29 minutes. Radiation time series are also offset by ~24 hours when taking into account the date on the Figure 4B from Toulkeridis et al. (2019). B: example of an earthquake without radiation anomaly within 6 hours before the occurrence. C: example of a radiation anomaly with its corresponding precipitation peak and no earthquake. D: M 7.8 earthquake on 16th April 2016, with a clear precipitation peak at the time of the radiation anomaly. M 5.5 earthquake not shown in Toulkeridis et al. (2019). Orange line: Vivero weather station; red line: Colcas weather station, blue line: NOVACERO radiation detection; green star: earthquakes with time and magnitude from the NEIC catalog (https://earthquake.usgs.gov/earthquakes/search/); red star: wrongly located earthquake in Toulkeridis et al. (2019).

According to our results, the alarm rate (number of anomalies divided by the duration of the time series, which is 462 days, ~15 months) is 10.8 alarms per month, with a success rate (number of anomalies detected prior to the earthquakes divided by the total number of anomalies) of 2.5%. Furthermore, the association level between earthquakes and anomalies (number of earthquakes preceded by a radiation anomaly divided by the total number of earthquakes) is 21%. In other words, the method proposed by Toulkeridis et al. (2019) would have emitted one valid alarm out of every five earthquakes, with $M \geq 5$, and would have provided 40 false alarms for every true earthquake during the studied period. Based on our statistical analysis, we refute the authors statement that their method allows to predict earthquakes or to issue medium term forecasts. Furthermore, we observe that the authors chose to present only the few earthquakes that support their claim. They sloppily use earthquakes with magnitudes $M < 5$, and shifted in time an earthquake in their Figure 4B so that it supports their claim.

Considering the high alarm rate, the large percentage of false alarms, and the low association level between earthquakes and radiation anomalies, the methodology presented by Toulkeridis et al. (2019) does not provide a valid operational earthquake precursor detector. In the next section we explore a different source for the gamma radiation anomalies.

2.3. Counter-hypothesis: atmospheric anomalies

Toulkeridis et al. (2019) consider that “anomalies may occur due to a variety of natural or artificial effects, such as strong rainstorms” but in their analysis they fail to present any early procedure to distinguish storm-related gamma rays (Suszcynsky et al., 1996, Marisaldi et al., 2013) from those related to earthquakes. According to the instrument manual user, the background radiation level is constantly changing due to cosmic events, weather and other influences (LUDLUM, 2014). In particular, the operator’s manual clearly states that “changes in background radiation due (especially) to precipitation can increase the radiation level seen by the detector by 300%”. We therefore assess the impact of rainfall on the radiation time series.

We collected hourly rain precipitation data from two rain gauges, Vivero (Lat.: S 0.6947°, Long.: W 78.5887°) and Colcas (Lat.: S 0.7013°, Long.: W 78.5351°), operated by Aglomerados Cotopaxi S.A. located respectively at 11 and 13 km N-NE from the NOVACERO sensor where no rain gauge is installed. To compare the gamma radiation and precipitation time series, we interpolate the hourly rain data to minutes, so that every minute within an hour has the same hourly value. In addition, gaps are filled with a negative value, and only positive precipitation values are then used in subsequent analysis. In order to compare the precipitation and the radiation anomalies, we compute all radiation anomalies (NOVA INDEX in Figure C2) occurring during rainfall periods (RG INDEX in Figure C2). Both sequences are highly similar, and 138 of the 162 radiation alarms (85%) correlates with local rains (Figures C1 and C2). The found correlation between rainfalls and radiation anomalies includes all the alarms interpreted as earthquake precursors by Toulkeridis et al. (2019) in their Figure 4, and includes the 16th April 2016 earthquake (Figure C1). The 24 remaining alarms could not be associated with the precipitation time series, perhaps because of more localized rainfalls occurring at Lasso and not recorded by the two rain gauges, or because of other atmospheric or cosmic processes. However, none of them correlate with $M \geq 5$ earthquakes within the specified time windows. From our radiation analysis, we conclude that most radiation background anomalies at the RPM correlate with local rainfalls. The occurrence of an earthquake within a 250 km radius from the RPM could easily coincide with the frequent rainfalls in the area.

Gamma radiation and rain precipitation

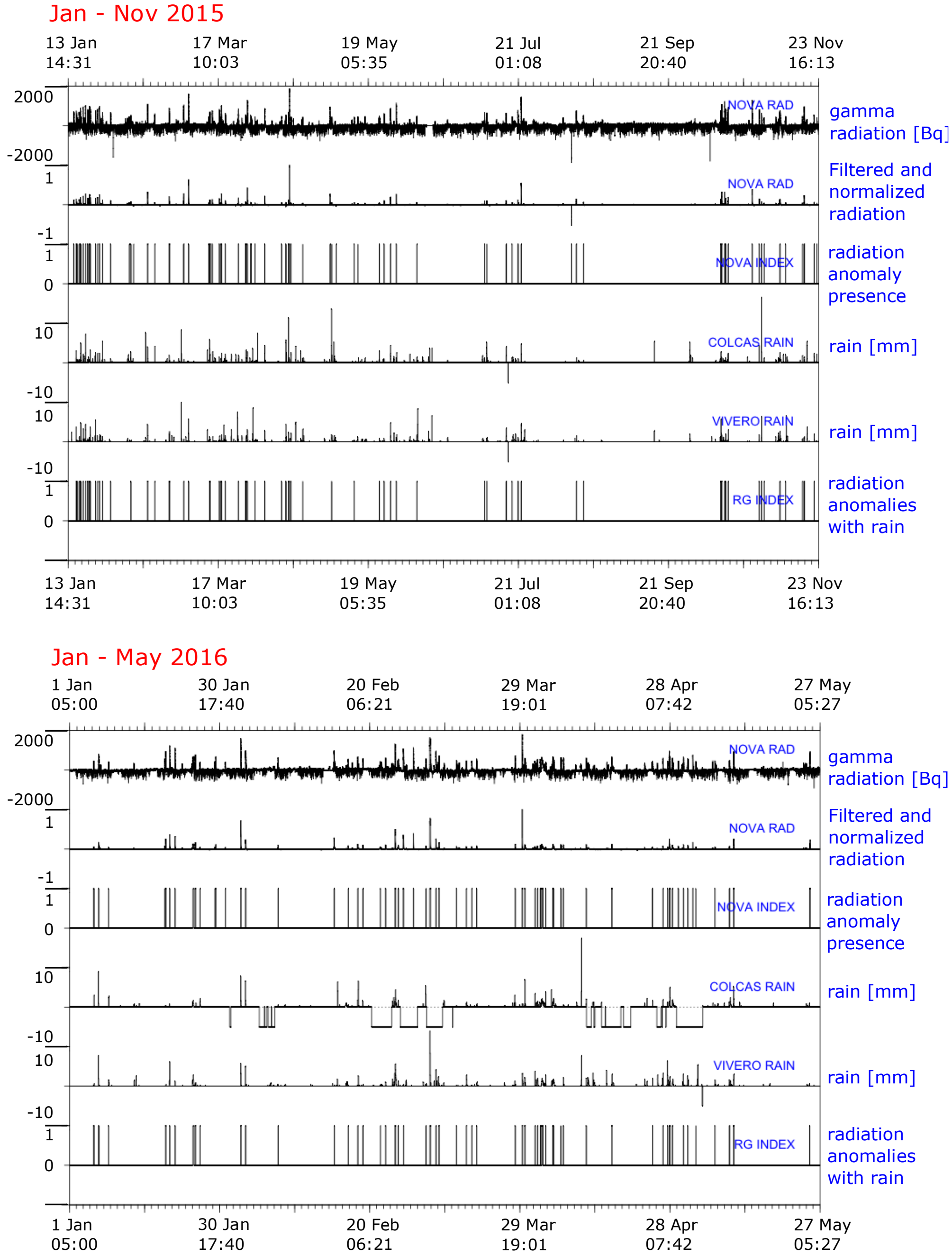

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Figure C2. Gamma radiation and rain precipitation time series and statistical analysis. Top (Jan – Nov 2015) and bottom (Jan – May 2016) panels include the following time series, from top to bottom at each panel. Trace 1: Gamma radiation after its trend is removed (NOVA RAD). Trace 2: Filtered gamma radiation for periods larger than one hour. Trace 3: One-zero index detecting radiation anomalies (NOVA INDEX). Trace 4: rain precipitation in COLCAS weather station. Trace 5: rain precipitation in VIVERO weather station. Trace 6: One-zero index to simultaneously select those radiation anomalies that occur during rain periods (RG INDEX).

3. GPS data

Toulkeridis et al. (2019) show GPS 1-sample-per second kinematic analysis result for sites located from a few tens to a few hundreds of kilometers from the rupture area. Summarized in their Figure 7, the general behavior of the calculated positions is: (1) a random apparent displacement confined within a ~1 m wide ellipse during the hours before the M 7.8 earthquake; (2) a westward to southwestward transient motion of several tens of centimeters, exceeding a meter at a few sites during "several minutes prior the main earthquake event"; (3) a sudden northward jump, taking place during a single second and at the same second at all sites. This displacement is similar in direction at all sites and exceeds one meter in magnitude for more than half of the sites, including sites located at ~200 km (CHEC) or even ~300 km (FOEC) from the rupture area; (4) a random displacement within ~60 cm during the seconds following the jump.

3.1. GPS co-seismic offsets

The displacements during the earthquake proposed by Toulkeridis et al. (2019) are physically impossible. This is because if two GPS stations record the jump at the same second but are located at a different distance from the source, as presented in Toulkeridis et al. (2019), then the seismic waves must have travelled at a velocity faster than the difference of their distance from the epicenter during less than a second. Taking for instance, ONEC (long. W 80.10°, lat. S 0.70°, 50 km from the epicenter) and FOEC (long. W 76.99°, lat.S 0.46°, 300 km from the epicenter), would give a seismic velocity larger than 250 km/s, that is roughly two orders of magnitude faster than known P-wave velocity traveling the lithosphere. Movement of more than 1 m in a second would imply a very large acceleration that would have resulted in significant damages all over Ecuador which is at odd with the report of damages and observation from the accelerometric network (Beauval et al., 2017). Third, the offsets reported by Toulkeridis et al. (2019) is northward for all sites, regardless their location with respect to the rupture area. NJEC (long. W 79.62°, lat. S 2.67°), CHEC (long. W 77.81°, lat. S 0.34°) or FOEC (long. W 76.99°, lat.S 0.46°), all located more than 200 km from the rupture, show larger displacements than ONEC (long. W 80.10°, lat. S 0.70°) located ~50 km from the rupture. These results are inconsistent with the prediction of elastic models for a slip on the megathrust, that should mainly induce trenchward displacements with magnitude of displacement decreasing with increasing distance from the slip area.

Moreover, the offsets reported by Toulkeridis et al. (2019) are inconsistent with previously reported offset for the same sites from kinematic analysis (Nocquet et al., 2017) and co-seismic offsets derived from a regional static analysis of GPS data (Nocquet et al., 2017, Mothes et al., 2018). Static offsets can also be estimated from the high-rate GPS kinematic analysis presented in Ruhl et al. (2018) (freely available at https://zenodo.org/record/1434374). Ruhl et al. (2018), Nocquet et al. (2017) and Mothes et al. (2018) results consistently show a maximum static offset of 75 cm and 50 cm on the horizontal and vertical components respectively near the rupture area, rapidly decreasing to less than 7 cm and 2 cm at QVEC (95% confidence level). The static co-seismic displacement at QVEC (long. W 79.47°, lat. S 1.01°) can be independently assessed from InSAR results published using Sentinel-1 and ALOS ascending and descending tracks (He et al., 2017, Nocquet et al., 2017, Gombert et al., 2017, Yi et al., 2018). For all results, the InSAR data indicate less than 10 cm of co-seismic displacement in the satellite line-of-site, consistent with GPS estimates. The estimates from Toulkeridis et al. (2019) are therefore ~20 to 35 times larger than all other InSAR and GPS estimates.

High-Rate GPS kinematic analysis of Ecuador GPS sites recorded the seismic waves induced by the Pedernales earthquake (Nocquet et al., 2017, Rulh et al., 2018) and are further consistent with kinematic modelling of the rupture propagation (Nocquet et al., 2017, Gombert et al., 2018) or with the Peak Ground Displacement-Moment Magnitude scaling relationship (Ruhl et al., 2018). Magnitude and timing of onset of the seismic waves differs among stations as a function of their location with respect to the evolving slip during the rupture as expected from elasto-dynamic solutions. Toulkeridis et al. (2019) results are inconsistent with the known physics of earthquakes and seismic waves propagation.

3.2. Kinematic analysis of QVEC data

Proper kinematic analysis of high-rate GPS data including phase measurements typically show precision of a few centimeters or less (e.g. Genrich and Bock, 2006). Toulkeridis et al. (2019) results prior the M 7.8 Ecuador earthquake show a dispersion of the order of 1 meter or more (their Figure 5 & 7), that is 50 times larger than state-of-the-art kinematic analysis. We present our own processing of the same data as Toulkeridis et al. (2019) for the QVEC site focusing on a time window starting ~20 minutes before the earthquake. The red line in Figure C3 corresponds to the time origin of the earthquake provided by the USGS at 23:58:36 UTC. We translate this time into GPS time so that our figure can be readily compared with figure 5B from Toulkeridis et al. (2019) as they do not mention the GPS time-UTC correction. With respect to Toulkeridis et al. (2019), our processing shows the following differences: (1) the first peak displacement develops during almost 20 seconds and not during a single second; (2) the maximum amplitude is less than 15 cm for all components and not 1 meter; (3) the east component records significant displacement; (4) the static displacement seen at the end of the signal is -4 cm, +5 cm, -2.5 cm on the east, north and up components respectively in agreement at the centimeter level with the values published in Nocquet et al. (2017) and Mothes et al. (2018).

On the contrary to Toulkeridis et al. (2019), our processing shows a stability with no departure larger than 2 cm from the mean for the horizontal components (standard deviation 0.5 and 0.6 cm for the north and east components respectively). The vertical component is noisier as expected with a standard deviation of 3.0 cm.

As a consequence, a processing which shows a low noise compared to Toulkeredis et al. (2019) GPS results, provides results consistent with the timing and amplitude of the seismic waves and static offset does not see any evidence of abnormal transient motion during the minutes preceding the Pedernales earthquake. Centimeter level fluctuations rather reflect changing geometry of the satellite, mismodelling of tropospheric delays, but certainly not “normal displacement” as written in Toulkeridis et al. (2019). Our processing rules out any displacement larger than 2 cm and definitively excludes the one-meter precursory motion proposed by Toulkeridis et al. (2019).

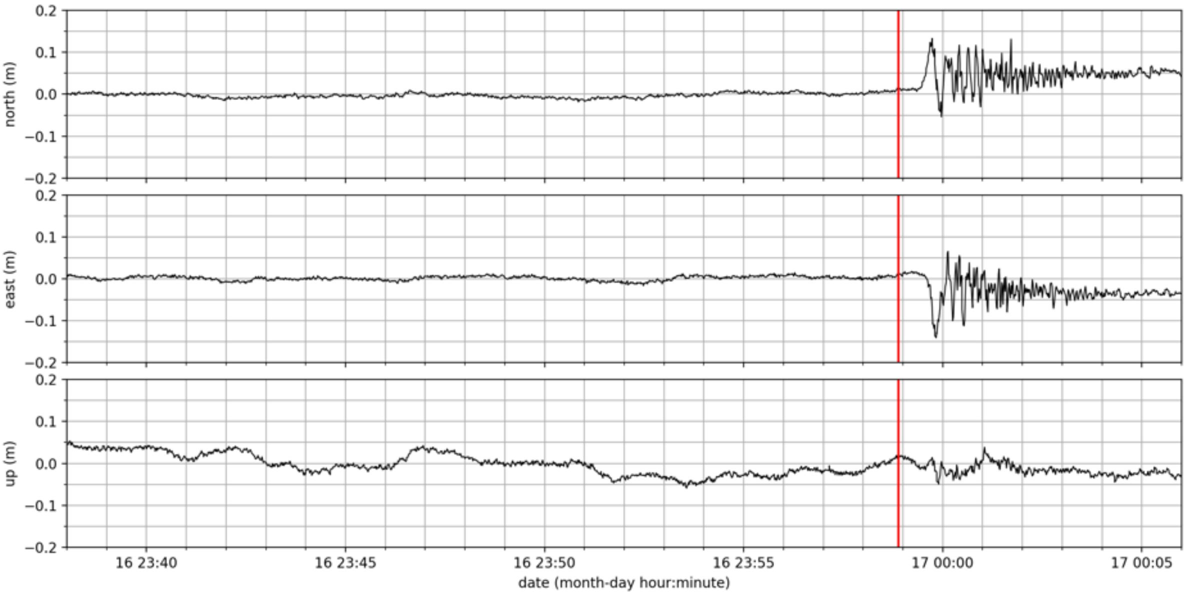

Figure C3: 1-sample-per-second kinematic analysis of QVEC site GPS data. The red line indicates the origin time of the M M 7.8 Pedernales earthquake on April 16th 2016 (23:58:36 UTC) in GPS time (23:58:53).

4. Conclusion

Both analyses of radiation and GPS time series from Toulkeridis et al. (2019) show major flaws. We demonstrate that radiation anomalies are seen only for the three earthquakes shown in Toulkeridis et al. (2019) over a set of 19 M≥ 5 earthquakes, while a total of 162 radiation anomalies occurred during the 15-month period of analysis. Therefore, their hypothesis that radiation anomalies are reliable earthquake precursors has to be rejected. We also show that radiation anomalies and rainfalls recorded near the sensor show a high time correlation. Research is required to explore the triggering mechanisms for radiation anomalies, before any further use. There is no obvious ground displacement during the minutes preceding the Pedernales earthquake and Toulkeridis et al. (2019) results about the displacement during the earthquake are unrealistic. As a consequence, we conclude that the earthquake prediction methodology and the early warning system proposed by Toulkeridis et al. (2019) are unfounded.

Earthquake prediction/forecast science has made sustained progress in the last decades, but the unique determination of the location, time and magnitude of a specific earthquake beforehand still remains elusive (Jordan et al. 2011). A variety of proposed precursors –seismic, geodetic, electromagnetic, geochemical, radiation– do not yet provide the diagnostic capability needed for operational predictions because the signal behavior in the absence of earthquakes is often not characterized (REMAKE, 2016). Nevertheless, the study of earthquake precursors should not be abandoned. Negative results are also important elements of scientific progress (Nature Editor, 2017), but research cannot self-correct when information is missing. Therefore, we suggest that all the data presented in Toulkeridis et al. (2019) should be openly accessible so that any scientist can evaluate them. Independent and rigorous assessment of precursors is particularly important if public authorities are to be able to use scientific results confidently to define earthquake prevention and preparedness policies, and the scientific community as a whole must ensure that this confidence is maintained.

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