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Meteorological and soil surface effects in gamma radiation time series - Implications for assessment of earthquake precursors

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ABSTRACT

Monitoring of environmental radioactivity for the purpose of earthquake prediction requires the discrimination of anomalies of non-tectonic origin from seismically-induced anomalies. This is a challenging task as time series of environmental radioactivity display a complex temporal pattern reflecting a wide range of different physical processes, including meteorological and surface effects. The present study is based on the detailed time series of gamma radiation from the Eastern North Atlantic (ENA) site in the Azores, and on very high resolution precipitation intensity and soil moisture time series. The results show that an abrupt shift in the average level of the gamma radiation time series previously reported as a potential earthquake precursor can also be explained by a corresponding abrupt change in soil moisture. It was concluded that the reduction of false positive earthquake precursors requires the detailed assessment of both precipitation and soil moisture conditions at high temporal resolution.

1. Introduction

Radon (Rn-222) is considered a potential earthquake precursor based on diverse laboratory experiments showing that radon is released during rock fracturing (Holub and Brady, 1981; Mollo et al., 2011; Nicolas et al., 2014). It has also been shown that the connection of initially isolated cracks in crustal rocks before rupture can cause a release of radon transients measurable at the surface (Girault et al., 2017). However, the majority (~90%) of preseismic anomalies in radon concentration are not associated with seismic activity but rather with meteorological, hydrological, and environmental conditions (Jordan et al., 2011). Therefore, it is crucial for the application of radon as a geodynamic proxy to identify the origin of radon anomalies, which is a challenging task as anomalies of non-tectonic origin can be strikingly similar to seismo-tectonically induced radon anomalies (Woith, 2015; Arora et al., 2017)).

The investigation of radon as a potential earthquake precursor requires long and continuous time series of field measurements. The long-term monitoring of Rn-222 at high temporal resolution can be performed using solid detectors or ionization chambers counting the alpha particles from radon decay, or alternatively by counting the gamma rays emitted by radon progeny. Crystal scintillators for gamma ray detection are advantageous for long-term monitoring in stable subsurface conditions due to their significantly higher capability to resolve temporal variations and ability to monitor directly short-term radon variations within the geological media, without the time delay required for the radon to move and reach equilibrium within the air volume sensed by the alpha detector (Zafrir et al., 2011). Thus, gamma-ray detection systems can be useful for long-term monitoring for earthquake prediction purposes.

Anomalous variations in the temporal variability of gamma-ray counting rates have been reported preceding earthquake events (e.g. Tsvetkova et al. (2001, 2014); Fu et al. (2015); Novikov et al. (2016)). However, gamma radiation typically displays a complex temporal pattern, and equally strong variations can be also found in the absence of earthquakes. Thus, it is fundamental to examine not only the association between anomalies in gamma radiation and earthquake events, but to also consider the whole temporal variability of gamma radiation and its relation to meteorological factors, including both atmospheric and surface effects. The temporal variability of gamma radiation is well known to be strongly influenced by precipitation (e.g Inomata et al. (2007); Mercier et al. (2009); Bossew et al. (2017); Melintescu et al. (2018)) and by the soil water content (Carroll, 1981). A further influence is radon build-up within the stable boundary layer (e.g. Chambers et al. (2011)).

The present study illustrates the relevance of considering

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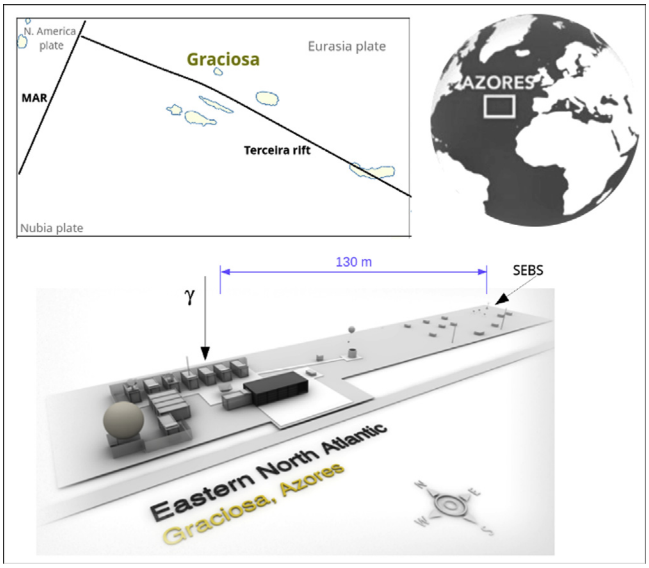

Fig. 1. Geographical location of the gamma radiation monitoring campaign at the Graciosa Island, Azores (top) and detail of the Eastern North Atlantic (ENA) ARM site (bottom). Soil moisture is obtained from SEBS (Surface Energy Balance System) measurements, at a distance of 130 m from the gamma measurements.

simultaneously meteorological and soil surface conditions when assessing potential earthquake precursory signs in gamma radiation time series. Based on a detailed record from the gamma radiation monitoring campaign at the Eastern North Atlantic (ENA) site in the Azores (Barbosa et al., 2017), this work focuses on a previously reported potential earthquake precursor (Barbosa et al., 2016), and how it can actually be explained by a combination of very specific meteorological and surface conditions at the monitoring site.

2. Material and methods

2.1. Geographic setting

The Eastern North Atlantic (ENA) facility is a permanent ARM (Atmospheric Radiation Measurement) site installed at the Graciosa Island (39°N, 28° W) of the Azores archipelago in the middle of the North Atlantic Ocean (Fig. 1). The location is unique from a geophysical point of view because it is located at the Azores triple junction of the Eurasian, North American, and African plates in a seismically and volcanically active area (Hildenbrand et al., 2014; Hipólito et al., 2014). The ENA station is located in the northern part of the Graciosa Island, situated in the northwestern tip of the slow-spreading Terceira rift separating the Eurasian plate to the North from the Nubian plate to the south (Vogt and Jung, 2004).

The climate of Graciosa is dictated by its geographical setting and its interaction with the surrounding sea, as well as by its size and altitude. From its position north of the central group of islands of the Azores, the island is very well exposed to the path of the intense meteorological activity that occurs along the Polar Front, crossing the archipelago by north from west to the east. The prevailing winds at the ENA site are also West-East. Due to its small dimension (only 61 square kilometers) and low altitude (only 402 m high), the island does not interfere much with the marine boundary layer above, which led to the choice of Graciosa for the installation of the ENA facility (Nitschke and de Azevedo, 2015). According to the Köppen climate classification, the littoral climate of Graciosa is included in the temperate climates category with oceanic features (group Csb). It is characterized by having a summer and a winter, average annual temperature above 17°C, and annual average precipitation of 845 mm at sea level. Due to its lower altitude, Graciosa Island is one of the more sunny islands of the archipelago and also the one with less ability to produce orographic rain, making it one of the most driest islands of the Azores (Azevedo, 2015).

The soil of Graciosa reflects the volcanic origin of the island, being mainly derived from the evolution of tephra and basaltic rock in the mild and humid climate of the Atlantic (Madruga et al., 2015).

2.2. Monitoring set-up

Gamma radiation is continuously monitored at the ENA station since May 2015 in the framework of the Gamma Radiation Monitoring campaign. The gamma detector is a NaI(Tl) scintillator (Scionix, the Netherlands) equipped with an electronic total count Single Channel Analyzer (SCA) that detects gamma radiation in the energy range from 475 keV to 3 MeV in order to reduce the Compton background in the 50–475 keV low-energy range (Zafrir et al., 2011). The sensor is installed inside a metal container at 1 m above ground with the scintillation head facing upwards.

2.3. Data

The gamma radiation data consist of a time series of total gamma-ray counts with a 15-min temporal resolution that has been collected since 2015/05/08 in counts per minute (cpm). The measurements were performed every 15-min from May 2015 to April 2016, and then every 1-min since May 2016. For consistency between the two measurement periods, the time series considered hereafter consists of 15-min counts from the 1st period and the counts resulting from the temporal aggregation (sum) of the 1-min counts from the 2nd period. The data is publicly available at the ARM archive (https://doi.org/10.5439/1441191) and can be also freely obtained from a CKAN repository (https://rdm.inesctec.pt).

Precipitation and soil moisture data are routinely measured at the ARM-ENA facility, and they are freely available from the ARM data archive. Precipitation data are obtained from laser disdrometer measurements (Parsivel2, Germany) every 1-min. Soil moisture data is obtained from SEBS (Surface Energy Balance System) measurements using a capacitive sensor (SMP1, Radiation and Energy Balance Systems, Inc.) yielding soil water potential from temperature-corrected resistance measurements. The soil water potential is further converted to gravimetric soil moisture using a generic soil water characteristic equation and assuming a very fine sandy loam as the soil type (Cook, 2016). The resulting values of soil moisture are available at 5 cm, 10 cm and 15 cm depths with a temporal resolution of 30 min. In this study, the soil moisture time series are further re-scaled to an arbitrary range between 0 (dry) and 1 (wet) corresponding to the daily minimum and maximum values of the time series.

3. Results

3.1. Gamma radiation

The time series of gamma counts from the gamma monitoring campaign at ENA is shown in Fig. 2 for the year 2015. The time series displays very sharp peaks, typically lasting <6 hours, which are more frequent and of higher magnitude from mid-September to December. These sharp peaks are associated with concurrent precipitation events (Barbosa et al., 2017) and result mainly from the deposition of radon progeny, Pb-214 and Bi-214 (Livesay et al., 2014).

The time series of gamma counts shows an apparent break in the mean level in mid-August 2015. The break is confirmed by the Mann-Whitney non-parametric test for detecting shifts in the mean (Ross, 2015), which identifies a small (<2%) but statistically significant change in the mean level of counts from 7564 cpm to 7440 cpm on 26th August 2015 at 02h45 (vertical dashed line in Fig. 2). Fig. 3 shows a zoom of the time series of gamma counts and precipitation rate around