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Spectral-decomposition techniques for the identification of radon anomalies temporally associated with earthquakes occurring in the UK in 2002 and 2008

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Abstract. During the second half of 2002, the University of Northampton Radon Research Group operated two continuous hourly-sampling radon detectors 2.25 km apart in the English East Midlands. This period included the Dudley earthquake (M_L=5, 22 September 2002). Also, at various periods during 2008 the Group has operated other pairs of continuous hourly-sampling radon detectors similar distances apart in the same region. One such period included the Market Rasen earthquake (M_L=5.2, 27 February 2008).

Windowed cross-correlation of the paired time-series was used to identify simultaneous short-duration anomalies. In the 2002 data, only two periods of significant cross-correlation were observed, each corresponding temporally to a UK earthquake, one to the Dudley earthquake and the other to a smaller earthquake in the English Channel (M_L=3, 26 August 2002). In the 2008 data, cross-correlation initially revealed little evidence of simultaneous short-duration anomalies but cross-correlation of data de-noised and detrended using Empirical Mode Decomposition (EMD) revealed clear simultaneous short-duration anomalies which correspond temporally to the Market Rasen earthquake.

1 Introduction

Globally, earthquakes have resulted in millions of deaths and the destruction of built and natural environments. Hence the interest in identifying geophysical precursors to predict earthquakes. According to Bolt (2004) earthquakes can be classified into five stages, i.e. precursor stages I–III, earthquake at stage IV, rapid stress-relief and aftershocks at stage V. Changes in various parameters are associated with these stages, including radon emissions. During stage II, micro-cracks form in the rocks increasing their surface area, thus exposing more of the radon to water in rocks with higher dissolution, transport and release to the atmosphere (Meyer, 1977; Asada, 1982). During stage III, as ground uplift and tilt decrease, micro-cracks stop forming and radon emissions decrease. Changes during stage II may enable short/medium-term predictions, although this is complicated by the fact that radon emissions, and other precursors, can differ (a) from place to place and (b) in time at the same place.

Variations in radon concentration in well/borehole water and groundwater prior to major earthquakes have been reported, e.g. the 1966 Tashkent earthquake (Asada, 1982) and the 1995 Kobe earthquake (Igarashi et al., 1995). An increase in radon groundwater concentration was noted near Izu-Oshima-Kinkai in Japan in 1978 as an earthquake precursor by the IASPEI report (1997). Koch and Heinicke (1994) recorded radon anomalies associated with numerous micro-quakes ($M<4.0$) at Bad Brambach, Germany. Many attempts have been made to use both variations as earthquake predictors (Finkelstein et al., 1998; Zmazek et al., 2000; Planinic et al., 2000; Bella and Plastino, 1999; Plastino et al., 2002). However, these have so far proved to be unreliable (Wakita, 1996; Kerr, 2009). Also, it is important to observe that Climent et al. (1999) found no relationship between radon levels and earthquakes in Japan.

In addition to well-catalogued problems associated with interpreting the influences of factors (e.g. geological, meteorological) on radon emission (e.g. Wakita, 1996; Climent et al., 1999; Chyi et al., 2001; Walia et al., 2005, 2006), much of this work has been impeded on two other grounds. First, the use of integrating (e.g. track-etch) detectors significantly limits observation of short-term variations (e.g. hours to days). Second, monitoring at a single location precludes investigation of the spatial nature of any variation: monitoring at two or more locations can determine whether the variations are highly localised or more widespread (Crockett et al., 2006a).

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Table 1. Earthquake Data (BGS, USGS).

Location		Date/Time (UTC/GMT)	Mag. (M_L)	Dist (km)	Depth (km)
English Channel		26 Aug 2002/23:41	3.0	250	4
Dudley	main	22 Sep 2002/23:53	5.0	91	9
	aftershock	23 Sep 2002/03:32	3.2	90	9
	aftershock	24 Sep 2002/09:29	1.2	90	7
Manchester (swarm, typical)		*21–29 Oct 2002*	$\leq$*4.3*	$\approx$*160*$\pm$*5*	$\approx$*4*$\pm$*1*
Market Rasen	main	27 Feb 2008/00:57	5.2	130	19
	aftershock	27 Feb 2008/02:46	1.8	129	10
	aftershock	27 Feb 2008/09:03	1.8	128	23
	aftershock	27 Feb 2008/16:54	2.2	129	19

According to Musson (1996), small and moderate earthquakes are quite common in the UK with an average of ca. 20 earthquakes a month with a stable, established but non-uniform spatial distribution. Two of the UK's largest earthquakes ($M\approx5$) occurred in the Dover Straits in 1382 and 1580 and both caused much damage in London. Significantly, Musson observes that populations have grown considerably since those events, particularly in the London area, and so in the event of a similar earthquake occurring in the future there would be considerably more loss of life and damage to infrastructure. Prediction of such events in the UK therefore has real value.

The solid geology around Northampton, in the English East Midlands, essentially consists of sedimentary rocks. These are mainly Lower and Middle Jurassic to Upper Lias sediments, predominantly Northamptonshire sandstone ironstone, with Inferior Oolite in the west and south of the region (Hains and Horton, 1969; Poole et al., 1968). There is also significant overlying unconsolidated surficial material in parts of the area such as fluvio-glacial deposits, pre-glacial river gravels and glacial tills (Hains and Horton, 1969; Boulton, 1992; Smith et al., 2000; Toghill, 2004). Also, East Midland post-glacial river terraces, such as those found along the river Nene (with associated alluvium) may pass laterally into deposits of angular or subangular material that is very difficult to distinguish from head deposits. The variability of the overlying surficial deposits in the area influences radon levels due to variations in gas permeability. The Northamptonshire sandstone (ironstone), which underlies the area containing the deployed radon detectors, and the Lincolnshire limestone found in the surrounding area are associated with raised radon levels (the situation is complicated by the presence of uraniferous pebbles in the Liassic clays underlying the ironstone, and organic-rich shales underlying the limestones).

2 Radon monitoring and results

During the second half of 2002, the University of Northampton Radon Research Group operated two continuous hourly-sampling radon detectors 2.25 km apart in Northampton, in the English East Midlands (UCN, 2003). This period included the Dudley earthquake (M_L=5, 22 September 2002) which was widely noticed by members of the public in the Northampton area (Crockett et al., 2006a; Gillmore and Crockett, 2008). Subsequently, at various times when the monitoring equipment has been available, the Radon Research Group has operated pairs of detectors in various combination "sniffing" for simultaneous anomalies. One such period in 2008 included the Market Rasen earthquake (M_L=5.2, 27 February 2008) which was also widely noticed by members of the public in the Northampton area (Crockett and Gillmore, 2009). The earthquake incidence data are summarised in Table 1 (BGS (http://www.bgs.ac.uk), 2003; ANSS (http://quake.geo.berkeley.edu/anss/), 2008).

During the periods of monitoring which encompass these earthquakes, two time-series of radon readings were obtained, one from each deployed detector. These paired time-series have been analysed for evidence of simultaneous similar anomalies. The premise for analysing simultaneous similar anomalies is that these are less likely to be coincidental than simultaneous dissimilar anomalies, and anomalies arising from different stimuli are less likely to be similar than anomalies arising from a common stimulus. Thus, a big disturbance, such as an earthquake, occurring at a relatively large distance compared to the detector separation should produce simultaneous similar anomalies (Crockett et al., 2006a).

A "rolling cross-correlation" technique for identifying simultaneous similar features was described in that investigation (Crockett et al., 2006a). For the 2002 time-series, this entailed cross-correlating the paired time-series over windows of 1–30 days duration rolled forwards through the time-series at 1-h intervals. This revealed (a) two periods of

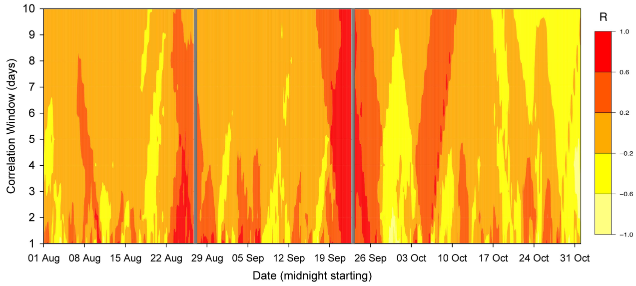

Fig. 1. Rolling Cross-Correlation of the 2002 Paired Time-Series, August–October 2002, showing periods of significant Cross-Correlation at the times of the English Channel and Dudley Earthquakes (earthquakes indicated by grey vertical bars).

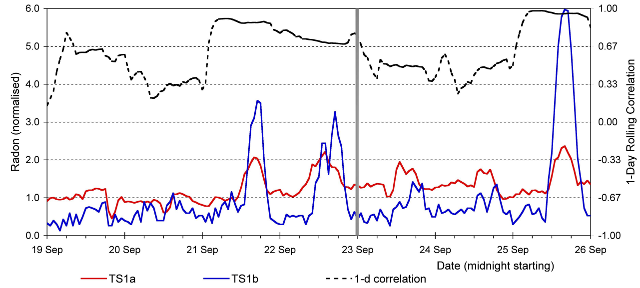

Fig. 2. Radon Anomalies in the 7-day period around the Dudley Earthquake of 22 September 2002, 1-day rolling cross-correlation coefficient (dashed black line) shown for reference. Main earthquake timing is indicated by grey vertical bar.

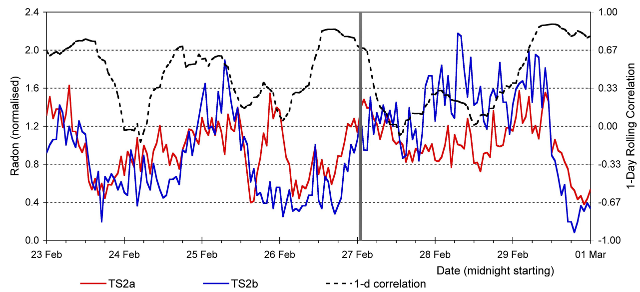

Fig. 3. Radon Concentrations in the 7-day period around the Market Rasen Earthquake of 27 February 2008, 1-day rolling cross-correlation coefficient (dashed black line) shown for reference. Main earthquake timing is indicated by grey vertical bar.

significant positive cross-correlation across the paired time-series and (b) the majority of useful information is obtained using windows of 1–10 days duration. The 1–10-day detail of that analysis is shown in Fig. 1, and the two periods of high correlation are evident at 24–27 August and 20–26 September 2002.

Analysis of these two periods of high correlation revealed similar sequences of simultaneous anomalies of 3–6-h duration in the paired time-series, sequences not apparent elsewhere in the data. The more distinct of these two sequences is shown in Fig. 2, accompanied by the 1-day rolling correlation coefficient for reference with Fig. 1, and corresponds temporally to the Dudley earthquake. The other sequence corresponds temporally to a smaller earthquake which occurred in the English Channel. Analysis of both time-series revealed no meteorological influence or cyclic feature which could explain these anomalies (Crockett et al., 2006a).

The scope for performing similar rolling cross-correlation of the 2008 data is limited by the short duration of the paired time-series, 11.5 days. This means that only windows of up to 4–5 days maximum duration can be usefully rolled through the time-series. However, the 2002 results indicate that this should not compromise the identification of sequences of simultaneous similar anomalies temporally associated with the Market Rasen earthquake, although it is not possible to investigate whether any such anomalies only associate with earthquakes. Furthermore, subsequent observations (Crockett et al., 2006b) indicate that bi-weekly tidal-periodic variations in radon concentrations could anyway limit the maximum useful, unambiguous window for detecting earthquake-related anomalies to approximately 7–8 days (quarter lunar month, half bi-weekly tidal cycle).

Cross-correlating the paired time-series from 2008 revealed a half-day period of high correlation immediately preceding the earthquake although, as shown in Fig. 3, evidence of sequences of simultaneous short-duration anomalies is less clear than for the Dudley earthquake. Figure 3 also shows the 1-day rolling correlation coefficient for reference and comparison. However, there is one important difference between the 2002 and 2008 data which offers a partial explanation: one of the 2008 time-series (TS2a) was obtained using a Genitron AlphaGUARD and the other (TS2b) was obtained using a Durridge RAD7 whereas both the 2002 time-series were obtained using Durridge RAD7s. Also, factors such as the geology at and between Market Rasen and Northampton will be part of the explanation.

The Durridge RAD7 is an actively pumped device whereas the Genitron AlphaGUARD relies on natural diffusion, and this operational difference means that it cannot be assumed that the two time-series share the same high-frequency characteristics. More specifically, transient phenomena with periods on the order of the sampling periods (hourly in both cases) will be differently revealed according to this operational difference. This does not influence longer-period phenomena and variations – which was rapidly confirmed by moving-averaging the data as well as being confirmed in Fig. 4 (below). It was this feature of the 2008 monitoring which provided the stimulus for the newer investigation, the working hypothesis being that if the machine-dependencies of the time-series could be removed or reduced, simultaneous short-duration anomalies such as those at the time of the Dudley earthquake might be more clearly

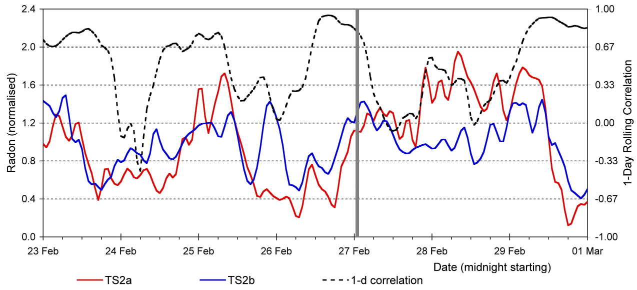

Fig. 4. De-Noised Radon Concentrations (Residual 1) in the 7-day period around the Market Rasen Earthquake of 27 February 2008, 1-day rolling cross-correlation coefficient (dashed black line) shown for reference. Main earthquake timing is indicated by grey vertical bar.

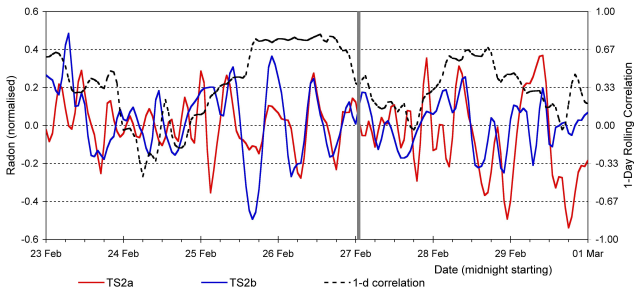

Fig. 5. De-Noised and De-Trended Radon Concentrations (IMFs 2 and 3) in the 7-day period around the Market Rasen Earthquake of 27 February 2008, 1-day rolling cross-correlation coefficient (dashed black line) shown for reference. Main earthquake timing is indicated by grey vertical bar. Note that de-trending the data, i.e. removal of the higher-order IMFs and the Residual, results in (normalised radon) data that vary negatively as well as positively as described in Sect. 2.1.

revealed. We used Empirical Mode Decomposition (EMD) to de-noise, and subsequently also to de-trend, both time-series to more clearly reveal underlying common features of the paired time-series.

2.1 Empirical Mode Decomposition (EMD)

For a fuller description of EMD see, for example, Huang et al. (1998). In brief, EMD considers a signal to comprise a set of layers (Intrinsic Mode Functions, IMFs), each determined according to frequency content, built onto an aperiodic underlying state (the Residual). In operation, it iteratively identifies, "sifts", the IMFs from highest to lowest frequency content until no further IMFs can be identified and the Residual is obtained. Thus, for initial data (time-series assumed for convenience), $T_0(t)$, the output of the first iteration is $T_1(t)$ and at a general i-th iteration, i.e. $T_{i-1}(t) \rightarrow T_i(t)$, EMD:

i) identifies the local maxima and minima in the input data $T_{i-1}(t)$;

ii) from these, interpolates the separate maximum and minimum envelopes, i.e. $\mathrm{Max}_i(t)$, $\mathrm{Min}_i(t)$ (cubic-splining is generally but not necessarily used for the interpolation);

iii) from these, calculates the mean envelope which is the iteration-residual, $R_i(t)$, i.e. $R_i(t) = \frac{1}{2}\,(\mathrm{Max}_i(t) + \mathrm{Min}_i(t))$;

iv) from these, calculates the iteration-IMF, $I_i(t)$, as the data minus the residual $I_i(t) = T_{i-1}(t) - R_i(t)$ and so $T_{i-1}(t) = I_i(t) + R_i(t)$;

v) the residual $R_i(t)$ is either a) passed as the input to the next, (i+1)-th, iteration as $T_i(t) = R_i(t)$, or b) becomes the overall Residual at final iteration $R(t) = R_i(t)$;

vi) at the final iteration, for a total n iterations, $R(t)=R_n(t)$ and

$$T_0(t) = I_1(t) + I_2(t) + \ldots + I_n(t) + R(t).$$

Thus, at each iteration, the highest frequency component in the data is "sifted" as the IMF. During an EMD process, successive IMFs have progressively lower-frequency content and, because the process is empirical and does not assume any time-frequency structure in the data, any individual IMF will be more or less frequency-homogeneous depending on the data undergoing the decomposition process. Depending on the time-frequency characteristics of the data, it might be necessary to consider the sum of two or more adjacent IMFs to obtain a complete description of any given frequency component in the data. Note that IMFs vary negatively as well as positively for non-negative data such as radon time-series. The EMD library for R (statistical language, http://www.r-project.org) was used for this investigation (Kim and Oh, v1.2, 2008).

The de-noised 2008 time-series (first EMD residuals) for the seven-day period around the Market Rasen earthquake are shown in Fig. 4, with their 1-day correlation coefficient shown for comparison with preceding figures. These time-series are the raw data minus the first IMFs which contain the highest frequency components. The correlation coefficient peaks at the same time as for the raw data shown in Fig. 3, but the de-noised data reveal clearer evidence of short-duration anomalies preceding the earthquake than in the raw data. However, it is also clear that there are longer-period variations – trends – still present in the de-noised data.

The de-noised and de-trended 2008 time-series (second and third IMFs, i.e. components having periods in the approximate range 4–24 h) for the seven-day period around the Market Rasen earthquake are shown in Fig. 5, with their 1-day correlation coefficient shown for comparison with preceding figures. The correlation coefficient peaks at the same time as for the previous figures, but the de-noised and de-trended data reveal much clearer evidence of short-duration anomalies preceding the earthquake.

3 Discussion

Radon anomalies preceding the Dudley earthquake of 2002 are clearly apparent in the raw data (Figs. 1 and 2) but radon anomalies preceding the Market Rasen earthquake of 2008 are not so clearly apparent in the raw data (Fig. 3). However, the first EMD residuals of the 2008 data (Fig. 4) reveal simultaneous short-duration (3–6 h) anomalies. This is because the de-noised data in the first EMD residuals, i.e. the raw data minus the first IMF, yield the best representation of machine-independent data (it is the first IMF which will contain the most variations attributable to operational differences between the two detectors). These anomalies are even more clearly revealed in the de-noised and de-trended data in the second and third IMFs (Fig. 5), i.e. the de-noised data (considered above) minus longer-period variations and aperiodic trends in radon concentrations.

The 2002 data (paired RAD7 time-series) were also de-noised and de-trended. As expected, rolling correlation of the IMFs did not significantly enhance the August and September anomalies, but did reveal an additional period of enhanced correlation not apparent in the raw data, corresponding to the Manchester earthquake swarm of October 2002. However, as was the case for the raw data (Crockett et al., 2006a), no evidence of simultaneous anomalies temporally associated with these earthquakes was revealed, despite some of the magnitudes exceeding that of the English Channel earthquake. Possible contributory factors include the geology at and between the Manchester and Northampton areas and blurring of anomalies owing to the small temporal separation of these earthquakes. The investigation of techniques to identify simultaneous anomalies is ongoing.

4 Conclusions

The extensions of the techniques used to identify radon anomalies temporally associated with the Dudley and English Channel earthquakes of 2002 have been successfully employed to identify radon anomalies temporally associated with the Market Rasen earthquake of 2008. In all three cases, some of these anomalies occur before the earthquake in question.

More specifically with regard to the techniques, it has been clearly demonstrated that EMD can be used to isolate anomaly-informative IMFs (layers) and so improve the identification of simultaneous short-term radon variations/anomalies. However, use of EMD in practice to detect radon anomalies on a potential earthquake-predictive basis requires further investigation.

Whilst this is work in progress, these results demonstrate that there is the potential for such techniques (and other frequency-filtering techniques) to enhance the possibility that simultaneous real-time monitoring of radon levels for short-term simultaneous anomalies at several locations in earthquake areas might provide the core of an earthquake prediction method.

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