**Natural Hazards
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Comparison of seasonal variability in European domestic radon measurements

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Abstract. Analysis of published data characterising seasonal variability of domestic radon concentrations in Europe and elsewhere shows significant variability between different countries and between regions where regional data is available. Comparison is facilitated by application of the Gini Coefficient methodology to reported seasonal variation data. Overall, radon-rich sedimentary strata, particularly high-porosity limestones, exhibit high seasonal variation, while radon-rich igneous lithologies demonstrate relatively constant, but somewhat higher, radon concentrations. High-variability regions include the Pennines and South Downs in England, Languedoc and Brittany in France, and especially Switzerland. Low-variability high-radon regions include the granite-rich Cornwall/Devon peninsula in England, and Auvergne and Ardennes in France, all components of the Devonian-Carboniferous Hercynian belt.

1 Introduction

In temperate zones, domestic radon concentration levels are generally seasonally dependent, the measured level reflecting convolution of two time-dependent functions, namely the source soil-gas radon concentration itself and the pressure-difference between interior and exterior environment, the principal force driving radon into the building from the soil. While meteorological influence can be regarded as relatively uniform on a European scale, being defined largely by the influence of North-Atlantic weather systems, soil-gas radon, essentially geologically dependent, is generally more variable. The extent of seasonal variability of domestic radon

concentration may therefore be expected to vary with location, and this is found to be the case (Groves-Kirkby et al., 2009).

To compensate for domestic radon variability when assessing long-term health risks, individual short-term measurement results are conventionally converted to equivalent mean annual levels by use of a multiplier Seasonal Correction Factor (SCF) (Pinel et al., 1995), typically derived from measurements of a large number of homes, reflecting the period of the year during which the measurement took place. Following concern as to the universal applicability of a single SCF set, studies in the United Kingdom (UK) (Pinel et al., 1995; UKCC, 2002) and France (Baysson et al., 2003) have reported location-specific SCF sets for different regions of each country. UK SCFs differ significantly from those applicable in Continental Europe and elsewhere in both amplitude and phase, supporting the thesis (Denman et al., 2007) that seasonal variability in indoor radon concentration cannot realistically be compensated for by a single national or international SCF correction policy.

2 Method

Published data characterizing seasonal variability of national domestic radon concentrations was collated and analyzed, in order to identify correlations between published datasets and local geographic/geological conditions. This data included regional SCF figures from the UK (Pinel et al., 1995; UKCC, 2002) and from France (Baysson et al., 2003), together with nationally-consolidated results from a number of other countries in Europe and elsewhere in the Northern Hemisphere.

While processing this data, the authors became aware of the use of the Lorenz Curve (Lorenz, 1905) and Gini Coefficient, G, (Gini, 1913) as tools for analysing and quantifying
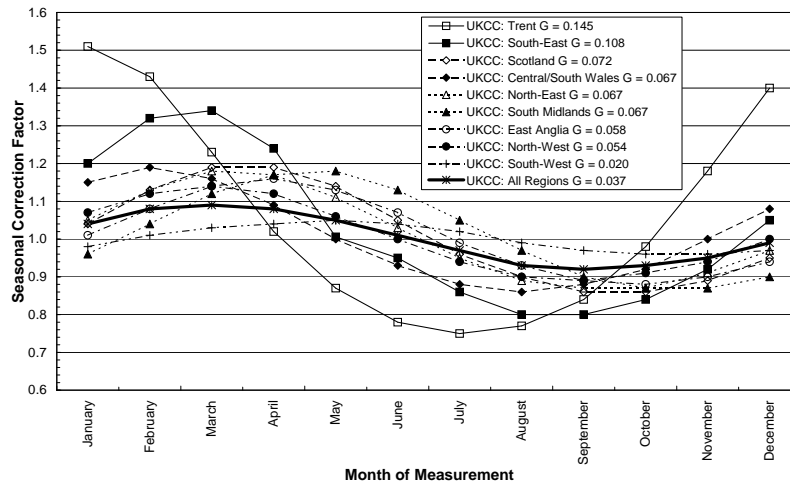

Fig. 1. Regional variation of Seasonal Correction Factors for 6-month exposures in Great Britain (UKCC, 2002) with derived values of the Gini coefficient.

data representing non-uniform socio-economic distributions, and identified an analysis of seasonal data (Lee, 1996) which interpreted the Gini Coefficient as a probability function characterising temporal clustering. Following this approach, we recently reported single-parameter characterisation of seasonal radon variability via the Lorenz Curve and the Gini Coefficient (Groves-Kirkby et al., 2009). Gini coefficients were derived from each SCF data set, using the following methodology:

1. for each month for which either SCF or mean radon concentration data are available, the fraction of the total annual exposure experienced is calculated, taking account of the variable month length of the Gregorian calendar;

2. months are ranked by increasing exposure fraction;

3. using the ranked data, the Gini Coefficient, G, is calculated using the formula given by Brown (1994):

$$G = \left| 1 - \sum_{k-1}^{n} (X_{k-1})(Y_k - Y_{k-1}) \right| \quad (1)$$

where:

X_k is the cumulative fractional elapsed time for $k = 0, \ldots n$, with $X_0 = 0$, $X_1 = 1$;

Y_k is the cumulative fractional radon exposure for $k = 0, \ldots n$, with $Y_0 = 0$, $Y_1 = 1$.

In the context of radon concentration seasonality, a Gini Coefficient of 0 indicates that radon concentration levels are uniform throughout the year. A coefficient of 1 indicates that all of the exposure occurs within one measuring period (e.g. 1 month for 1-month measurements). It does not indicate

during which measuring period that exposure occurs. Values for radon seasonality are in the range 0.05 to 0.3, where higher values indicate increased seasonal variability.

3 Geographic/geological analysis

3.1 United Kingdom

The UK Childhood Cancer collaboration (UKCC, 2002) investigated domestic radon gas as a carcinogen, reporting monthly SCFs for geographical regions within Britain and for the island as a whole. Figure 1 presents the seasonal variability of the regional SCFs graphically, while Table 1 summarises Gini Coefficients from this and other reported UK datasets. While all regions show seasonal variability, significant inter-regional differences also exist. Gini Coefficients range from 0.02 in South-West England to 0.145 in the Trent Region, while a wide region, ranging from East Anglia to Wales and extending North to Scotland, shows values of G in the range 0.05–0.07. Finally, national-average SCFs reported by UKCC (2002) and the UK Health Protection Agency (HPA) (Wrixon et al., 1988; Woods et al., 2000) give values for G of 0.037 and 0.038 respectively, showing very good agreement considering that these were derived from independent experimental studies.

In ascribing origins for SCF variability, the geography of the extreme values, 0.02 in the granite-rich south-west peninsula and 0.145 in the limestone-based south-Pennines, both known high-radon areas, offers insight. Devon and Cornwall both form part of the Devonian-Carboniferous Hercynian orogenic belt (Ziegler, 1990), which extends from the Iberian peninsula through South-West Ireland and South-West England to France and Germany. The dense uranium-rich granite batholith in Devon and Cornwall provides a constant radon

Table 1. Seasonal variation of domestic radon concentrations in the UK.

Region	Source	Dataset	Gini Coefficient	(Max–Min)/ Mean
South-West	UKCC, 2002	731	0.020	0.090
North-West	UKCC, 2002	772	0.054	0.248
East Anglia	UKCC, 2002	467	0.058	0.277
Central/South Wales	UKCC, 2002	538	0.067	0.326
North-East	UKCC, 2002	745	0.067	0.307
South Midlands	UKCC, 2002	573	0.067	0.306
Scotland)	UKCC, 2002	860	0.072	0.326
South-East	UKCC, 2002	429	0.108	0.526
Trent	UKCC, 2002	563	0.145	0.715
All Regions	UKCC, 2002	5678	0.037	0.169
UK – NRPB	Wrixon et al., 1988		0.195	1.204
UK	Woods et al., 2000	2093	0.194	1.184
South-West	Pinel et al., 1995		0.113	0.541

flux, its location close to the surface and strongly fissured nature suggesting a relatively constant emanation rate throughout the year. In contrast, the geology in the Trent region comprises porous Carboniferous limestone in the Pennines and Jurassic bedrock overlain by permeable soils in the Trent valley and Lincolnshire Wolds. This is a combination where the influence of climatic effects, particularly air convection within the ground (Arvela et al., 1988), can be expected to be more significant (Eaton and Scott, 1984). The observed Gini coefficient, 0.145, supports this expectation. Intermediate, with $G = 0.108$, is South-East England, underlain by Cretaceous rocks with relatively low radon potential.

3.2 France

Baysson et al. (2003) studied radon seasonality in France using data from the whole country and from a case-control study in five principal regions. Regional variability was comparable with that within the UK, and Gini coefficient analysis is summarised in Table 2. Auvergne and Ardennes, with $G = 0.03$, are also parts of the Hercynian belt, with comparable lithology to Devon and Cornwall and, particularly in Auvergne, with igneous rocks close to the surface. The low values of G found in these regions are therefore not unexpected on the basis of the previous argument. The Languedoc and Bretagne regions of France, also underlain by igneous rocks, exhibit more extensive and diverse superficial sedimentary geology, suggestive of the observed relatively high values of G, 0.095, with Languedoc influenced by the Pyrenees massif. The overall national Gini Coefficient, $G = 0.050$, is slightly higher than that of UK.

3.3 Other continental Europe locations

Table 3 summarises seasonal radon variability reported from other European countries. With $G = 0.223$, Switzerland

Table 2. Seasonal variation of domestic radon concentrations in France (Baysson et al., 2003).

Region	Dataset	Gini Coefficient	(Max–Min)/ Mean
Auvergne	315	0.030	0.130
Ardennes	329	0.033	0.159
Limousin	587	0.043	0.199
Languedoc	294	0.095	0.448
Bretagne	656	0.096	0.449
All Regions	11186	0.037	0.169

(Tapia et al., 2006), at the centre of the extensive ongoing Alpine orogeny and with much of the densely inhabited areas overlain with light, porous, recent sediments, exhibits the greatest level of European seasonality yet encountered. Comparable variability ($G = 0.21$) is found in a single study from Italy (Azimi, 1996), likewise a region of relatively recent geological activity still prone to seismic events. In contrast, the Gini coefficients of 0.13 and 0.14 from Poland (Karpinska et al., 2004) and Ireland (Madden et al., 1994) respectively are comparable to figures from the English Midlands, reflecting the relatively stable sedimentary geology found in both areas.

3.4 North America/Asia/Australasia

USA seasonality data are limited, with values for G ranging from 0.065 in North Dakota (Momčilović et al., 2007) to 0.223 in Minnesota (Steck et al., 2004) (Table 4). Outside the USA, $G = 0.227$ is found in the Winnipeg, Manitoba, Canada (Krewski et al., 2005), while the highest value so far identified worldwide, $G = 0.265$, is found in Amritsar, India (Singh et al., 2008). Winnipeg is situated on the recent deep

Table 3. Seasonal variation of domestic radon concentrations in European countries.

Country	Source	Dataset	Gini Coefficient	(Max–Min)/ Mean
Poland	Karpinska et al., 2004	10	0.132	0.704
Ireland	Madden et al., 1994		0.142	0.759
Austria	Bossew and Lettner, 2007	7280	0.167	1.030
Italy (Roma)	Azimi, 1996	120	0.214	1.328
Switzerland	Tapia et al., 2006		0.223	1.525

Table 4. Seasonal variation of domestic radon concentrations in Northern Hemisphere countries outside Europe.

Country	Source	Dataset	Gini Coefficient	(Max–Min)/ Mean
USA (ND)	Momčilovič and Lykken, 2007	2492	0.065	0.373
USA (MN)	Steck et al., 2004	1	0.223	1.486
Canada (Winnipeg)	Krewski et al., 2005		0.227	1.113
India (Amritsar)	Singh et al., 2008	1	0.265	1.382

clay bed of pre-historic glacial Lake Agassiz (Upham, 1895), while Amritsar, on the Punjab plain, is located on granite bedrock overlain with several hundred metres of quaternary limestones and dolomites (Kochar, 2004). Since glacial sediments are known to be susceptible to enhanced radon permeability (Arvela et al., 1988), and since radon mobility in permeable strata is known to be sensitive to climatic influences (Arvela et al., 1994), the enhanced seasonal variability in these strata, as confirmed by the high values for G, is not surprising.

4 Conclusions

Analysis of published SCF data shows significant differences in seasonal variability between different countries and different regions within those countries. On the basis of the limited available data, it is possible to draw tentative conclusions as to the relationship between underlying geology and seasonable radon variability. Radon-rich sedimentary strata, particularly high porosity limestones etc., exhibit high seasonal variation, while radon rich igneous geologies demonstrate relatively constant, but somewhat higher, radon concentration levels. Examples of the former can be found in the Pennines and Trent valley in England, and in Languedoc and Bretagne in France, where values of G range from 0.07 to 0.14. Low-variability high-radon regions include the granite-rich Cornwall/Devon peninsula in England, and Auvergne and the Ardennes in France, where values of G are significantly lower (0.02–0.03). The dense uranium-rich granite dominating Devon and Cornwall is strongly fissured and located close to the surface, suggesting a high, yet rel-

atively constant, emanation rate throughout the year. Locally, the Devon/Cornwall granites are subject to greisenisation. This post-magmatic process, associated with high-silica granites, leads to feldspar and mica decomposition (and thence to changes in permeability), polymetallic mineral formation, localised texture and uranium content variations. Although these all have the potential to introduce elements of geographic variability, this spatial detail is inevitably lost when data collected across an extended geographical region is consolidated, as in the present case. Moderate-variability high-radon regions, including the deep sedimentary Jurassic and Cretaceous of central and south-eastern England, Ireland and the plains of eastern Poland, all show intermediate values of G.

The Gini Coefficient would appear to provide a convenient single index of seasonal radon variability. However, the loss of the time dimension might empirically be thought to be problematic, and have the potential to hide important features of such a variation, such as a sharp single peak in radon levels. However, as a result of the seasonal radon variation being essentially sinusoidal, the Gini Coefficient tracks the difference between minimum and maximum radon levels with a high degree of correlation ($R^2 > 0.9$), as shown in the final column of each table, thus supporting its value in this application.

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