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Seasonal variation of radon concentrations in UK homes

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Abstract
The patterns of seasonal variation of radon concentrations were measured in 91 homes in five regions of the UK over a period of two years. The results showed that there was no significant difference between the regions in the pattern or magnitude of seasonal variation in radon concentrations. The arithmetic mean variation was found to be close to that found previously in the UK national survey. Differences in the pattern between the two years of the study were not significant. Two-thirds of homes in the study followed the expected pattern of high radon in the winter and low radon in the summer. Most of the rest showed little seasonal variation, and a few showed a reversed seasonal pattern. The study does not provide any clear evidence for the recorded house characteristics having an effect on the seasonal variation in radon concentrations in UK homes, though the statistical power for determining such effects is limited in this study. The magnitude of the seasonal variation varied widely between homes. Analysis of the individual results from the homes showed that because of the wide variation in the amount of seasonal variation, applying seasonal correction factors to the results of three-month measurements can yield only relatively small improvements in the accuracy of estimates of annual mean concentrations.

(Some figures may appear in colour only in the online journal)

1. Introduction

A number of studies have shown that indoor radon concentrations in various countries typically vary with the seasons (Wrixon *et al* 1988, Majborn 1992, Steck 1992, Pinel *et al* 1995, UKCCSI 2000, Baysson *et al* 2003, Krewski *et al* 2005, Denman *et al* 2007, Burke *et al* 2010). These have shown that the most common pattern of variation is a high concentration in winter and a low concentration in summer, though some homes show a reversed pattern or no clear pattern. Work in the US (Steck *et al* 2004) has noted that well sealed energy efficient homes with central heating and cooling exhibited reduced seasonal variability, although due to the more temperate UK climate, this type of home is uncommon. Specific geological formations with very high permeabilities, such as eskers, are known to cause anomalous seasonal radon patterns in some homes (Arvela *et al* 1988, 1994), but such geological formations underlie an extremely small proportion of UK homes. Wrixon *et al* (1988) analysed data collected in the UK national survey of radon, using results from 2093 homes which were each measured over two six-month periods, spread over several years. They found that the mean indoor radon concentration reached a maximum in January and a minimum in July. Pinel *et al* (1995) studied the results from 1873 homes in South West England which were monitored for one six-month period each. Although the area covered by this study was very different from that covered by the UK national survey, Pinel *et al* (1995) reported that the seasonal variation found corresponded very closely to that found by Wrixon *et al*.

Despite the general agreement on the typical pattern of variation, the magnitude of the variation found differs between studies, and areas of uncertainty remain. Miles (2001) showed that some homes have patterns of variation that are influenced by wind speed and direction more than by outdoor temperature, and some homes have little seasonal variation or a reversed pattern. UKCCSI (2000) analysed results from measurements over a single six-month period in 5678 homes in England, Wales and Scotland, and found differences in seasonal patterns between nine areas. Denman *et al* (2007) studied 34 houses in Northamptonshire, UK, and found deviations from the seasonal pattern reported by Wrixon *et al* (1988) and Pinel *et al* (1995).

All of the earlier UK studies referred to were based on data which had been collected for purposes other than determining the pattern of seasonal variation in radon concentrations. The concentrations found in the larger studies (Wrixon *et al* 1988, Pinel *et al* 1995, UKCCSI 2000) were generally low, with the result that measurement uncertainties were often comparable in magnitude to the variations being measured. These studies also suffered from the disadvantage that measurements were made over six-month periods: two consecutive periods in each home in the case of Wrixon *et al* (1988) and a single period in each home in the cases of Pinel *et al* (1995) and UKCCSI (2000). Determining seasonal variation in radon concentrations in individual homes is impossible with data of this type. In order to determine average seasonal variation, it is necessary to group house measurement data according to the month in which measurements started, using sufficiently large numbers of homes so that the substantial differences in concentrations between homes that happened to start measurements in different months are averaged out. The relatively small study by Denman *et al* (2007) included one-month and three-month measurements in 34 homes in Northamptonshire, over a 12-month period. Interpretation of the results was complicated by the fact that the etched-track detectors used suffered from high background track densities (Phillips *et al* 2004).

Because of the drawbacks of these earlier studies, it was decided to carry out a new study, specifically designed to measure the pattern of seasonal variation in radon concentrations in UK homes. The study reported here was designed to determine whether there were significant differences in the pattern of seasonal variation between different parts of the UK, and to determine the proportion of homes which deviate from the typical pattern. The data also allowed an analysis of the effects of applying seasonal correction factors based on the typical pattern of variation to radon measurement results from homes that do not follow the typical pattern.

2. Materials and methods

The householders who were approached to take part in this study were selected from among those whose homes had previously been measured by the Health Protection Agency (HPA) between 2002 and 2005, as part of surveys of homes in high radon areas funded by the UK government. Homes were originally measured over a period of three months, and annual mean radon concentrations estimated using the correction factors given by Howarth and Miles (2008). The homes were not clustered, but spread over large areas. Only homes previously found to have estimated annual mean radon concentrations between 75 and 125 Bq m^{-3} were included in the study. This range of concentrations was chosen so that the uncertainties associated with the measurements would be small compared with the measured concentrations, but the concentrations were not so high that the householders had been advised to take remedial action to reduce the concentrations, as such action could affect the seasonal pattern.

A total of 119 UK households were recruited to take part in a two-year study. Approximately equal numbers of households were recruited from five different regions of the UK: North East England, South West England, Northern Ireland, Scotland and Wales. Within each of these regions the homes recruited were on a range of different geological units. Some units which have a substantial effect on indoor radon concentrations are present within some regions but absent from others, such as the granites which are present is South West England but absent from North East England. Some differences in the degree or pattern of seasonal variation in radon might be expected between these regions because of differences between them in their geology, climate, building styles and in the Building Regulations that apply. Although England and Wales have a common set of Building Regulations, Scotland and Northern Ireland each have separate regulations.

Measurements were made over eight consecutive three-month periods from November 2005 to November 2007 in the living rooms and bedrooms of the homes. The measurement periods were November to February, February to May, May to August, and August to November to correspond with the seasons. Measurements were carried out using the HPA passive radon detector (Miles *et al* 2004). Householders were asked to complete a questionnaire about the type of home, the date of building and various characteristics of the home. Detectors were sent out by post. Mean radon concentrations for each home for each three-month period were calculated using a weight of 0.45 for living room results and 0.55 for bedroom results (Wrixon *et al* 1988).

Although this study covers a relatively small number of homes, it has considerable advantages over earlier studies. In particular, the mean concentrations in homes in the larger earlier studies were only a factor of two or three higher than the uncertainties on the measurements, so that in most cases calculation of seasonal variation for individual homes was not feasible as the uncertainties would be too large. Such studies had to use averages across numbers of homes, so could not estimate the proportions of homes for which applying seasonal correction factors improved the estimate of annual average radon concentration. The study reported here is the first study in the UK to allow such calculations. It is also the first to measure radon concentrations in substantial numbers of homes using multiple measurements over two full years.

3. Results

The numbers of homes measured in different regions are shown in table 1. At the end of the study, 91 homes had a complete set of eight results. Analysis here is confined to those homes with eight complete results.

Gunby *et al* (1993) showed that the overall distribution of radon concentrations in UK homes was consistent with the lognormal distribution. Although the homes in this study were chosen from those found earlier to have a limited range of radon concentrations, the distribution of the 728 radon concentrations in eight three-month periods in 91 homes appears

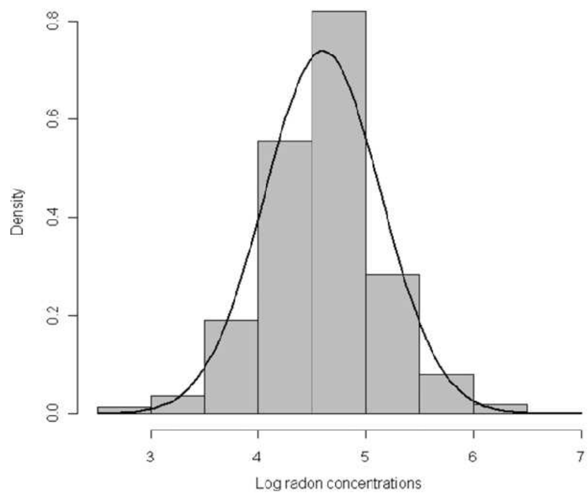

Figure 1. Histogram (with a normal density curve) of average radon concentration (Bq m^{-1}) in 91 homes under a logarithmic transformation.

Table 1. Numbers of homes starting and completing the study.

Region	Number of homes starting measurements	Number completing with eight three-month results
North East England	23	16
South West England	27	23
Northern Ireland	23	19
Scotland	22	18
Wales	24	15
Total	119	91

to be lognormally distributed except for a few values at the lower end (figure 1). The Shapiro–Wilk test is used for testing normality: if the test statistic is significant ($P < 0.05$), then the hypothesis that the distribution is normal should be rejected. The Shapiro–Wilk W test produced a large probability ($P = 0.98$) for the log radon data, suggesting that the log radon data are compatible with a normal distribution.

The arithmetic mean (AM) and the geometric mean (GM) radon concentrations in the homes are shown in table 2. Means were also calculated for subsets of the data with various characteristics in common: region, single or multiple storey, glazing type, draught proofing, floor type and house type. The AM radon concentration of all 728 results was 116 Bq m^{-3} (17–698 Bq m^{-3}, GM 100 Bq m^{-3}). Winter and summer AMs were 137 Bq m^{-3} (18–698 Bq m^{-3}, GM 119 Bq m^{-3}) and 88 Bq m^{-3} (17–403 Bq m^{-3}, GM 76 Bq m^{-3}) respectively. Regional AM ranged from 100 Bq m^{-3} (GM 97 Bq m^{-3}) in Wales to 138 Bq m^{-3} (GM 124 Bq m^{-3}) in North West region. Single storey homes, those with suspended flooring, double-glazing, draught-proofing or a mid-terrace position had the highest average radon measurement in winter, while in the summer homes with these characteristics had the lowest radon concentration, albeit these differences between grouping variable were not statistically significant.

Table 2. Summary statistics for winter, summer and overall average radon concentrations in 91 homes, based on 8 consecutive three-month measurements over two years, a total of 728 measurements.

		Winter (Bq m^{-3})		Summer (Bq m^{-3})		All three-month measurement results (Bq m^{-3})			
	No. of homes	AM	GM	AM	GM	Min.	Max.	AM	GM
Region									
North East (NE)	16	165	140	99	91	18	420	138	124
Northern Ireland (NI)	19	136	106	83	70	17	698	109	92
Scotland (SC)	18	139	128	94	81	28	355	119	111
South West (SW)	23	129	116	90	74	23	490	114	103
Wales (WA)	15	120	112	71	66	23	262	100	97
Storey									
Single	28	150	130	77	69	17	698	117	105
Multiple	49	126	114	91	80	31	490	112	103
Unknown	14	149	121	99	83	18	562	126	108
Double glazing									
Full	60	140	125	78	73	23	698	113	105
Partial or none	21	119	78	94	76	17	490	109	72
Unknown	10	161	126	130	108	18	562	146	120
Draught proofing									
Full	21	147	120	72	67	17	698	113	99
Partial or none	45	130	117	91	81	31	490	116	106
Unknown	25	141	126	95	78	18	562	119	107
Floor type									
Solid	49	134	118	91	78	17	698	115	104
Mixed	18	135	123	74	69	23	418	110	103
Suspended	12	150	135	78	72	28	420	121	109
Unknown	12	140	113	106	90	18	562	124	106
House type									
Detached	60	127	114	85	73	17	490	109	99
Semi-detached	14	144	130	90	86	43	418	124	116
Mid-terraced	3	263	208	79	75	43	698	157	138
Flat	2	133	133	82	69	36	168	104	101
Other	3	147	132	73	72	60	273	115	109
Unknown	9	150	117	114	96	18	562	132	110
All homes	91	137	119	88	76	17	698	116	100

The arithmetic mean radon concentrations by region and by measurement period are shown in figure 2. The pattern and magnitude of variation is remarkably consistent between the regions, despite the differences in geology, climate, building style and Building Regulations. All regions show the expected summer low and winter high radon concentrations.

Figure 3 shows the arithmetic means of all results in this study, grouped by measurement period. The results of this study are compared in this figure with the results expected from the seasonal variation found in the UK national survey (Wrixon *et al* 1988), for the same times of year of measurement. For this purpose, the monthly variation shown in figure K9 of Wrixon *et al* (which was also based on arithmetic mean) was grouped into suitable three-month periods and normalised to the mean concentration of all results found in this study.

Estimated radon concentrations based on the mean outdoor temperatures during the exposure periods (calculated using the relationship derived by Miles (1998)) are also plotted in figure 3. Temperature records for the regions at the time of the measurements were obtained

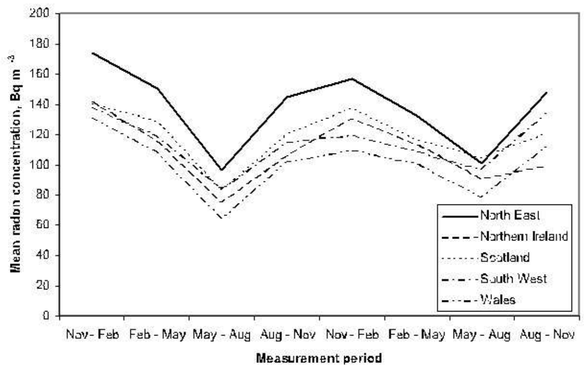

Figure 2. Variation in arithmetic mean radon concentrations over the study period, by region.

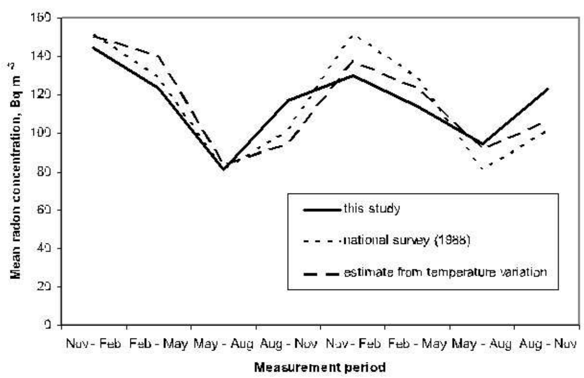

Figure 3. Variation in arithmetic mean radon concentrations over two years in this study compared with results expected based on the seasonal variation found in the UK national survey and those expected based on the variation in outdoor temperature during the study.

from data published by the Meteorological Office. The pattern of variation found in this study is not significantly different either from that found by Wrixon *et al* (1988), or from that derived using Miles's temperature corrections ($P = 0.94$). This is notable in view of the fact that the mean radon concentration in this study was 116 Bq m^{-3}, compared with 22 Bq m^{-3} in Wrixon *et al*'s study, implying that the pattern is consistent across the range of radon concentrations found in 98% of UK homes.

4. Statistical analysis

4.1. Seasonality index

To assist in the analysis, a 'seasonality index' was devised, calculated for each home by dividing the mean of the two winter measurement results (November–February) for each home by the mean of the two summer measurement results (May–August). The normal seasonal pattern of variation with high radon concentrations in winter and low concentrations in summer gives a seasonality index greater than one. Of the homes in this study, 18% had a seasonality index less than one, and 82% had an index greater than one. The distribution of seasonality indices is

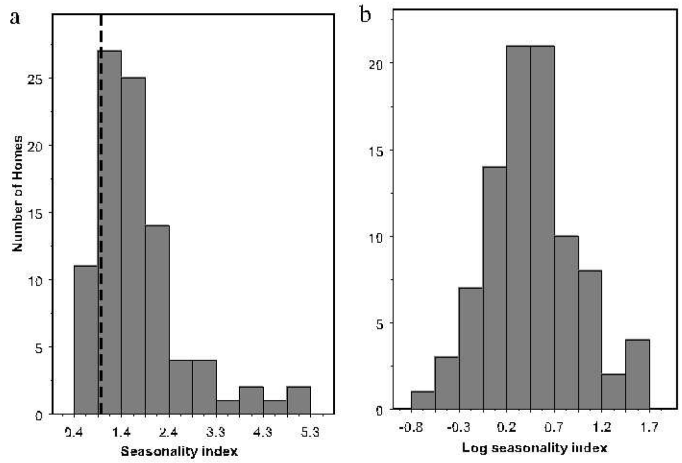

Figure 4. Numbers of homes with different seasonality indices. (a) Raw data, the seasonality index value 1 is marked as a vertical line; (b) after log transformation.

Table 3. Percentages of homes with different degrees of seasonal variation.

Pattern of seasonal variation	Seasonality index	% of homes (%)
Winter low, summer high	<0.75	4
Little variation	0.75–1.25	27
Winter high, summer low	>1.25	68

shown in table 3 and figure 4. The results show that about two-thirds of the homes tested had a substantial seasonal variation with winter high and summer low. About a quarter of homes had little seasonal variation, and a small percentage had a reversed seasonal variation.

The distribution of seasonality indices in figure 4(a) is highly skewed and not near to a normal distribution. However, after a log transformation the data have a nearly normal distribution, as shown by figure 4(b). This suggests that it would be more appropriate to use the geometric mean value of seasonality index than the arithmetic mean when analysing these results. It is also important to apply a log transformation to the seasonality index before carrying out multivariate analysis on the data, as normality of the data is assumed in the multivariate regression model.

4.2. Multivariate analysis

Multivariate analysis was carried out to investigate the relationship between house characteristics and seasonality index and also to examine whether the seasonality index varies between regions in the UK. Table 4 shows the mean seasonality index for the data grouped by such characteristics. The ratio appears to be higher for homes in Wales, detached homes, single storey buildings, fully double glazed homes, draught proofed homes and for those with suspended flooring.

Multivariate regression analysis was performed, using logarithmically transformed data for the seasonality index as a dependent variable and region and house characteristics (region, house type, ground floor type, glazing type, draught proofing, single storey) as independent variables. Using backward stepwise regression, only glazing type and number of storeys

Table 4. Summary statistics for the seasonality index of the 91 homes.

		Seasonality index	
	N	AM	GM
Region			
North East England	16	1.75	1.55
Northern Ireland	19	1.73	1.51
Scotland	18	1.80	1.56
South West England	23	1.80	1.55
Wales	15	1.99	1.67
Storey			
Single	28	2.16	1.88
Multiple	49	1.60	1.44
Double glazing			
Full	60	1.91	1.71
Partial or none	21	1.74	1.39
Draught proofing			
Full	21	1.99	1.81
Partial or none	45	1.56	1.43
Floor type			
Solid	49	1.77	1.51
Mixed	18	2.02	1.78
Suspended	12	2.06	1.88
House type			
Detached	60	1.80	1.57
Semi-detached	14	1.69	1.53
All homes	91	1.81	1.57

Table 5. Summary of the multivariate analysis of house characteristic for seasonality index derived from 91 homes.

Fixed effect parameters	N = count	Estimates (95% CI)	p-value	p-value for heterogeneity
Intercept	728	1.64 (1.18–2.27)	<0.01	
Double glazing				
Full	60	1		
Partial or none	21	0.93 (0.73–1.18)	0.57	0.03
Unknown	10	0.46 (0.29–0.74)	0.002	
Storey				
Single	28	1		
Multiple	49	1.24 (1.00–1.54)	0.04	0.03
Unknown	14	1.45 (1.00–2.11)	0.05	

showed significant relationships ($p < 0.05$) with radon concentrations. The rest of the variables were dropped from the model.

The results from the final model are presented in table 5. There are statistically significant differences between categories in glazing type and in storey. The main category driving differences between glazing types is 'glazing type unknown'. As we have no information about glazing for this category, finding a difference is of no value. For the storey categories, the homes with multiple storeys had slightly higher seasonality indices than homes with single storeys, though marginally significant ($p = 0.04$). It is therefore concluded that although this study does not provide any clear evidence for the recorded house characteristics having an

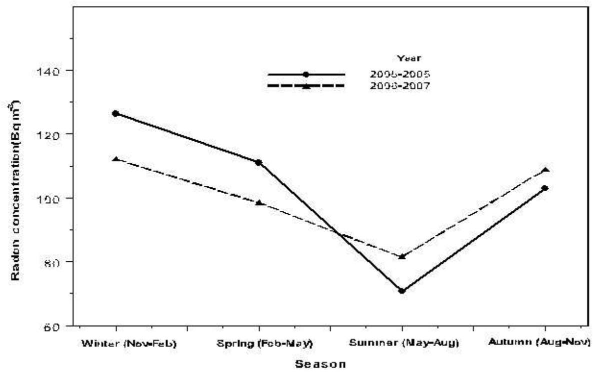

Figure 5. Geometric mean (GM) radon concentrations for eight consecutive three-month measurement periods, aligning the seasons in the two years.

effect on the seasonal variation in radon concentrations in UK homes, the number of storeys and double glazing were found to have a weak association. The suggestion by UKCCSI (2000) and Denman *et al* (2007) that different regions of the UK may have different patterns or magnitudes of seasonal variation is not supported.

4.3. Sinusoidal variation of geometric mean

Figure 5 shows the geometric mean radon concentrations that were found for homes in the four seasons for two consecutive years. Clearly the radon concentration was highest in winter (November–February) and lowest in summer (May–August) for both years 2005–6 and 2006–7. Although there is a small difference between years in radon concentrations in homes, the difference is not statistically significant ($p = 0.74$).

Pinel *et al* (1995) showed that radon concentrations in homes in South West England had a regular sinusoidal pattern with a period of 12 months, and they fitted a sine–cosine curve to derive the seasonal correction factors. The model was defined as:

$$m_t = \mu + A\sin(\omega t) + B\cos(\omega t) \tag{1}$$

where m_t is the geometric mean of the observed radon value at time t ($t = 1, \ldots, 12$ months); μ is the mean value of radon concentration and $\omega = 2\pi/\tau$ where τ is the period or cycle length ($\tau = 12$). The parameters A and B indicate how much weight to give to the sine and cosine components. The parameters μ, A and B can be estimated using least square regression methods to obtain the best fit. Pinel *et al*'s methods have been used by scientists in other countries to assess seasonal correction factors (Baysson *et al* 2003, Krewski *et al* 2005, Burke *et al* 2010).

Because the data in this study includes only three-month measurements in the four seasons, rather than in twelve separate months, it is not possible to apply the model in equation (1) directly to the data. In particular, the data cannot be used to identify in which months the maximum and minimum radon concentrations occur.

A cycle with a period of four seasons was fitted to the geometric mean of measured radon concentration. The data was fitted to equation (1) with the value of ω set at $2\pi/4$. In order to obtain estimates of the weights for the cosine and sine terms, least squares regression analysis was used. The equation that describes the cyclic pattern for this data is:

$$m_t = 101 + 21.6\cos(\omega t) + 0.58\sin(\omega t). \tag{2}$$

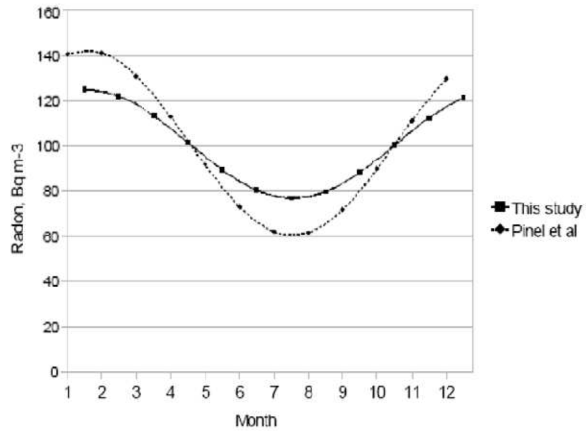

Figure 6. Sinusoidal fit of monthly geometric radon concentrations for the new study (solid line) and those presented by Pinel *et al* (1995), normalised to the same geometric mean radon concentration (dashed line). Note the values for this study refer to the middle of each month, whereas Pinel *et al*'s refer to the first day of each month.

From the fit of the data, the four-season cycle accounts for 83% of the variance in the observed radon concentration. In order to apply this relation to monthly mean radon concentrations, it is necessary to identify in which months the maximum and minimum radon concentrations occur. Data from other studies was used to provide this information. Wrixon *et al* (1988) assigned all results starting on any day in a particular month to that month, and found that the maximum and minimum radon concentrations occurred in January and July. Pinel *et al* (1995) assigned a measurement to a particular month if it started between the middle of the previous month and the middle of month of assignment, in effect calculating variation for monthly periods centred on the first day of each month. They found that the maximum radon concentration occurred with almost equal values for January and February, but because their dates are referred to the first day of each month, this implies a maximum in the calendar month of January, as with the Wrixon *et al* data. Similarly for the month with the minimum concentration, the Pinel *et al* (1995) data are consistent with the minimum in July as found by Wrixon *et al* (1988). For this work it will therefore be assumed that the maximum and minimum UK radon concentrations occur in January and July.

Equation (2) also requires correction for the fact that a three-month radon measurement averages the concentration in the month with the maximum concentration with those in adjacent months which have lower concentrations. A similar effect occurs with the minimum of the variation. The maximum and minimum values of equation (2) are therefore lower than would have been found if monthly measurements had been made. Because the pattern of variation assumed is sinusoidal, it is simple to correct for this difference. The revised relation, taking into account the effect of three-month measurements and assigning the maximum and minimum concentrations to January and July, is given in the following model:

$$m_t = 101 + 24\cos(\pi(t - 1.5)/6) + 0.64\sin(\pi(t - 1.5)/6). \quad (3)$$

Figure 6 shows the sinusoidal fit for the monthly geometric mean of radon concentrations for this new data using equation (3). The data from Pinel *et al* (1995) are also shown, shifted by half a month to take account of the fact that their data are referred to the start of the month rather than the middle. The data from Pinel *et al* (1995) are more appropriate for comparison here than the data from Wrixon *et al* (1988), since the Wrixon *et al* (1988) data showed arithmetic

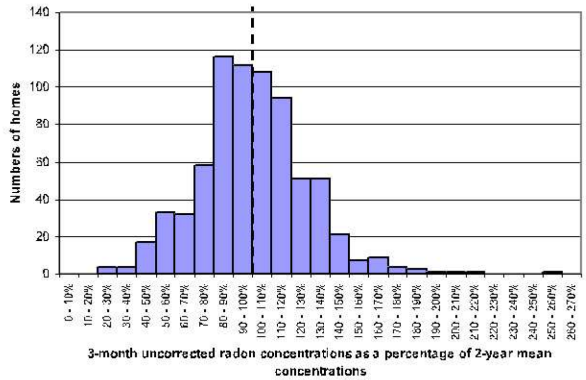

Figure 7. Comparison of three-month uncorrected radon concentrations with the two-year mean concentrations in the same homes.

means, whereas the new analysis and Pinel *et al*'s analysis are based on geometric means. The patterns of variation are necessarily similar since both are based on a sinusoidal form, with the maximum in equation (3) set at the middle of January. Pinel *et al*'s study shows a somewhat greater magnitude of variation than the current study.

5. Seasonal correction factors

Figure 7 shows the distribution of ratios of uncorrected three-month mean radon concentrations to the two-year mean results in the same homes. About three-quarters of three-month results are within 30% of the two-year mean, while some are more than a factor of two different from the two-year mean.

Seasonal correction factors are used to allow estimates to be made of the annual mean radon concentrations in homes which are measured over a shorter period than a year. The seasonal correction factors given in Howarth and Miles (2008) and the temperature correction factors given in Miles (1998) were based on the seasonal variation reported by Wrixon *et al* (1988). That pattern of seasonal variation was based on arithmetic mean values of radon concentrations found in the national survey of radon in the UK. The finding above that the seasonality index is more likely lognormally distributed than normally distributed suggests that geometric mean values would be more appropriate than arithmetic mean values as the basis of correction factors. Seasonal correction factors based on equation (3) were calculated and are shown in table 6.

The 728 three-month results from this study were corrected to estimated annual mean concentrations using different methods: (1) no correction; (2) seasonal correction factors given in Howarth and Miles (2008); (3) temperature correction factors based on Miles (1998); (4) seasonal correction factors from table 6. The results are shown in table 7. In addition, results are shown for uncorrected results for spring and autumn results only. Majborn (1992) suggested that restricting radon measurements to only these seasons could improve the accuracy of estimated annual mean concentrations, because winter and summer results were generally further from the annual mean. This table shows the percentage of all corrected three-month results that are within 30% of the actual 2-year mean concentration for the home. The choice of 30% is somewhat arbitrary: it was chosen to allow a comparison of the effects of the use of different corrections (or no correction) when reporting results.

Table 6. Seasonal correction factors for radon measurements starting in any month, and with duration 1–11 months

Start month	Duration (months): 1	2	3	4	5	6	7	8	9	10	11
1	0.81	0.82	0.84	0.88	0.98	0.98	1.03	1.06	1.07	1.06	1.05
2	0.83	0.86	0.90	0.96	1.07	1.07	1.10	1.10	1.09	1.07	1.05
3	0.89	0.94	1.00	1.07	1.14	1.14	1.14	1.12	1.10	1.07	1.05
4	0.99	1.06	1.13	1.17	1.18	1.18	1.16	1.12	1.09	1.06	1.04
5	1.13	1.19	1.23	1.24	1.18	1.18	1.14	1.10	1.07	1.05	1.03
6	1.25	1.28	1.28	1.24	1.15	1.15	1.10	1.06	1.04	1.02	1.02
7	1.31	1.29	1.24	1.18	1.08	1.08	1.04	1.01	1.00	1.00	1.01
8	1.26	1.20	1.14	1.08	0.99	0.99	0.97	0.96	0.96	0.98	1.00
9	1.14	1.07	1.02	0.97	0.92	0.92	0.91	0.92	0.95	0.98	1.01
10	1.01	0.95	0.91	0.89	0.88	0.88	0.89	0.92	0.96	0.99	1.02
11	0.90	0.86	0.85	0.84	0.87	0.87	0.91	0.95	0.99	1.02	1.03

Table 7. Effects of different types of correction on the accuracy of estimates of annual mean radon concentrations

Type of correction applied to three-month result to obtain estimate of annual mean concentration	Percentage of all corrected three-month results that are within 30% of the two-year mean concentration for the home
No correction	74%
Seasonal correction based on Howarth and Miles (2008)	71%
Temperature correction based on Miles (1998)	76%
Seasonal correction based on equation (4)	79%
Use only spring or autumn results	85%

It is clear from the table that the correction factors given in Howarth and Miles (2008) are unsuccessful in improving the accuracy of the majority of individual estimated annual mean concentrations, compared with the uncorrected results. Temperature correction factors and the seasonal correction factors based on equation (3) do, however, produce a modest improvement in the accuracy of estimated annual mean concentrations. This is consistent with the finding of Miles (2001), who noted that, in a smaller dataset, for a three-month exposure, application of a seasonal correction factor modestly improved the accuracy of the result. Denman *et al* (2007) found that exposures of less than 3 months gave variable results, but the variability of 3-month exposures was less, and the seasonal corrections were more modest.

Overall, applying corrections based on the arithmetic or geometric mean variation has little effect on the proportion of corrected results close to the long-term mean concentration. The principal reason for this is the wide range of magnitudes of seasonal variation found in different homes, as demonstrated by the fact that the seasonality index is lognormally distributed. A correction calculated for an average home is either too large or too small for most homes.

Restricting measurements to two seasons provides only slightly better accuracy in estimating long-term means, and has the disadvantage that it would restrict measurement starting times to two short periods, at the start of the spring and autumn seasons. For most radon measurement laboratories, this restriction on measurement programmes would not be feasible in practice.

6. Conclusions

The results of this study are consistent with the average pattern of seasonal variation in UK homes found by earlier studies. No significant difference was found between regions of the UK in the average pattern or magnitude of seasonal variation. The amount of seasonal variation, measured using a seasonality index, varied very widely between homes. The distribution of seasonality index is consistent with a lognormal but not with a normal distribution. There was no clear evidence for the recorded house characteristics having an effect on the amount of seasonal variation in radon concentrations. Because of the wide variation in the amount of seasonal variation, applying seasonal correction factors to the results of three-month measurements can bring only relatively small improvements in the accuracy of estimates of annual mean concentrations.

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References

Arvela H, Voutilainen A, Honkamaa T and Rosenberg A 1994 High indoor radon variations and the thermal behaviour of esker *Health Phys.* **67** 254–260

Arvela H, Voutilainen A, Mäkeläinen I, Castrén O and Winqvist K 1988 Comparison of predicted and measured variations of indoor radon concentration *Radiat. Prot. Dosim.* **24** 231–5

Baysson H, Billon S, Laurier D, Rogel A and Tirmarche M 2003 Seasonal correction factors for estimating radon exposure in dwellings in France *Radiat. Prot. Dosim.* **104** 245–52

Burke Ó, Long S, Murphy P, Organo C, Fenton D and Colgan P A 2010 Estimation of seasonal correction factors through Fourier decomposition analysis-a new model for indoor radon levels in Irish homes *J. Radiol. Prot.* **30** 433–43

Denman A, Crockett R, Groves-Kirkby C, Phillips P, Gillmore G and Woolridge A 2007 The value of seasonal correction factors in assessing the health risk from domestic radon—a case study in Northamptonshire, UK *Environ. Int.* **33** 34–44

Gunby J A, Darby S C, Miles J C H, Green B M R and Cox D R 1993 Factors affecting indoor radon concentrations in the United Kingdom *Health Phys.* **64** 2–12

Howarth C B and Miles J C H 2008 Validation scheme for organisations making measurements of radon in dwellings *2008 Revision. HPA-RPD-047*

Krewski D, Mallick R, Zielinski J M and Létourneau E G 2005 Modeling seasonal variation in indoor radon concentrations *J. Exposure Anal. Environ. Epidemiol.* **15** 234–43

Majborn B 1992 Seasonal variations of radon concentration in single-family houses with different substructures *Radiat. Prot. Dosim.* **45** 443–7

Miles J C H 1998 Mapping radon-prone areas by lognormal modelling of house radon data *Health Phys.* **74** 370–8

Miles J C H 2001 Temporal variation of radon levels in houses and implications for radon measurement strategies *Radiat. Prot. Dosim.* **93** 369–75

Miles J C H, Kendall G M, Ibrahimi Z-F and Howarth C B 2004 Practical procedures for a radon etched track dosimetry service *J. Radiol. Prot.* **24** 165–71

Phillips P S, Denman A R, Crockett R G M, Groves-Kirkby C J and Gillmore G K 2004 Comparative analysis of weekly vs. three-monthly radon measurements in dwellings *Report No. EPG1/4/72: RW 8/17/6* (London: DEFRA)

Pinel J, Fearn T, Darby S C and Miles J C H 1995 Seasonal correction factors for indoor radon measurements in the United Kingdom *Radiat. Prot. Dosim.* **58** 127–32

Steck D J 1992 Spatial and temporal indoor radon variations *Health Phys.* **62** 351–55

Steck D J, Capistrant J A, Dumm J P and Patton E S 2004 Indoor radon exposure uncertainties caused by temporal variation *11th Int. Congr. of the International Radiation Protection Association (Madrid)* (Fontenay-aux-Roses: IRPA)

UKCCSI (UK Childhood Cancer Study Investigators) 2000 The United Kingdom Childhood Cancer Study: objectives, materials and methods *Br. J. Cancer* **82** 1073–102

Wrixon A D, Green B M R, Lomas P R, Miles J C H, Cliff K D, Francis E, Driscoll C M H, James A C and O'Riordan M C 1988 Natural radiation exposure in UK dwellings *NRPB R190* (London: HMSO)