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A critical analysis of climatic influences on indoor radon concentrations: Implications for seasonal correction

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ABSTRACT

Although statistically-derived national Seasonal Correction Factors (SCFs) are conventionally used to convert sub-year radon concentration measurements to an annual mean, it has recently been suggested that external temperature could be used to derive local SCFs for short-term domestic measurements. To validate this approach, hitherto unanalysed radon and temperature data from an environmentally-stable location were analysed. Radon concentration and internal temperature were measured over periods totalling 1025 days during an overall period of 1762 days, the greatest continuous sampling period being 334 days, with corresponding meteorological data collected at a weather station 10 km distant. Mean daily, monthly and annual radon concentrations and internal temperatures were calculated.

SCFs derived using monthly mean radon concentration, external temperature and internal-external temperature-difference were cross-correlated with each other and with published UK domestic SCF sets. Relatively good correlation exists between SCFs derived from radon concentration and internal-external temperature difference but correlation with external temperature, was markedly poorer. SCFs derived from external temperature correlate very well with published SCF tabulations, confirming that the complexity of deriving SCFs from temperature data may be outweighed by the convenience of using either of the existing domestic SCF tabulations.

Mean monthly radon data fitted to a 12-month sinusoid showed reasonable correlation with many of the annual climatic parameter profiles, exceptions being atmospheric pressure, rainfall and internal temperature. Introducing an additional 6-month sinusoid enhanced correlation with these three parameters, the other correlations remaining essentially unchanged. Radon latency of the order of months in moisture-related parameters suggests that the principal driver for radon is total atmospheric moisture content rather than relative humidity.

1. Introduction

1.1. Environmental radon gas and public health

Radon, ^{222}Rn, a naturally occurring radioactive gaseous decay product of radium (^{226}Ra, itself a decay product of uranium), is widely distributed in the geological environment in a variety of rocks and soils, and in building materials incorporating or manufactured from these. Ionising radiation is well known to have adverse health effects, and inhalation of radon gas and its solid progeny ^{218}Po and ^{214}Po, both readily adsorbed onto atmospheric particulates, provides the majority of the radiation dose to the human respiratory system, leading to chemical and radiological damage to the sensitive inner lining of the lung, thereby increasing the risk of lung-cancer. This risk increases with cumulative long-term radon exposure, a convenient quantification being the estimated annual average radon level in a building. If a measurement is made over a shorter time period, then a seasonal correction is appropriate to estimate the annual average. In Europe, mortality from exposure to radon in buildings is estimated (Darby et al., 2004) to represent 9% of all deaths from lung-cancer and 2% of all cancer deaths. Total annual lung-cancer mortality in 2006 in the United Kingdom (UK) was 34,150, around 1110 (3.3%) being attributed to residential exposure to radon and its progeny (AGIR, 2009; Gray et al., 2009). These figures were little changed in

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2010, with 1376 radon-attributable deaths from lung cancer (3.4% of the total) (Parkin and Darby, 2011).

Radon protection in England and the Devolved Administrations (Scotland, Wales and Northern Ireland) within the UK, formerly administered by the National Radiological Protection Board (NRPB), is currently the responsibility of the Centre for Radiation, Chemical and Environmental Hazards (CRCE), lately part of the UK Health Protection Agency (HPA) and now a division of Public Health England (PHE). Responding to the health threat posed by domestic radon in the UK, the NRPB initially established a residential Action Level of 200 $Bq \cdot m^{-3}$ (O'Riordan, 1990), declaring as radon Affected Areas those geographical entities where over 1% of measurements in the existing housing stock showed radon concentrations above the Action Level. While the growing number of available radon measurements from domestic properties, and the development of enhanced geological mapping techniques, has enabled potential Affected Areas to be indicated more precisely (Denman et al., 2013), there is still much to learn about radon and geology, especially as uranium and radon can, under the right hydrogeological circumstances, be transported for considerable distances. Geological evidence can therefore only ever be indicative, rather than diagnostic, of an indoor radon problem, and definition of a single SCF for the UK, which exhibits some of the most varied geology spatially in the world, is consequently extremely problematic.

1.2. Radon and climate

Previous attempts to relate indoor radon concentration level and climate have proved inconclusive. While Postendörfer et al. (1994) concluded that, in a building with relatively stable air temperature, wind-speed was the principal factor determining indoor radon concentrations, an extended study (3000 daily samples in three near-continuous groups) (Kobayashi, 2000) failed to identify such a correlation, although the power-spectrum of the radon progeny ratio was shown to be similar to that of wind-speed. Miles (2001) demonstrated good correlation between mean radon concentration and monthly temperature, but only while outdoor temperature is lower than that indoors, as required by the indoor under-pressure model (Eaton and Scott, 1984). Climent et al. (1999) showed radon concentration correlating inversely with air temperature and soil temperature at 300 mm soil depth, and directly with humidity, rainfall and wind direction, in each case with minimal latency. No correlation was evident with soil temperature at 100 mm depth, with wind speed or with seismic activity within a 100 km range. Dolejs and Hulka (2003), investigating the effect of climate on the difference between short- and long-term radon outcomes, showed that while atmospheric pressure and rainfall were not significant, external weekly mean temperature was a significant factor. Investigations into the effect of climate on radon concentration in three undisturbed domestic basement rooms in Northamptonshire failed to demonstrate rigorous causality, although weak correlations with precipitation and mean daily temperature were identified (Groves-Kirkby et al., 2006). Florea and Duliu (2012), reporting eighteen years of continuous observation of atmospheric radon, identified negative correlation between radon concentration and precipitation, temperature and sky cloudiness. Wavelet and power spectra confirmed the predominance of one year periodicity, with additional components with periodicity of 1.2, 1.5, 2.8 and 7.2 years. Finally, Perrier et al. (2009, 2013) have demonstrated the sensitivity of soil-gas radon flux and concentration to atmospheric pressure changes, in particular to periodic signals such as the semi-diurnal barometric tide S2 (Simpson, 1919), the response being dependent on the presence or absence of an interface, such as that between bed-rock and surface drift strata, and on the presence or absence of air and water.

1.3. Seasonal variability of domestic radon

Soil-gas radon flux at a particular location is primarily determined by the location and quantity of its precursor radionuclides, while its subsequent migration and advection into buildings depends on the underlying rock and its fragmentation, soil stratification and water content. Soil characteristics are influenced by changes in meteorological conditions, many of which exhibit periodic, often annual, variability; temporal variations of soil-gas radon concentration are consequently widely observed (Neznal et al., 2004; Perrier and Girault, 2013). Since geomorphology varies from location to location, significant spatial variability of soil-gas radon can exist over an area of apparently stable soil geochemistry (Neznal et al., 1996).

Soil-gas radon can enter a building through any opening (cracks in solid floors, gaps in suspended floors, apertures around service entry points) in contact with the ground. In climates where homes are heated for at least part of the year, indoor air is generally warmer and less dense than outdoor air. The consequent pressure differential, the prime driving force for entry of soil-gas and its entrained radon, is modulated by the Bernoulli effect influence of wind passing around and over the building, with wind-speed contributing significantly in determining radon ingress (Eaton and Scott, 1984).

Phenomenologically, indoor domestic radon concentration levels are generally higher at night than during the day and generally higher in winter than in summer. These variations reflect reduced domestic activity at night, increased interior/exterior temperature difference at night and during the heating season and, where soil-gas advection forms the predominant radon source, the underlying climatically-defined seasonal variability in soil-gas radon content. In addition to the natural daily cycle, longer periodicities are evident, related to other causes. These include: external temperature (Karpinska et al., 2004; Miles, 2001); barometric pressure and wind direction (Miles, 2001); rainfall (Mose et al., 1991); occupancy patterns (Paridaens et al., 2005); seismic events (Crockett et al., 2006a); tidal effects, including barometric tides (Perrier and Girault, 2013) and ocean tidal-loading and earth-tides (Crockett et al., 2006b; Groves-Kirkby et al., 2006); the underlying geology (Gillmore et al., 2005; Miles and Appleton, 2005).

1.4. Seasonal correction factors

To compensate for seasonality when assessing radon risks, short-term measurement outcomes are generally converted to equivalent mean annual levels by application of a Seasonal Correction Factor (SCF). In the UK and elsewhere, this is a set of multiplying factors, generally (multi-) monthly by calendar month and national scope, applied to a medium-term radon concentration measurement, the current recommendation being 3 months (AGIR, 2009), to derive a meaningful annual average radon concentration, the standard quantifier of long-term health risk. SCF calculation requires knowledge of the measurement start-date and duration, and assumes annually-periodic, typically sinusoidal, variation (Pinel et al., 1995).

Initial concern as to the applicability of a single SCF set was raised by Pinel et al. (1995), who argued that, due to the UK's extensive geological variability, domestic SCFs derived from earlier nationwide study (Wrixon et al., 1988) might not be applicable in areas such as south-west England, which differs geologically to much of the remainder of the country. Subsequent study of radon levels in a set of homes situated on radon-rich Jurassic strata in Northamptonshire, England (Denman et al., 2007a) confirmed that the UK domestic SCF set was, indeed, not replicated by the experimental data. Using published data, Groves-Kirkby et al. (2009a,