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Seasonality, Atmospheric Conditions, and Variation in Household Radon, 1990-2015

Nicholas Conley
University of Kentucky, nicholas.conley@uky.edu

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Nicholas Conley, Student

Dr. Mary Kay Rayens, Committee Chair

Dr. Sarah Wackerbarth, Director of Graduate Studies

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Author: Nicholas Conley

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Committee Co-Chair: Mary Kay Rayens, PhD

Committee Co-Chair: Jay Christian, PhD

Committee Member: Ellen J. Hahn PhD, RN, FAAN

Abstract

Background:

Radon is a colorless, odorless, and tasteless radioactive gas. Indoor radon exposure is responsible for at least 21,000 lung cancer deaths per year in the U.S. Radon concentrations vary greatly, with atmospheric conditions as one of the major factors contributing to this variation. There is also a link between season of the year and indoor radon values, with higher readings in winter compared with summer months. Seasonality studies are necessary in order to determine the best time for radon exposure screening. The purpose was to determine if atmospheric conditions (i.e., temperature, precipitation and wind) were predictive of observed home radon values, in addition to seasonality (i.e., 3-month intervals starting in January).

Methods:

We used data from 116 Kentucky counties over a 26-year period (1990-2015). A mixed model assessed the factors significantly associated with quarterly averaged log-transformed radon values. We did not retain temperature in the model given its strong association with seasonality, and wind measurements were only available for counties with airports.

Results:

In the full model with 116 counties, seasonality was a significant predictor of radon values; precipitation was not significant. In the 8-county wind model, season and wind were significant predictors; precipitation remained nonsignificant. Both models indicated higher radon in seasons 1 and 4 (Oct-March); wind was positively associated with radon values in counties with airports.

Conclusions:

It may be most beneficial for homeowners and certified radon measurement professionals to screen for radon during the months of October-March, when radon concentrations are the highest. High winds are associated with higher indoor radon values; to accurately assess long term radon exposure, it may be warranted to conduct radon testing during typical atmospheric conditions.

Keywords: Radon, precipitation, temperature, wind speed, season, seasonality, lung cancer

Introduction

Radon is a colorless, odorless, and tasteless radioactive gas; because of these characteristics it is easy for radon to go unnoticed. Radon is the daughter product of decaying Uranium, a ubiquitous element in the Earth's crust.[1] Radon emanates from the soil and can accumulate in a dwelling through breaks or cracks in a foundation. Radon is the heaviest of the noble gases; being denser than air, it tends to accumulate in lower areas where ventilation is poor.[1] Exposure to radon is the second leading cause of lung cancer, tobacco smoke being the number one cause.[2] Radon exposure is estimated to be responsible for an approximate 21,000 U.S. lung cancer deaths per year and individuals who are exposed to both radon and tobacco smoke are more likely to develop lung cancer.[3]

Proper testing of a household is the only way to accurately determine radon exposure. It is recommended by the EPA that all homes be tested for radon. There are two testing methods used for measuring radon, short-term and long-term testing. Short term testing last between 2-90 days and is the quickest method to obtain radon levels.[4] Long term testing last longer than 90 days and will be more likely to give a reading that is more representative of a household's year round exposure.[4] The EPA action level for radon mitigation is 4.0 pCi/L; however, the EPA also recommends residents consider mitigation if household radon levels are between 2-4 pCi/L.[4]

Indoor radon gas concentrations vary greatly. Radon's potential for variation increases the likelihood of inconsistent test results that do not necessarily reflect true exposure potential. These variations are caused by many factors; two of the most influential factors are geology and atmospheric conditions. Radon is derived from the daughter products of decaying uranium. [5] Uranium is found in almost every rock and soil type in varying amounts, and it is this geological variation that contributes, in part, to differing household radon levels. While there is no doubt that geology has an effect on radon concentration, there is also evidence that meteorological variations significantly affect radon levels.[6] Ball and colleagues (1991) have suggested that radon concentrations in soil are just as likely to be affected by meteorological factors as by geological variables.[7]

While radon seasonality studies are plentiful, there is some inconsistency in the direction of the relationship between season and radon concentration. Denman and colleagues (2007) have stated that it is typical to see higher radon levels in dwellings during cooler seasons compared to warmer seasons.[8] However, the opposite was found in homes in Alabama, where radon concentrations were distinctively higher in the summer months.[9] The majority of the radon seasonality studies have been conducted outside of the United States. These studies only represent radon behavior for the typical season and weather conditions of these locations. It is important to conduct seasonality and weather studies in diverse geographic locations in order to increase our knowledge of radon behavior. Kentucky's climate makes it an ideal study location because unlike other areas of the U.S., Kentucky does not have distinct "wet" or "dry" seasons.[10] The purpose of this study was to determine if atmospheric conditions (i.e., temperature, precipitation and wind) and seasonality are predictive of observed home radon values.

Methods

Data Sources and Measurement: Radon data were obtained from short-term indoor radon tests conducted in Kentucky households between 1990 and 2015. The complete radon database with all available values was obtained as part of an ongoing study conducted by BREATHE (Bridging Research Efforts and Advocacy Toward Healthy Environments) at the

University of Kentucky College of Nursing.[11] Proprietary data were obtained from the two commercial radon testing companies that had provided radon test kits to the state radon program from 1990 to 2015. Precipitation and temperature data for 119 of the 120 Kentucky counties were available from the National Oceanic and Atmospheric Association's (NOAA) Climate Data Online. At the time of the study, Bath County, Kentucky was not included in the database. There are 8 counties in the state with airports (Fayette, Breathitt, Boone, Franklin, Jefferson, Laurel, McCracken, and Warren); wind data for these counties were obtained from NOAA.

The seasonality measure was quarter of year the radon testing occurred, with quarters defined as: January-March (1), April-June (2), July-September (3), and October-December (4). Summary scores were created for the dependent (radon) and independent (temp, precipitation, wind) variables by determining the median of each variable for a given season in a given year and county. This strategy is appropriate for summarizing quarterly measures because of the variability and potential for out-of-range values in the full dataset. The median is the most accurate summary in this context because it is not influenced by extreme values on either end. Precipitation and wind datasets provided one measure per day while the temperature dataset provided three: MAX, MIN and observation. The observation was used in all cases except where there were missing values. In the case of missing observation values for temperature, the MAX value was used.

Statistical Analysis: All of the statistical analyses for this study were conducted using SAS, v. 9.4; an alpha of .05 was used for inferential testing. A natural log transformation was applied to the median radon values prior to analysis because of the tendency for radon values to have a right-skewed distribution.

Descriptive analysis, including means and standard deviations, was used to summarize each of the study variables. For the log-transformed median radon values, geometric means and standard deviations were used for these summary statistics. A mixed model for repeated measures was used to assess the association of log of the radon level with precipitation, wind, temperature, and seasonality, with measurements nested within county. Post-hoc pairwise comparison of the geometric means were conducted to determine if significant differences among seasons were present. There are 104 time points included (26 years x 4 seasons), with 116 of the 120 counties in Kentucky included in the full model. This reflects all available counties with non-missing precipitation and radon data.

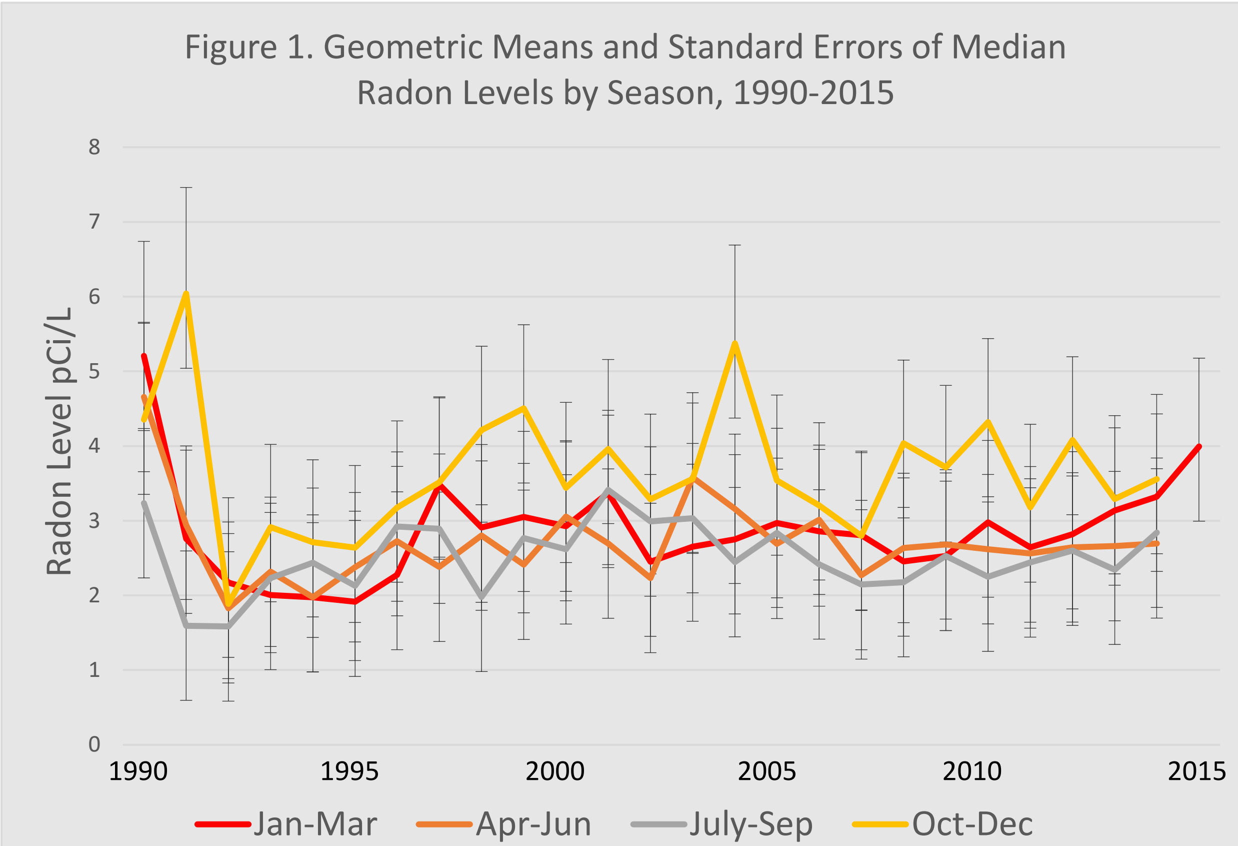
Because of the potential for introducing multicollinearity into the mixed models given the association between the seasonality factor and ambient temperature, we omitted temperature from the models but retained seasonality. This was done after also considering models that excluded seasonality but retained temperature, but these were not as readily interpretable given temperature is a continuous variable and seasonality a 4-category factor, so comparisons among seasons is more intuitive among models containing seasonality. In the model that included wind as a predictor, only 8 counties were available for analysis. Both of the models also contained a time variable ranging from 1 to 104; this variable, which is the quarter number starting with Jan-Mar 1990 and ending with Oct-Dec 2015, tests for a linear trend in radon values over the course of the 26-year trajectory.

Results

Table 1. Means and Standard Deviations of Variables by Season

Season	Variable	Mean	Standard Deviation
1 (Jan-March)	Median Radon	2.86	0.68
	Average Precipitation	0.14	0.03
	Average Median Wind	7.78	0.88
2 (Apr-June)	Median Radon	2.7	0.55
	Average Precipitation	0.16	0.05
	Average Median Wind	6.43	1.03
3 (Jul-Sep)	Median Radon	2.51	0.46
	Average Precipitation	0.13	0.04
	Average Median Wind	4.85	0.92
4 (Oct-Dec)	Median Radon	3.65	0.88
	Average Precipitation	0.13	0.04
	Average Median Wind	6.42	0.96

The descriptive summary of the study variables is shown in Table 1. For median radon, the geometric mean of the average median value by season across years and counties is highest in Season 4 (Oct-Dec), followed by Season 1 (Jan-Mar). As expected based on prior studies, the values are lower in Season 2 (Apr-Jun) and Season 3 (Jul-Sep). Average precipitation demonstrated little variability from season to season, with a range from a low of 0.13 inches (in Seasons 3 and 4) to 0.16 inches (Season 2); Season 1 had an average precipitation of 0.14 inches. The average of median wind values across counties and years had a low of 4.9 miles per hour in Season 3 (Jul-Sep) and a high of 7.8 miles per hour in Season 1 (Jan-Mar). Seasons 2 and 4 both had an average value of 6.4 miles per hour. The pattern of radon level by season over the 26-year period demonstrates that Season 4 values exceed those of every other season in nearly every calendar year (see Figure 1). While there is variability among values, as evidenced by the width of the standard error bars in this figure, the trend is for Season 4 values to exceed the other three for any fixed year.



The results of the mixed modeling are shown in Table 2. In the full model with 116 counties, as shown in the first column of the table, both seasonality and time were significantly associated with log of the radon value. In particular, there was a significant difference in average median radon level between Seasons 1 vs. 4 (p< 0.001), 1 vs. 3 (p= .02), 2 vs. 4 (p< 0.001), and 3 vs. 4 (p< 0.001). The differences between Seasons 1 vs. 2 (p= .14) and 2 vs. 3 (p= .37) were not significant. The significant time effect indicated a trend in increasing radon values over the 26-year period (p< .001). Precipitation was not significant in the model, suggesting no association between precipitation values and indoor radon readings (p= .25).

Table 2. Mixed Models to Determine Predictors of Radon Value

Significance of Variables included in Mixed Models:		
Variable	Model 1: Full Dataset (*N*= 116 counties)	Model 2: Counties with Wind Measurements (*n*= 8 counties)
Precipitation	F= 1.4; p= .25	F= 0.3; p= .57
Wind	--	F= 5.5; p= .02
Season	F= 33.7; p< .001	F= 8.1; p< .001
Time	F= 23.9; p< .001	F< 0.1; p= .77

Geometric means (GM) and post-hoc testing* of the significant Season effect:		
Season 1	GM= 2.71[a]	GM= 3.09[a]
Season 2	GM= 2.57[a,b]	GM= 2.79[a]
Season 3	GM= 2.48[b]	GM= 2.91[a]
Season 4	GM= 3.47	GM= 4.10

*Within each model, GMs with the same letter are not significantly different at alpha=.05

In the 8-county model that included wind, seasonality and wind were significant, but the time factor was not. Post-hoc comparisons of the geometric means of the median radon values by season indicated that the significant comparisons were between Seasons 1 vs. 4 (p= 0.002), 2 vs. 4 (p< .0001), and 3 vs. 4 (p= .0002). The pairwise comparisons among Seasons 1, 2, and 3 were not significant, with p-values ranging from .28 to .68. The p-value for the significance of the effect of wind was .020, and the direction of the estimate suggested higher wind values were associated with greater radon readings. This is somewhat consistent with the descriptive findings in Table 1: wind values tended to be higher in cooler months (Seasons 1 and 4), and this was also true for radon. Distinct from the full model, the association between radon level and the time trend was not significant (p= .77). Consistent with the full model, precipitation was not a significant predictor in this 8-county model (p= .57).

Discussion

Seasonality and wind were predictors for indoor radon concentrations. The post-hoc pairwise comparisons of the seasonality factor were consistent with other studies in the literature.[12] Both models indicated lower radon levels in Seasons 2/3 (April-September). These findings are consistent with the findings from the majority of the seasonality research. It is likely that this is due in part to Kentucky experiencing all four distinct seasons. Wind was found to be positively associated with radon; a 1-unit increase in wind speed was associated with an increase in radon of 0.058. This finding was not consistent with one study reporting that wind was negatively associated with radon.[13]

Time was a significant predictor for radon in the first, larger model. We believe that this can be attributed to increase in awareness. This increase in testing could be the result of the 1987 EPA report naming radon as the most serious environmental health hazard threatening American households.[14]

Strengths and Weaknesses

One strength is the availability of a large statewide registry of radon values over a 26-year period. The inclusion of weather surveillance data from the same 26-year period adds to the strength of the study, allowing us to retain 116 of the 120 counties in the state in the full analysis. The primary limitation was the few number of counties with wind data due to limited data collection in Kentucky outside of airport locations. Not atypical with secondary data analysis, lack of consistently reliable data for all study variables is also a limitation. For instance, precipitation and wind datasets only had one measure for each time point for each county (as opposed to also including maximum or minimum for a given day), so for some dates and counties there were missing values. Another major contributor of indoor radon is building materials.[15] The lack of building materials data is acknowledged as another limitation.

Conclusions

Homeowners may feel more confident in evaluating their maximum potential for radon exposure when they test during times of known higher radon levels. Based on these findings, we recommend that residents screen for radon exposure during the colder months of October-March, when radon concentrations are the highest. These seasons are most likely to provide the most accurate representation of radon exposure.

The wind observations in this study imply that radon testing may be preferable when performed during typical atmospheric conditions. Testing during high winds could exaggerate true radon exposure. This is reiterated in another study that suggest short-term screening not be conducted during wind storms.[16]

The observations made in this study are valuable to environmentalists, public health practitioners, cancer clinicians and researchers, certified radon measurement and mitigation professionals, and homeowners concerned about their health. Radon is the second leading cause of lung cancer. Theoretically, there’s a potential to save 21,000 lives, annually from accurate radon testing. By conducting studies, such as this one, we increase our knowledge of radon testing and identify potential changes in best practice for environmental public health.

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