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The Influence of Meteorological Parameters on Indoor and Outdoor Radon Concentrations: A Preliminary Case Study

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Abstract

In this study the influence of meteorology on indoor and outdoor radon concentrations in four different locations in a Mediterranean country have been studied. Indoor, daily radon concentrations were generally higher (0.2 – 85.0 Bq m^{-3}) than outdoor daily concentrations (0.8 – 3.6 Bq m^{-3}) in all locations studied with the exception of one that was built on pylons, thus reducing infiltration of radon from the ground. Indoor and outdoor meteorological parameters influence both the indoor and outdoor radon concentrations. In particular, outdoor wind speed and relative humidity show a negative correlation with both outdoor and indoor concentrations at all locations. Radon concentrations were also measured at two different levels of a terraced house (a common household type in Malta), in the basement and on ground floor. Results show that if the interconnecting door is left open, the radon in the basement infiltrates to the ground floor, increasing the average radon daily concentration in the living area by approximately 1.5 times.

Keywords: Radon; Indoor; Outdoor; Basement; Air Exchange Rate; Meteorological Parameters

Highlights:
- Indoor/outdoor radon concentrations dependent on wind speed and relative humidity
- High-resolution concurrent radon measurements in basement interconnected with a ground floor
- Ground floor radon levels increase by 1.5 times when interconnecting door is opened

Introduction

Radon (^{222}Rn) is a naturally occurring radioisotope which has been linked with adverse human health [1,2]. Residential radon is considered as the second most common cause and leading risk factor of lung cancer after cigarette smoking [3,4]. It is estimated that between 3% and 14% of all lung cancers in a country are related to radon exposure. However this varies between countries as it depends on national average radon concentrations as well as smoking prevalence [4]. Various frameworks have been developed within Europe to analyse the efficient reduction of indoor exposures such as exposure to radon through optimization of ventilation, filtration and indoor sources controls [5,6]. In Europe, about 2% of all deaths from cancer, particularly in smokers and ex-smokers are associated with radon exposure [3]. Mean annual indoor radon gas in European countries ranges from 20 to 100 Bq m^{-3} with countries having sedimentary soil resulting in low concentrations such as the Netherlands, Poland and UK [7]. In contrast countries with old granite soil are more prone to radon emissions, typically occurring in the Czech Republic, Serbia-Montenegro and Finland [7]. The World Health Organisation (WHO) annual average reference level for radon is of 100 Bq m^{-3} however, there is no threshold below which radon exposure carries no risk [4]. The risk of lung cancer increases by 16% per 100 Bq m^{-3} increase in long-term averages with the risk from radon estimated to be 25 times larger for smokers than non-smokers [4].

Short-lived progenies from radon gas are categorised under two size fractions. The smaller, *unattached progeny* have typically high diffusivities and cluster to form small particles, typically of diameter < 5 nm. The larger, *attached progeny* (diameter > 5 nm) tend to stick to surfaces including aerosols present in the indoor atmosphere [8,9]. At high ventilation rates, the unattached fraction increases but under low ventilation conditions and presence of aerosols the attached fraction increases [10]. The exposure to radon comes almost exclusively from the inhalation of both aerosol fractions [11].

Upon emission from the ground to open air, radon is diluted to low concentrations however, in enclosed spaces such as caves, mines and buildings; radon can reach high concentrations as it penetrates through foundations, cracks in the walls and through the hydraulic drainage systems by diffusion [12]. With people spending more time indoors, conducting radon indoor surveys and more importantly identifying the drivers leading to high indoor radon is essential to aid for example future policies focusing on limiting indoor radon exposure to humans.

Radon levels are influenced by emission from subsoil, building materials and ventilation [13-16]. In addition, different meteorological parameters also play an important role in determining radon concentrations both indoors and outdoors [17,18]. Studies have shown high radon concentrations in the early hours and low radon concentrations in the early afternoon due to diurnal variations in for example wind speed, air pressure and temperature as well as ventilation patterns [13,17,18]. In a study by Li *et al.* (2018) focusing on short-term variations of indoor and outdoor radon concentrations in a typical semi-arid city of north-west China, the authors suggest lower radon concentrations during rainy days [13]. This apparent reduction in radon concentrations was associated with lower atmospheric pressure, high humidity and increase in soil moisture which blocks radon movement, decreasing soil porosity and permeability. Low wind speeds and mixing layer heights can also lead to the accumulation of near ground radon concentrations due to weaker horizontal transport and vertical mixing [13].

Focussing on the influence of environmental factors on indoor radon concentration levels in the basement and ground floor of a building in Midwestern USA, Xie *et al.* (2015) found that indoor radon levels are negatively correlated with indoor humidity (R = −0.3) and outdoor temperature, dew point temperature and wind speed (R = −0.3, −0.17 and −0.25, respectively) [17]. In contrast a positive correlation is suggested between indoor radon concentrations and outdoor barometric pressure (R = 0.35) (Xie *et al.*, 2015) [17]. However, no clear correlations are suggested between indoor radon concentrations and indoor temperature, indoor barometric pressure and outdoor wind direction (Xie *et al.,* 2015) [17]. These correlations of indoor radon concentrations are, however, highly dependent on the specific environmental parameters under study [17]. Xie *et al.* (2015) report radon concentrations of 1083 Bq m^{-3} in an unventilated basement compared to an average of 28 Bq m^{-3} at the ground floor. Measured radon levels at the ground level are lower in the summer months than those in winter with a significant month-to-month variation [17]. In contrast a limited seasonal variation in radon levels is noted for radon concentrations in the basement.

A national, geographically based survey on annual mean radon concentrations was conducted in the Maltese Islands between November 2010 and November 2011 in 85 buildings to identify indoor areas with annual mean radon concentrations higher than the WHO 100 Bq m^{-3} limit [19]. Across the Maltese Islands, Baluci *et al.* (2013) suggest a mean annual indoor radon gas concentration of 32 Bq m^{-3} [19]. The highest radon concentrations (92 Bq m^{-3}) were found in Qala, Gozo and Pembroke while the lowest radon concentrations of 8 Bq m^{-3} and 10 Bq m^{-3} were measured in Birzebbuga and Luqa, respectively. Although the measurements in this study outlined the typical indoor concentrations of radon, the leading causes of these levels in a typical southern European, Mediterranean country have not yet been studied. In this study we therefore focus on the influence of meteorological parameters on both indoor and outdoor radon concentrations at various locations in the Maltese Islands.

Method

The indoor and outdoor radon concentrations in ambient air were measured using a Tracerlab RDM/RM-2S/SF1 Radon-222-Detector (Tracerlab GmbH, Germany) at 4-hourly intervals at four different locations in the Maltese Islands. In all instances the instrument was placed in the centre of the sampling room at a height of 1 m from the floor. The radon concentration is calculated by an active α-spectrum analysis of the radon progeny Po-218. Indoor and outdoor temperature and relative humidity are measured at 1-minute intervals. Wherever possible wind speed and wind direction are also recorded.

Measurement sites

Most residences in the Maltese Islands are found on the two predominant stratigraphic formations. The *Lower Coralline Limestone* is the oldest, hard, limestone formation exposed on the islands. The *Globigerina Limestone* overlies the abovementioned formation. It is a soft, fine-grained limestone and further subdivided into the *Lower, Middle and Upper Globigerina* members [20]. The four locations used in this study are, Xewkija in the island of Gozo and Naxxar, Msida and Marsaxlokk that represent the North, Central and South regions of Malta. The sampling site characteristics and the type of rock over which the dwellings under study were built are listed in Table 1.

Site	Lat / Lon	Start Date - End Date	Stratigraphy Description	Vol. of sampling room	Characteristics
Msida	35°54'04.8"N / 14°28'51.5"E	28/07/2016 - 22/08/2016 (22 days)	Lower Globigerina Limestone	First floor: 100 m^3	• 2 windows • 1 door
Xewkija	36°02'02.4"N / 14°15'52.6"E	03/07/2017 – 10/07/2017 (8 days)	Upper Globigerina Limestone	Ground floor: 45 m^3	• 2 doors • 1 window
Marsaxlokk	35°50'05.8"N / 14°32'38.1"E	17/04/2017 – 11/05/2017 (24 days)	Middle Globigerina Limestone	Ground floor: 33 m^3	• 1 door • 1 window
Naxxar	35°54'35.8"N / 14°26'14.2"E	08/12/2018 – 20/12/2018 (13 days)	"Xlendi" Lower Coralline Limestone	Ground floor: 288 m^3 Basement: 383 m^3	Basement: • Front door • 2 windows Ground floor: • Interconnecting door to basement • 3 doors • 4 windows

Table 1: Description of sampling sites. The term 'basement' refers to the level beneath street level while the term 'ground floor' refers to the level above the basement

Baluci *et al.* (2013) suggest a seasonal variation in radon concentrations in Malta with higher concentrations between November and May and lower concentrations between June and October [19]. For this reason, radon concentrations and meteorological parameters at Xewkija and Msida were taken in the hot season while measurements at Msida and Naxxar were taken in the cold season as tabulated in Table 1.

Sampling was done in indoor environments that have been built during the last 30 years. Apart from the portacabin in Marsaxlokk all the other buildings were built from globigerina limestone, which was the most commonly used building material used on the islands until recently.

In Msida, sampling was carried out in a classroom on the first floor with two windows overlooking a carpark while in Xewkija sampling was done in a ground floor office with a single window in a detached two storey building about 50 m away from a road. In Marsaxlokk, sampling was done in an empty portacabin elevated on concrete pylons and having a single window. Sampling in Naxxar was done using two identical radon instruments, one in a basement garage and the other in an open space of the ground floor of a two-storey terraced house. A flight of steps and a door interconnected the garage with the ground floor. The indoor temperature and relative humidity of both spaces were measured. The outdoor temperature, relative humidity and wind speed were concurrently measured on the roof of the same house.

In Msida, Marsaxlokk and Xewkija all windows were kept closed as an air conditioning unit was in use during the campaigns. In Naxxar, sampling was carried out in naturally ventilated spaces. Two small louver windows in the garage door provided the ventilation in the basement garage. The ground floor had two doors that were opened occasionally for a short time and three windows, with only one window in front of the interconnecting door being left open throughout the campaign. From 08/12/2018 till 12/12/2018, the interconnecting door was opened and closed only sparingly to reach the garage. In the morning of the 12/12/2018 the interconnecting door was opened and left open till the evening of the 18/12/2018 where it was closed again.

The air exchange rate (AER) was estimated twice for each time period listed in Table 1 and for each level. This was done by using the decay rate of a tracer gas, carbon dioxide (CO_2) following the method suggested by Aglan (2003) [21]. In brief, this method suggests that the indoor concentrations during any instance can be modelled following equation 1 below:

$$C_i(t) = (C_0) - (C_0 - C_{i0})e^{-at} \tag{1}$$

Where C_i is the indoor concentration, C_0 is the outdoor concentration, C_{i0} is the initial background concentration, t is time and a is the air exchange rate (AER). Using non-linear regression, a shifted exponential decay function was fit to each decay cycle where the maximum and minimum CO_2 concentrations represent the initial parameters used for ($C_0 - C_{i0}$) and C_0, respectively. Extech SD800 and EA80 CO_2 data loggers were used to log CO_2 concentrations at one-minute intervals from which the AER could then be determined.

Results and Discussion

The range and average daily indoor radon concentration, temperature and relative humidity in the four locations are summarised in Table 2. For three weeks in July 2017, indoor radon levels at Marsaxlokk ranged between 0.2 to 1.0 Bq m^{-3} (Table 2 and Figure 1a) with a daily average of 0.35 Bq m^{-3}. Indoor relative humidity and temperature were relatively constant for the duration of the campaign at this location with levels generally settling at an average of 56% and 16 °C, respectively (Table 2). In Xewkija, indoor radon concentrations in July 2017 range between 8 to 76 Bq m^{-3} (Table 2 and Figure 1b) with a daily average of 34.9 Bq m^{-3}. Relative humidity in Xewkija was also constant at 57 %. Average temperature on the other hand reaches 21 °C (Table 2) and varies by approximately 1 °C between the first few days and the end of the campaign (Figure 1b).

From end of July through August 2016, the range of indoor radon concentrations in Msida was 10 – 48 Bq m^{-3} with a daily average of 27.1 Bq m^{-3} (Table 2). No indoor meteorological parameters were recorded at this location. In Naxxar, the indoor radon levels at the ground floor ranged from 20.8-85.2 Bq m^{-3} during the second and third week of December 2018 (Table 2 and Figure 1c). The average indoor relative humidity was 69% and the temperature was 18 °C.

Location	No. of observations	Radon Range (Bq m^{-3})	Average Radon (Bq m^{-3})	RH (%)	T (°C)
Marsaxlokk	24	0.2 – 1.0	0.35 ± 0.17	56± 1.91	16± 1.55
Xewkija	8	8.0 – 76.0	34.9 ± 18.53	58± 0.86	21± 0.31
Msida	22	10.0 – 48.0	27.1 ± 12.15	NA	NA
Naxxar (Ground floor)	13	20.8 – 85.2	54.0 ± 19.62	69± 2.85	18 ± 0.25

NA – Data not available

Table 2: Daily indoor radon concentration and indoor meteorological parameters averaged across the sampling period defined in Table 1. The corresponding standard deviation is also included for each parameter

Measured radon concentrations in Xewkija and Msida were lower than concentrations in Naxxar. One main difference between the campaign in Naxxar and the other two campaigns is that the campaign in Naxxar was conducted in the winter months [19]. Thus consistent with findings of Baluci *et al*. (2013), results in this study suggest higher concentration in the winter months compared to the summer months, typical of a Mediterranean climate (Prasad *et al*., 2018) [9]. An exception is Marsaxlokk where measured concentrations between April and May reach an average value of 0.35 Bq m^{-3}. This is however due to the presence of concrete pylons elevating the room from the subsoil thus limiting radon infiltration to a minimum.

In Europe, indoor radon exposure levels used for the burden of disease calculations range from 7 Bq m^{-3} in Cyprus to 140 Bq m^{-3} in the Czech Republic. Thus indoor concentrations reported in this study for Xewkija, Msida and Naxxar are similar to other European countries in particular Mediterranean countries such as Cyprus and Italy with indoor radon concentrations of 7 and 70 Bq m^{-3}, respectively (Asikainen *et al*., 2016) [6].

Correlation between indoor radon concentrations and indoor meteorological parameters

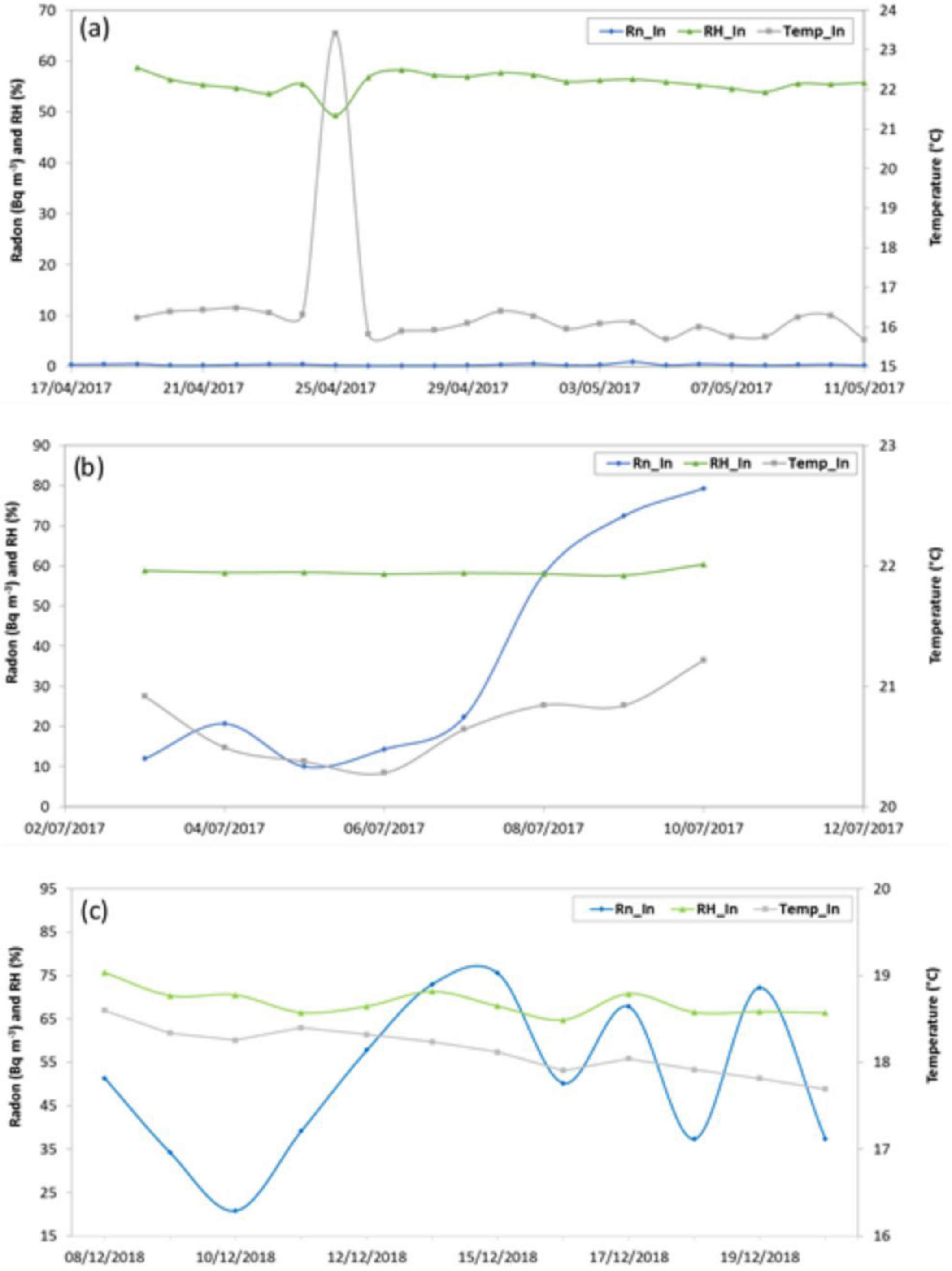

Figure 1: Indoor radon concentrations, temperature and relative humidity (RH) measured at **(a)** Marsaxlokk; **(b)** Xewkija and **(c)** Naxxar

Location	**Temp_In (°C)**			**RH_In (%)**		
Rn_In (Bq m^{-3})	**R-value**	**P-value**	**Beta coeff.**	**R-value**	**P-value**	**Beta coeff.**
Marsaxlokk	−0.09	0.68	-0.01	0.13	+0.56	+0.01
Xewkija	+0.74	0.03	+68.87	0.31	+0.46	+10.3
Naxxar	−0.06	0.85	-4.43	0.15	+0.63	+0.98

Table 3: Correlation coefficients (R value) between indoor radon concentration (Rn_In) and indoor temperature (Temp_In) and relative humidity (RH_In) in Marsaxlokk, Xewkija and Naxxar; The P value is also included to identify the statistical significance of the correlations shown (for $p<0.05$ the correlation is statistically significant). The beta coefficient is the degree of change in the outcome variable (e.g. indoor radon concentration) for every 1-unit of change in the predictor variable (e.g. indoor temperature and RH)

Indoor radon concentrations and indoor temperature and relative humidity at Marsaxlokk, Xewkija and Naxxar (ground floor) are shown in Figure 1a, b and c respectively. The correlation coefficient between indoor radon concentration and indoor meteorological parameters at Marsaxlokk is tabulated in Table 3. The low R values of -0.09 and 0.13 at Marsaxlokk (Table 3), suggest a low correlation between indoor radon concentrations and temperature and relative humidity, respectively which can also be noted from Figure 1a. The correlation for both cases is not statistically significant ($p > 0.05$). In Xewkija, the correlation between indoor radon concentration and relative humidity is also low and not statistically significant ($R = 0.31$, $p = 0.46$; Table 3). However, a statistically significant positive correlation of +0.74 is noted between radon concentrations and indoor temperature ($p = 0.03$; Table 3). The beta value is of +68.87 which suggest that for each 1 unit increase in the predictor variable (indoor temperature), the outcome variable (indoor radon concentrations) will increase by 68.87 units. The steep increase in indoor radon concentrations with increasing indoor temperature is illustrated in Figure 1b. Similarly to Marsaxlokk, indoor correlations in Naxxar are not statistically significant (Table 3).

Correlation between outdoor radon concentrations and outdoor meteorological variables

In this section the correlation between outdoor radon concentration and outdoor meteorological parameters in Marsaxlokk, Xewkija and Msida are presented. Daily mean outdoor radon levels range between 0.8 and 3.5 Bq m^{-3} in Marsaxlokk, between 1.2 and 3.5 Bq m^{-3} in Xewkija and between 1.5 and 3.6 Bq m^{-3} in Msida. In Marsaxlokk, the negative correlation noted between outdoor radon concentrations and outdoor temperature and relative humidity is not statistically significant ($R = -0.05$ and -0.22, $p = 0.80$ and 0.31 respectively; Table 4). Outdoor wind speed is also negatively correlated with outdoor radon concentrations in Marsaxlokk however, the correlation is statistically significant with a beta coefficient of -0.53 ($R = -0.74$; Table 4). This suggests that for each 1 unit increase in outdoor wind speed, outdoor radon concentrations will decrease by half. Similarly, in Xewkija, correlations between outdoor temperature and relative humidity are not statistically significant (Table 4). However, statistically significant negative correlation between outdoor radon concentrations and wind speed are again noted with a beta coefficient of -0.68 ($p = 0.02$; Table 4). At Msida, outdoor relative humidity and wind speed show a negative correlation with outdoor radon concentrations while a positive correlation is noted with outdoor temperature ($R = -0.24$, $R = -0.33$ and $R = +0.15$, respectively; Table 4). The sign of the correlations noted in Msida is consistent with results at Xewkija however correlations at Msida are not statistically significant (Table 4). The statistically significant negative correlation between outdoor wind speed and outdoor radon concentrations noted in Marsaxlokk and Xewkija can be due to an increase in the dispersion of radon as the wind speed increases. On the other hand, outdoor temperature and relative humidity may alter conditions in the ground which in turn influence the radon emissions. However, the correlations between outdoor radon concentrations, temperature and relative humidity are not statistically significant for all locations considered in this study and thus no robust conclusions can be drawn.

Location	**Temp_Out (°C)**			**RH_Out (%)**			**WS_Out (m s^{-1})**		
Rn_Out (Bq m^{-3})	**R-value**	**P-value**	**Beta coeff.**	**R-value**	**P-value**	**Beta coeff.**	**R-value**	**P-value**	**Beta coeff.**
Marsaxlokk	−0.05	0.80	-0.02	−0.22	0.31	-0.02	−0.74	4.28×10^{-5}	-0.53
Xewkija	+0.08	0.88	+0.02	−0.61	0.20	-0.02	−0.88	0.02	-0.68
Msida	+0.15	0.54	+0.09	−0.24	0.32	-0.02	−0.33	0.17	-0.15

Table 4: Correlation coefficients (R-value), P-value and Beta coefficients between outdoor radon concentration (Rn_Out) and outdoor temperature (Temp_Out), relative humidity (RH_Out) and wind speed (WS_Out) at Marsaxlokk, Xewkija and Msida

The correlations between indoor radon concentrations and outdoor meteorological variables

The influence of outdoor meteorological parameters on indoor radon concentrations is presented in this section. In Marsaxlokk, Xewkija and Msida, positive correlations are noted between outdoor temperature and indoor radon concentrations. In contrast results show a negative correlation with outdoor relative humidity and wind speed in these locations. However, the only statistically significant correlations are those between indoor radon concentrations and outdoor wind speed in Marsaxlokk and Msida (beta = -0.08 and -7.11, respectively; Table 5) and between indoor radon concentrations and outdoor relative humidity in Xewkija (beta =-2.39; Table 5). In Naxxar, no correlation is statistically significant at ground level however, at the basement, a p value of 0.056 is noted for the negative correlation between indoor radon concentrations and outdoor wind speed ($R = -0.54$ and beta = -7.18; Table 5). The negative correlation between outdoor wind speed and indoor radon may be explained through reductions in outdoor pressure as the outdoor wind speed increases due to Bernoulli's principle. Thus, resulting in a lower indoor radon concentration as the outdoor wind speed increases [18]. This phenomenon is clearly explained by (Schubert *et al.*, 2018) in their experimental study to estimate the influences of meteorological parameters on indoor radon concentrations in a steel container. The correlations between indoor radon and outdoor temperature and relative humidity may be linked with soil moisture content which alters radon emission rates. Differences in outdoor temperature can lead to movement of air from outdoors to indoors which in turn alter the relative humidity [22]. For example Akbari *et al.* (2013) suggest that when temperature indoors is lower than that outside, heat is transferred inside which in turn decreases the relative humidity indoors. Their results further show that radon concentrations falls as the relative humidity increases from 30% to 60% (Akbari *et al.*, 2013) [22].

Location	**Temp_Out (°C)**			**RH_Out (%)**			**WS_Out (m s^{-1})**		
Rn_In (Bq m^{-3})	**R-value**	**P-value**	**Beta coeff.**	**R-value**	**P-value**	**Beta coeff.**	**R-value**	**P-value**	**Beta coeff.**
Marsaxlokk	+0.00	1.00	+4.50 x 10-5	−0.16	0.45	-0.00	−0.56	0.00	-0.08
Xewkija	+0.69	0.13	+16.14	−0.98	0.00	-2.39	−0.68	0.13	-40.31
Msida	+0.22	0.33	+2.58	−0.41	0.06	-0.70	−0.52	0.01	-7.11
Naxxar (Ground)	−0.16	0.60	-4.31	+0.33	0.27	+1.66	−0.35	0.25	-1.90
Naxxar (Basement)	+0.15	0.63	+9.74	+0.45	0.13	+5.45	−0.35	0.06	-7.18

Table 5: Correlation coefficients (R-value), P-value and Beta coefficients between indoor radon concentration (Rn_In) and outdoor temperature (Temp_Out), relative humidity (RH_Out) and wind speed (WS_Out) at Marsaxlokk, Xewkija, Msida and Naxxar

Results in this section are somewhat comparable to the correlations between indoor radon concentrations and outdoor wind speed suggested by (Xie *et al.*, 2015) [17]. Results in both this study and that of (Xie *et al.*, 2015) show that outdoor wind speed is negatively correlated with indoor radon concentrations with R values ranging between −0.52 and −0.68 for this study and an R value of −0.25 for (Xie *et al.*, 2015) [17]. The different correlations found in this study compared to (Xie *et al.*, 2015) could be related to the difference in locations of the two studies, each having particular meteorological conditions pertaining to the country under study [17]. These differences would warrant further investigation.

Indoor radon concentrations in a two-storey house

The time series represented in Figure 2 shows the concurrent indoor radon concentration in the basement and the ground floor of a two-storey house in Naxxar from 08/12/2018 till 20/12/2018. These two levels are connected by an inter-connecting door as describe in Section 5.1. The times when the garage door in the basement was opened and closed are marked by blue crosses on the basement radon concentration time series (Figure 2).

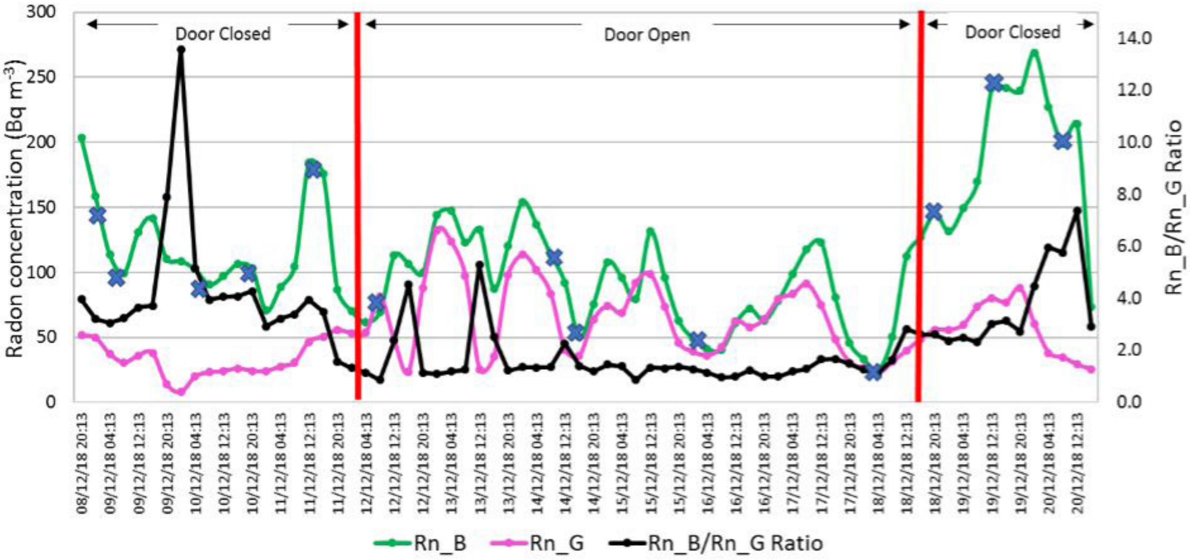

Figure 2: Indoor radon concentrations in basement (Rn_B) and in ground floor (Rn-G) and (Rn_B/Rn_G) ratio with time. Red lines indicate opening and closing of interconnecting door between basement and ground floor. Blue crosses indicated the times when the garage door in the basement was opened and closed

Throughout the whole campaign, the average radon concentration in the basement was 2.1 times higher than the concentration on the ground floor (Table 6) [8]. Results by Guo (2012) suggest indoor radon concentrations (office (11–20 Bq m^{-3})/residences (13–18 Bq m^{-3})) which are consistent with indoor radon concentrations presented in this study (Section 3.1 Table 2) and less than indoor radon concentrations measured by Guo (2012) at the basement level (224 Bq m^{-3}) [8].

Time-period	Inter-connecting door	Rn_B (Bq m^{-3})	Rn_G (Bq m^{-3})	Rn_B/Rn_G
08/12/2018-20/12/2018	-	114.8	54.4	2.1
08/12/2018-12/12/2018	Closed	116.9	29.0	4.0
12/12/2018-18/12/2018	Open	93.0	62.5	1.5
18/12/2018-20/12/2018	Closed	181.5	54.6	3.3

Table 6: Average daily radon concentration (in Bq m^{-3}) and (Rn_B/Rn_G) ratio in different time periods in the basement and ground floor

During the times in which the interconnecting door is kept closed, indoor radon concentrations in the basement are approximately 3.3 to 4 times higher than the concentrations at the ground floor (Figure 2 and Table 6). The basement whose only air entry points are two louvered windows seems to accumulate high radon concentrations which decrease when the garage door is open due to a rapid exchange of air (from indoors to outdoors). On closing the garage door, radon concentrations start to build up. When the interconnecting door was left open an exchange of air and infiltration of radon seems to occur between the two levels considered in this study. This in turn decreases the ratio between indoor radon concentrations at the basement and the ground level to approximately 1.5 times, until there is an equilibration of the radon concentration between the two levels. In support of this observation, two CO_2 releases were conducted for each time-period and at each level to estimate the air exchange rate (AER) following the method described in Section 5.1. The average AER for each time-period is listed in Table 7. When the interconnecting door was closed, the AER in the ground floor was about twice that in the basement, whilst when the interconnecting door was open, the AER in both floors essentially increased resulting in an overall similar AER across both levels.

Time-period	Inter-connecting door	AER	
		Basement	Ground
08/12/2018-12/12/2018	Closed	0.23 h^{-1}	0.53 h^{-1}
12/12/2018-18/12/2018	Open	0.69 h^{-1}	0.79 h^{-1}
18/12/2018-20/12/2018	Closed	0.31 h^{-1}	0.47 h^{-1}

Table 7: Average air change rates for each time-period at the basement and ground floor.

Conclusions

In this study an analysis of the correlations between indoor and outdoor radon concentrations and different meteorological parameters at four different locations in the Maltese Islands was presented. It appears that independently of the stratigraphy, the average, maximum outdoor concentration of radon in the sites sampled is 3.5 Bq m^{-3}, in corroboration to what was observed by (Vimercati *et al.*, 2018) due to the radon's rapid dispersion [12].

In contrast, average indoor radon concentrations measured at different sites range from 0.35 to 54 Bq m-3. The correlations between indoor and outdoor radon concentrations and indoor and outdoor meteorological variables were analysed. Given the small sample size considered in this study, some correlations are not statistically significant. However, a statistically significant positive correlation coefficient of 0.74 is found between indoor radon concentrations and indoor temperature in Xewkija. In addition, a statistically significant negative correlation is found between outdoor radon concentrations and outdoor wind speed in Marsaxlokk and Xewkija. The statistically significant negative correlation with outdoor wind speed also holds for indoor radon concentrations at Marsaxlokk and Msida. On the other hand, indoor radon concentrations in Xewkija are negatively correlated with outdoor relative humidity.

Apart from the influence of different meteorological parameters it was shown that on opening the interconnecting door between the basement garage and the ground floor living space in a typical Maltese home, air flows across the two levels increasing substantially the AER in both levels resulting in higher radon concentrations in the ground floor. The average daily concentration of radon in the basement exceeds the WHO 100 Bq m^{-3} but decreases when the interconnecting door is opened.

The AER values in the two floors were relatively low, indicating that the house was relatively well sealed, explaining the relatively high daily average values of radon in both floors compared to the other measured locations. It is important to keep in mind that the layout of offices and houses determines different aerosol conditions and ventilation rates which may cause a variation in the radon concentration [8,9].

This study with its unique focus on the Maltese Islands, suggests a clear correlation between different meteorological parameters and indoor and outdoor radon concentrations. In addition, results highlight the influence of high indoor radon levels in basements (due to low air exchange rates) on ground level indoor concentrations. This is amplified when an interconnected door between the two levels is left open. This is of great importance to further study similar buildings for a longer period of time to quantify the number of households exposed to such high levels of radon and to educate the public on possible mitigation measures.

Declaration of Interest

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