Daily variation of radon gas and its short-lived progeny concentration near ground level and estimation of aerosol residence time*

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Atmospheric concentrations of radon (^{222}Rn) gas and its short-lived progenies ^{218}Po, ^{214}Pb, and ^{214}Po were continuously monitored every four hours at the ground level in Jeddah city, Kingdom of Saudi Arabia. The measurements were performed three times every week, starting from November 2014 to October 2015. A method of electrostatic precipitation of positively charged ^{218}Po and ^{214}Po by a positive voltage was applied for determining ^{222}Rn gas concentration. The short-lived ^{222}Rn progeny concentration was determined by using a filter holder connected with the alpha-spectrometric technique. The meteorological parameters (relative air humidity, air temperature, and wind speed) were determined during the measurements of ^{222}Rn and its progeny concentrations. ^{222}Rn gas as well as its short-lived progeny concentration display a daily and seasonal variation with high values in the night and early morning hours as compared to low values at noon and in the afternoon. The observed monthly atmospheric concentrations showed a seasonal trend with the highest values in the autumn/winter season and the lowest values in the spring/summer season. Moreover, and in parallel with alpha-spectrometric measurements, a single filter-holder was used to collect air samples. The deposited activities of ^{214}Pb and the long-lived ^{222}Rn daughter ^{210}Pb on the filter were measured with the gamma spectrometric technique. The measured activity concentrations of ^{214}Pb by both techniques were found to be relatively equal largely. The highest mean seasonally activity concentrations of ^{210}Pb were observed in the autumn/winter season while the lowest mean were observed in the spring/summer season. The mean residence time (MRT) of aerosol particles in the atmospheric air could be estimated from the activity ratios of ^{210}Pb/^{214}Pb.

Keywords: daily variation, radon progeny concentration, meteorological variables

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1. Introduction

The radionuclide radon (^{222}Rn) of the uranium (^{238}U) decay chain is a noble gas produced by the decay of ^{226}Ra in the Earth's crust. Once the ^{222}Rn (half-life time of 3.8 day) escapes from the upper crust of the Earth, it begins its journey in the atmospheric air via diffusion and advection. The spread of ^{222}Rn in the atmosphere after its exhalation from the ground surface is mainly caused by diffusion turbulence and is limited only by radioactive decay.[1] ^{222}Rn concentrations in the open air show from-site-to-site differences related not only to exhalation rates from the ground surface of the investigated area but also to the prevalent meteorological conditions and mainly to local atmospheric transport phenomena on the horizontal and vertical scale.[2–4] After the radioactive decay of ^{222}Rn, its progenies (heavy metals) rapidly attach to the surface of aerosol particles in the air forming the radioactive aerosols. Due to attachment, their behavior is largely determined by the physical behavior of the aerosol particles in the air. The elimination of these attached progeny from the atmospheric air occurs either by removal processes (dry deposition, washout, rainout) or radioactive decay.[1]

The variation of the concentration of ^{222}Rn gas and its progenies in the air depends on the meteorological conditions and height above the ground surface. In addition, the progeny concentration is influenced by the radioactive decay and the transport with the associated aerosols.[2,5] In Table 1, the attached short- and long-lived ^{222}Rn progeny in the atmosphere together with their activity concentration range is illustrated.[3] In this Table, the highest activity concentration results from the short-lived ^{222}Rn progenies (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po). The long-lived (half-life $>$ 1 day) ^{222}Rn progenies (^{210}Pb, ^{210}Bi, and ^{210}Po) show the lowest activity concentration. ^{210}Pb is often used as an atmospheric tracer for studying the meteorological processes and for investigating the dynamics of aerosol deposition. Particularly, the concentrations of ^{210}Pb in the troposphere are often higher than in the mid-altitudes due to removal in the latter region by rainfall, and formation from ^{222}Rn at height with a long residence time for ^{210}Pb. Moreover, the coagulation processes between the attached ^{210}Pb aerosol particles in the atmosphere have a

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dominant influence on its concentration and on the change of its original size distribution by deposition.[6]

Table 1. Activity concentration range of short- and long-lived ^{222}Rn progeny in free atmosphere near the ground level. (∗) refers to short-lived radon progeny: ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po; and (∗∗) refers to the long-lived radon progeny.[3]

Radionuclide	Half life	Activity concentration/ mBq·m^{-3}
Rn*	164 μs –26.8 min	1000–5000
^{210}Pb**	22.60 y	0.20–1.00
^{210}Bi**	5.01 d	0.05–0.20
^{210}Po**	138.40 d	0.03–0.30

About 50% of the mean received dose in the environment is derived by inhalation of the naturally occurring short-lived ^{222}Rn progeny.[4,7] Therefore, information on the fluctuations of short-lived ^{222}Rn progeny concentration with the meteorological parameters is important to study their behaviors. Moreover, the equilibrium equivalent concentration (EEC) is an important parameter to evaluate the radiation exposure from short-lived ^{222}Rn progeny in the environment. The determination of this parameter is a traditional procedure used to know the levels of exposure due to inhalation of short-lived ^{222}Rn progeny. The total attached aerosol concentration with short-lived ^{222}Rn progeny in the air, which is characterized by the equilibrium equivalent concentration (EEC), is given by [8]

$$\begin{aligned}\mathrm{EEC} &= 0.105(^{218}\mathrm{Po}) + 0.516(^{214}\mathrm{Pb}) \\ &\quad + 6\times 10^{-8}(^{214}\mathrm{Po}). \end{aligned} \tag{1}$$

Several researchers have measured the daily concentration variations of ^{222}Rn and its short-lived progenies in atmospheric air, but not limited.[9–15] They have found that the daily concentration variation exhibits correlation with the relative air humidity, and anti-correlation with the air temperature, which indicates that the concentration is mainly influenced by the turbulent diffusion caused by the changes in temperature. However, most of the observed concentrations show a maximum occurring in the early morning and a minimum in the late afternoon. The variation between maximum and minimum levels of concentration on the same day is an index of the maximum height of the mixed layer.[16]

2. Aerosol residence time in the atmospheric air

The estimation of mean residence times (MRT) of aerosol particles is associated with the atmospheric air boundary layer where most of the contaminations are found. Radioactive nuclides as tracers are useful for estimating the MRT due to their decrease with time, and most of these radionuclides after their production are attached immediately to the aerosol particles. The activity concentration ratio of attached ^{210}Pb to other attached radon daughters is used to evaluate the residence time of aerosol particles in the atmosphere.[17,18] Several researchers have estimated the MRT of atmospheric aerosol particles from the activity ratios of ^{210}Pb/^{222}Rn, ^{210}Bi/^{210}Pb, and ^{210}Po/^{210}Pb.[19–25] However, all these studies have indicated contradictions between the MRT obtained from these three pairs due to different processes, which include the reality that these radionuclides are attributable to different portions in the atmosphere. The advantages of the ^{210}Bi method are: i) the half-life of ^{210}Bi (5 d) is comparable to the MRT of aerosol particles and the water vapor is in lower atmospheric air than ^{210}Po;[19] ii) the changeable nature of ^{210}Po could result in additional sources of ^{210}Po to the atmosphere, which could change the residence time based on ^{210}Po/^{210}Pb pair.[26] However, most observations have indicated that the MRT obtained from the ^{210}Po/^{210}Pb ratios (8–65 days) is longer than that from the ^{210}Bi/^{210}Pb ratios (6–13 days). On the other hand, the activity ratio ^{210}Pb/^{214}Pb has been used to estimate the MRT of aerosol particles in the urban air.[27] This ratio is suitable to estimate the MRT since both radionuclides are gamma-emitters (can detect together) and the only source for ^{210}Pb in the air is ^{214}Pb. However, in the literature few data are available on the estimation of MRT by ^{210}Pb/^{214}Pb ratios, except Refs. [28] and [29]. Generally, the MRT changes widely according to the origin of ^{210}Pb as well as its concentration, which is governed mainly by the large scale of weather factors.

Representative data on the daily concentration variation of ^{222}Rn and its short-lived progenies are still not found or scarce in atmospheric air of this area (Jeddah city). Therefore, the first aim of this study is to carry out continuous measurements of daily concentration variation of ^{222}Rn and its attached short-lived progenies (^{218}Po, ^{214}Pb, and ^{214}Po), and to determine the basic meteorological conditions. Moreover, the meteorological parameters responsible for these variations will be discussed. In addition, due to the difference in opinions expressed by several researchers about the contradiction in the values of aerosol residence time, the second aim of this study is to estimate the seasonal variations of the aerosol residence time by determining the ratios between ^{210}Pb and ^{214}Pb concentrations. In addition, this will combine with the determination of the basic meteorological parameters.

3. Experimental measuring technique

3.1. Radon gas monitor

The ^{222}Rn gas concentration in atmospheric air has been determined by using a ^{222}Rn gas monitor. The monitor has been constructed to be similar to that employed and calibrated by[30]. The monitor is an aluminum sphere with a volume of 1.8 L and operates at a flow rate of 100 L·h^{-1}. The sphere incorporates a surface barrier detector with an active area of 300 mm^2 and a diameter of 19.5 mm. The detector is isolated in a PVC mounting. The volume of the aluminum sphere

(1.8 L) is adapted to the flow rate, taking the half-life time of ^{222}Rn (3.82 d) into consideration. Therefore, a residence time of about 0.02 h passes until a small fraction of ^{222}Rn decays to ^{218}Po. With a known amount of radon gas (using a standard radium solution source), the monitor could be calibrated.[30] Within three hours' counting interval, the ^{222}Rn gas monitor can detect down to 2 Bq·m^{-3} with 30% statistical uncertainty.[30] The uncertainties in ^{218}Po and ^{214}Po can be calculated from the propagation of uncertainties through the entire analysis procedure, and from the uncertainty due to alpha counting.

For the purpose of ^{222}Rn gas detection, the positively charged atoms of ^{218}Po were collected on a surface barrier detector by an applied positive voltage of 10 kV between the sphere and the detector surface, which is connected to an α-spectrometric system. The air was dried, filtered to remove the ^{222}Rn decay products, and sucked into the aluminum sphere. The alpha disintegrations of ^{218}Po could easily be counted and identified by the α-spectrometric system with an energy resolution of 80 keV. The count rates of ^{218}Po and ^{214}Po are proportional to the ^{222}Rn activity concentration in the air. A typical alpha particle energy spectrum is obtained and shown in Fig. 1. The greatest peak is due to ^{214}Po ($E_\alpha = 7.69$ MeV), whose emission is equal to that of its precursor ^{214}Bi, because ^{214}Po has a very short half-life of 164 μs. Another peak in the spectrum refers to ^{218}Po ($E_\alpha = 6.00$ MeV). The other peaks in the spectrum refer to the thoron ^{220}Rn decay products.

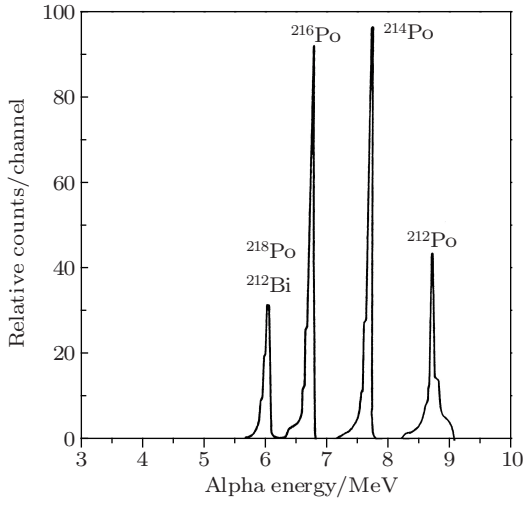


Fig. 1. Typical alpha particle energy spectrum of ^{222}Rn and ^{220}Rn progeny mixture resulting from electrode position on a surface barrier detector.

3.2. Determination of progeny concentration with alpha spectroscopy

The attached activity concentration of short-lived ^{222}Rn progeny in the open air was determined by using an alpha spectrometric technique. In this technique, a surface barrier detector mounted to a filter holder was applied. The air was drawn through a membrane filter by using a vacuum pump with a flow rate of 15 L/min. The filter used was a type Sartorius membrane filter type SM, 1.2 μm pore size, 25 mm diameter, and its efficiency is 99%. Since the radionuclides are collected on the filter, the surface barrier detector (diameter of 19.5 mm and active area of 300 mm^2) can register the alpha decay. The alpha particles were detected during and after air sampling. With a detector energy resolution of about 300±20 keV and a separation distance of 6 mm between the filter and the detector, it is easy to distinguish between the alpha-particle energies emitted during the decay of ^{218}Po (6.0 MeV) and ^{214}Po (7.8 MeV).[31] The detection efficiency of the system could easily be calculated using a Monte–Carlo method and be checked by a standard plane source. For the system geometry, which depends on the 4π emission, a detector counting efficiency of 17±0.5% was obtained.[32] The detector's detection efficiency does not depend on the energy range between ^{218}Po and ^{214}Po (6–7.8 MeV), i.e., it does not change with the α-energy in this range.

The measurements were carried out as follows: i) the alpha particle spectrum has been collected during a sampling with a time interval of 30 min; ii) after waiting for a time of 30 min without sampling, the alpha particle spectrum was measured again (during the decay time) for another 30 min. The purpose of the waiting time is to remove the ^{218}Po activity on the filter by radioactive decay. From the registered alpha-counts of ^{218}Po and ^{214}Po during the sampling period and alpha-counts of ^{214}Po during the decay time, the activity concentration of ^{218}Po, ^{214}Pb, and ^{214}Po in atmospheric air could be calculated.[31]

3.3. Determination of ^{214}Pb and ^{210}Pb activity concentration with gamma spectroscopy

The aerosol samples have been collected on a round glass fiber filter (125 mm diameter and a collection efficiency of 99%). The air samples were collected in parallel with the alpha spectrometric measurements mentioned above. The filter is placed on an open-faced filter holder mounted onto the inlet of a high-volume flow rate suction pump (50 m^3·h^{-1}). Due to the low concentration of ^{210}Pb in the air, the high flow rate was necessary for collecting detectable amounts. In each run, the air sucked for six hours and thus about 300 m^3 of air passed through the filter. Assuming a constant level of radioactivity in the air, the steady state concentration of ^{214}Pb on the filter will reach within about two hours. After the air-sampling procedure and by means of a hydraulic press, the filter was folded and pressed into a plastic cover in a tablet form. Therefore, the tablet was placed close to the active part of the detector, and the relative gross γ-ray emitting activities of ^{214}Pb and ^{210}Pb were detected for at least 24 hours. For calculation of the activity concentration of ^{214}Pb, the following formula was used:

$$C = N_o \lambda / IDQ \ (\mathrm{Bq \cdot m^{-3}}). \quad (2)$$

The previous formula is valid only if the sampling time is longer than the half-life time of the radionuclide. The following formula was applied for calculating the activity concentration of ^{210}Pb:

$$C = N_o\lambda^2/(1-e^{-\lambda t})(e^{-\lambda t_1}-e^{-\lambda t_2})IDQ\ (\mathrm{Bq\cdot m^{-3}}), \quad (3)$$

where N_o is the number of disintegrated radionuclides (in s^{-1}), λ is the decay constant of radionuclide (s^{-1}), I is the radionuclide transition probability, D is the detector efficiency, Q is the sampler air flow rate ($m^3{\cdot}s^{-1}$), t is the sampling time (s), t_1 is the difference in time between the end of air sampling and the beginning of detection, t_2 is the time difference between the end of air sampling and the end of detection (t_1 and t_2 are important for decay correction). From the activity ratio between ^{210}Pb and ^{214}Pb the aerosol residence time in the atmospheric air could be estimated by using the following approximation:[27]

$$\mathrm{MRT} = [C^{210}\mathrm{Pb}/C(^{214}\mathrm{Pb})] \times \lambda^{-1}_{\mathrm{Pb-210}}, \quad (4)$$

where $\lambda_{\mathrm{Pb-210}} = \ln 2/T_{1/2}(^{210}\mathrm{Pb})$.

4. Results and discussion

4.1. Activity concentration of radon and its short-lived progenies

The measurements of ^{222}Rn and its short-lived progeny concentration were carried out in Jeddah city. Jeddah is located on the eastern side of the Red Sea, South West of the KSA. Jeddah is located between latitudes 21°27′ and 21°30′ N, longitudes 39°9′ and 31°12′ E. Jeddah features an arid climate under Koppen's climate classification. It is directly affected by the climate of the geographic location, that is, high temperatures and humidity during the summer. The temperatures are around the early 40 s, when the city falls under the influence of a low seasonal zone with a solid and warm air mass. Humidity reaches its highest levels in summer (more than 85% and frequently 100%) because of the high temperature of seawater and it is lower in winter due to the impact of the moderate air mass associated with high pressure.

The most common type of rainfall is thunderstorms, which usually fall during the winter and spring seasons due to the passage of low pressure from the west to the east and their meeting with the low-pressure heat in the zone of Sudan.

The prevailing winds over Jeddah are north-west winds due to the city's coastal location on the shore of the Red Sea. The winds are usually light-to-moderate for most of the time in one year. However, sometimes southern winds blow through winter, spring and fall accompanied by a rise in temperature. These winds get active sometimes and their speed may cause great sandstorms. They may also be accompanied by thunderstorms and heavy rain. Dust storms happen in summer and sometimes in winter, coming from the Arabian Peninsula's deserts or from North Africa. The measurements were performed at a sampling site located at a height of two meters above the ground, flat area. This site is far from any direct pollution sources. Simultaneously, by using wireless weather station (Davis Instruments-6152), the local meteorological data, such as relative humidity, air temperature, and wind speed, were recorded. The obtained meteorological data were recorded every second and averaged for ten minutes' intervals. Since the measurements were performed continuously between November 2014 and October 2015, considerable fluctuations of ^{222}Rn and its short-lived progeny concentrations were observed due to different meteorological conditions during the year. The average activity concentrations of ^{222}Rn, ^{218}Po, ^{214}Pb, and ^{214}Po, the EEC over the four seasons, and the meteorological data along with their ranges of variations are listed in Table 2. The mean activity concentrations of ^{222}Rn, ^{218}Po, ^{214}Pb, and ^{214}Po over the year were found to be 9.8 ± 1.1, 7.6 ± 0.9, 5.5 ± 0.6, and 4.5 ± 0.3, respectively. These averages are lower than the published average values, which were determined in continental areas.[4,33] The present mean concentration value of ^{222}Rn is in quite good agreement with annual average values of 9.7 and 9.3 $\mathrm{Bq\cdot m^{-3}}$, which were obtained in India and Hong Kong, respectively.[36,37] A seasonal characteristic of high in winter and low in summer was also observed. A mean concentration value of ^{222}Rn of 5 ± 3.01 $\mathrm{Bq\cdot m^{-3}}$ was determined after three years of measurements from 2006 up to 2009 in the Qingdao area of China.[38] This mean value is considered typical for coastal regions but much lower than the average world concentration (10 $\mathrm{Bq\cdot m^{-3}}$).[34] However, the concentration of ^{222}Rn and its short-lived progenies in the air is governed by the type of soil from which radon is released; the flux density from the ground and the dispersion in the atmosphere, the latter is strongly influenced by weathering conditions. The statistical errors of the mean values were calculated from the analysis procedure of alpha counting.[31] A mean equilibrium equivalent concentration EEC of 3.71 ± 0.4 could be evaluated. Based on a mean atmospheric ^{222}Rn concentration of 9.8 $\mathrm{Bq\cdot m^{-3}}$, the annual effective dose in Jeddah is estimated using the following relationship:[34]

$$Y(\mu\mathrm{Sv}) = X(\mathrm{Bq\cdot m^{-3}}) \times 0.6 \times 1760\ (\mathrm{h}) \times 0.009\ \mu\mathrm{Sv}\ (\mathrm{Bq\cdot h\cdot m^{-3}})^{-1}, \quad (5)$$

where 0.6 is the average equilibrium factor of ^{222}Rn to its progeny outdoor, 0.009 μSv $(\mathrm{Bq\cdot h\cdot m^{-3}})^{-1}$ is the dose conversion factor of ^{222}Rn, and 1760 h is the average total duration for human activity outdoors in a year. The calculated annual atmospheric ^{222}Rn dose in the present study was around 93 μSv.

Table 2. Seasonal average activity concentrations of ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Po, EEC, and meteorological parameters (extreme values within each season in parenthesis) for surface air measurements at Jeddah city. The measurements were performed with the alpha spectrometric technique.

Season	Average activity concentration/Bq·m^{-3}					RH/%	Temp/°C	WS/m·s^{-1}
	^{222}Rn	^{218}Po	^{214}Pb	^{214}Po	EEC			
Winter	12.3	10.2	8.5	7.1	5.46	58	26	3.6
Nov.–Jan.	3.4–14.1	2.8–12.7	2.2–10.5	2.0 –8.9	1.4–6.8	16–94	15–37	1–2.3
Spring	8.4	6.1	4.3	3.3	2.85	56	27	3.92
Feb.–Apr.	1.9–10.2	1.4–9.2	1.1–7.2	0.8–5.7	0.7–4.7	8–89	17–39	1–12.3
Summer	8.9	6.8	4.5	3.5	3.24	53	32	3.99
May–July	2.6–10.9	2.1–9.8	1.5–7.5	1.1–6.0	1.0–4.9	4–94	22–49	1–12.3
Autumn	9.7	7.3	4.9	4.0	3.29	63	31	3.67
Aug.–Oct.	2.1–10.5	1.5–9.1	0.9–6.8	0.8–5.2	0.6–4.5	24–100	22–40	0.5–10
Mean	9.8±1.1	7.6±0.9	5.5±0.6	4.5± 0.3	3.71±0.4			

4.2. Seasonal variation

The meteorological processes are responsible for the seasonal variation of ^{222}Rn and its progeny concentrations in the boundary layer. The seasonal pattern of ^{222}Rn and its short-lived progeny concentration reflects the regional weather conditions prevailing at Jeddah city. For the four seasons, the average daily variations of these concentrations are shown in Fig. 2(a). The seasonal patterns were observed for the diurnal variations. For every season, the hourly mean values were averaged day-by-day and month-by-month to give an overall mean value for each hour of the day. During the autumn/winter months, strong inversion layers lead to higher concentration values. These strong inversion layers cause an enrichment of radioactive nuclides in the lower atmosphere. The minimum concentration values indicate higher turbulence in the atmosphere. In the autumn/winter season, the decrease in temperature and the increase of air humidity lead to a build-up of activity concentration in the air. In the spring/summer season, the convection currents are activated due to the higher temperature. Therefore, ^{222}Rn and its progeny transfer to the upper boundary layer of atmospheric air and there will be no enrichment of radioactivity in the lower layers. The average value of EEC (5.46 Bq·m^{-3}) in the winter season is higher than the summer season average value (3.24 Bq·m^{-3}). This is attributed to the higher air humidity in the winter season (mean value 58%) which increases the attachment rate of ^{222}Rn progeny to aerosol particles.[35] In spring, the EEC average value (2.85 Bq·m^{-3}) was found to be relatively smaller than that in the summer season (3.24 Bq·m^{-3}). Sometimes in the spring season, a number of atmospheric depressions, which are associated with hot winds, carried dust particles. This leads to the increase of air turbulences, which cause ^{222}Rn and its attached progenies to distribute over a wide range from their sources and therefore lower concentrations, observed near the ground. In the autumn season, the average value of EEC (3.29 Bq·m^{-3}) was found to be near the average value of the summer season.

The monthly mean values of diurnal variations of ^{222}Rn and its progeny concentration over one year of observation are shown in Fig. 2(a). It can be observed that the concentration is a maximum during the night and early morning hours (around 4 a.m. local time) of low turbulent mixing, which indicates a stable atmosphere at temperature inversions. The stable atmosphere means low transport into higher layers of atmospheric air due to high-pressure weather. Generally, mixing in the lower atmosphere is the strongest at noon (12 p.m. local time) and the air is unstable, resulting in low ^{222}Rn and its progeny concentrations. In the afternoon, mixing in the lower atmosphere becomes weak and therefore the concentration is slightly increased. Heating of the Earth's surface by the sun during the day and remixing of radon and its progenies take place in increasingly higher layers with a consequent decrease in concentration, and cooling air near the ground during the night accumulates ^{222}Rn isotopes from surface flux, causing a marked diurnal change in temperature near the surface. Figure 2(b) shows that the daily variation of relative humidity is inverse to that of temperature. Mostly, the maximum humidity is reached at night and in the early morning, followed by a steady decrease until the minimum in the afternoon, and *vice versa*. The obtained concentrations show a correlation with relative air humidity and anti-correlation with air temperature. This means that the concentration is influenced mainly by turbulent diffusion caused by changes in temperature. However, the variation on the same day between maximum and minimum concentration levels is an index of the maximum height of the mixing layer.[25] Generally, during a single day, the variation in concentrations was caused by the changes in the eddy diffusivity of the boundary layer.[36]

The inverse correlation between ^{222}Rn as well as its progenies with wind speed was related mainly to atmospheric turbulent processes. During strong winds, lower activity concentrations were observed near the ground. During calm weather, the concentrations reached higher values, which means that radon is produced locally. The differences between day and night concentrations were found to be small in cloudy weather. In principle, the results of this study show that daily variations of radon and its short-lived progeny concentrations are relatively similar to patterns observed worldwide.[1,9,10,12,14,36]

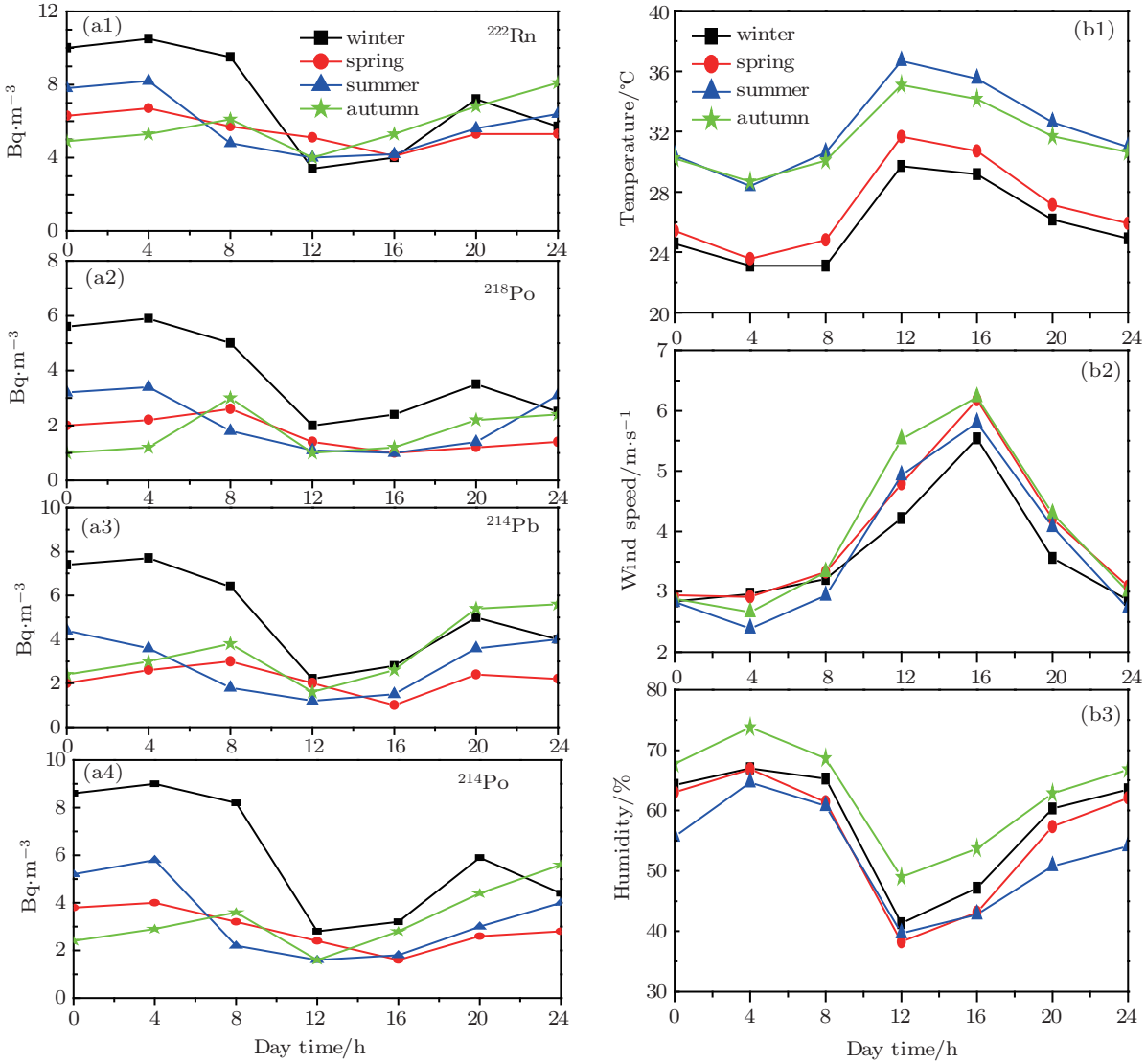


Fig. 2. (color online) (a) Average diurnal variation of ^{222}Rn and its short-lived progeny concentration for each season over a period of one year (November 2014-October 2015) for surface air measurements at Jeddah, KSA. (b) Average diurnal variation of relative humidity, air temperature and wind speed for each season over the same period of a year (November 2014-October 2015) for surface air measurements at Jeddah, KSA.

4.3. Daily variation

4.4. Activity concentration of ^{214}Pb and ^{210}Pb

The average activity concentrations of ^{214}Pb and ^{210}Pb, average activity ratios of ^{210}Pb/^{214}Pb, and mean residence time over the four seasons are listed in Table 3. The obtained average concentration value of ^{214}Pb was found to be close to the mean value obtained by the alpha spectrometric technique measurements (compare Tables 2 and 3). The activity concentrations of ^{210}Pb over the four seasons were found to be 6, 4, 3.9, and 4.7 with a mean concentration value of 4.6 mBq·m^{-3} (see Table 3). However, no significant differences have been observed in the activity concentrations of ^{210}Pb because most of long-lived radionuclides are removed very slowly from the atmosphere, and therefore the deposited activities that reach the ground surface will be low.[6] The obtained mean value is higher than the activity concentration range (0.2–1 mBq·m^{-3})[3] (see Table 1). In addition, this mean value was observed to be higher in autumn/winter months, which may be attributed to frequent inversion conditions of the surface layer, resulting in a build-up of radon and its progeny in the ground level air. The lower mean concentration in the spring/summer months is related to the efficient mixing of the troposphere caused by solar heating. Generally, the seasonal variations are attributed to the efficiency of vertical mixing of the lower atmosphere. The statistical errors in the mean values of ^{214}Pb and ^{210}Pb were calculated from the propagation of uncertainties through the entire analysis procedure of the filter evaluation.

4.5. Atmospheric aerosol residence time from ^{210}Pb/^{214}Pb ratio

Over the four seasons, different seasonal average ratios of ^{210}Pb/^{214}Pb have been observed. It varied between 7.4×10^{-4} and 1.02×10^{-3} with a mean value of $8.6\times10^{-4}\pm5.6\times10^{-5}$ (see Table 3). From the calculations based on the ^{210}Pb-^{214}Pb

couple, the obtained mean residence time (MRT) was estimated to be 9.9±0.68 d (range: 1.04–15.6 d), which is higher than a value of 6 d obtained in Ref. [27]. With the same activity ratio of ^{210}Pb/^{214}Pb, the present value of MRT is close to the value estimated in Egypt,[28] where a mean value of 10.5 d has been estimated, but a residence time between 1-2 days was evaluated in Italy.[29] Although no statistically significant differences were obtained in the present evaluation, the seasonal averages show a longer MRT in spring (11.8 d) and summer (9.8 d) than in autumn (9.5 d) and in winter (8.6 d). In addition, the present results suggest that the aerosol particles at the same location may display different MRTs with seasons. The obtained seasonal MRT differed to some extent with values in other countries, which is mainly due to the differences in weather conditions. The spring season in Jeddah city is characterized by a passage of a number of hot atmospheric depressions loaded with dust particles, which leads to an increase of atmospheric turbulences. In this case, both radionuclides distribute over a wide range from their sources. In the summer season, the air temperature reaches sometimes to its maximum value (49 °C). Therefore, both the radionuclides transfer by convection currents to the upper boundary layer of the atmospheric air resulting in low concentrations at the ground surface. Due to the removal by frequent precipitation, the MRT became relatively lower in the winter/autumn season. This is attributed to the relatively higher air humidity and lower temperature, which increases the condensation and coagulation processes between the attached radionuclides. Therefore, a continuous increase especially in the aerosol coarse mode particle size will take place, which increases the deposition probability.[6] However, the MRT varies widely owing to the origin of ^{210}Pb and its concentration, which is controlled mainly by the large scale of meteorological conditions. Figure 3 shows the monthly MRT of atmospheric aerosol particles. In this figure, the mean standard deviations of monthly values are attached to the mean values.

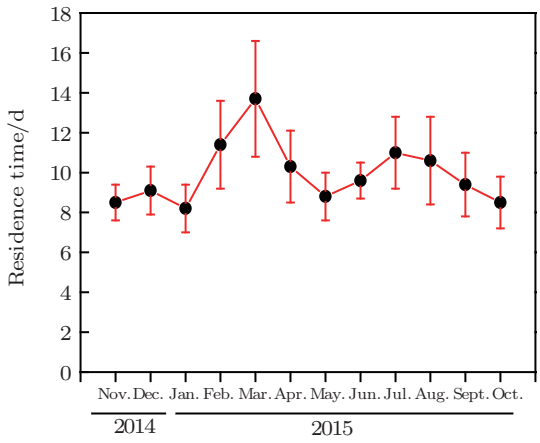


Fig. 3. (color online) Monthly mean residence times of atmospheric aerosols in Jeddah, KSA. The mean standard deviations of monthly values are attached to the mean values.

Table 3. Average activity concentrations of ^{214}Pb, ^{210}Pb, average activity ratios of ^{210}Pb/^{214}Pb and mean residence time (MRT). The measurements were performed with the gamma spectrometric technique.

Season	^{214}Pb/Bq·m^{-3}	^{210}Pb/mBq·m^{-3}	^{210}Pb/^{214}Pb	MRT/d
Winter	8.2±0.45	6 ± 0.08	7.4×10^{-4}	8.6±1.1
Nov.–Jan	2.0–10.1	0.18–9.46	0.9×10^{-4}–9.3×10^{-4}	1.04–10.8
Spring	3.9±0.29	4 ± 0.02	10.2×10^{-4}	11.8±2.3
Feb.–Apr.	1.4–6.8	0.2–9.2	1.4×10^{-4}–13.5×10^{-4}	1.6–15.6
Summer	4.6±0.33	3.9 ± 0.015	8.5×10^{-4}	9.8±1.3
May–July	1.6–7.9	0.5–8.7	3.1×10^{-4}–11×10^{-4}	3.6–12.9
Autumn	5.5±0.24	4.7 ± 0.013	8.2×10^{-4}	9.5±1.7
Aug.–Oct.	1.1–7.3	0.3–7.5	2.7×10^{-4}–10.2×10^{-4}	3.1–11.8
Mean	5.55±0.94	4.65 ± 0.48	$8.6\times10^{-4}\pm0.56\times10^{-4}$	9.9±0.68

5. Conclusions

We conclude that the mean activity concentrations differ from the obtained values in other countries as a result of differences in locations and meteorological factors. The daily variations, for the analyzed period, of radon and its short-lived progeny concentrations display a constant dynamic as reported in the literature. Cities that have the same concentrations of ^{222}Rn and its progeny, like the one studied here, can possibly be found in many countries and may become sources of information regarding the effect on the health of low doses due to the exposure to ^{222}Rn progenyoutdoors. The influence of the meteorological conditions is evident in the daily and seasonal variations of ^{222}Rn and its progeny concentrations in the boundary layer. More studies on the residence time of radioactive aerosols using the ^{210}Pb/^{214}Pb ratio are necessary with respect to altitude and latitude and to validate this observation. Moreover, long-term series of measurements for the concentration levels are necessary in the future for studying processes of dispersion characteristics of atmospheric pollutants.

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