Temporal Variations in Radionuclide Activity (^7Be and ^{210}Pb) in Surface Aerosols at a Coastal Site in Southeastern China

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ABSTRACT

Monitoring radionuclides in aerosols is critical to understanding the factors influencing the temporal variations in the atmospheric deposition of elements such as ^7Be and ^{210}Pb , which are frequently used as tracers in atmospheric studies. However, long-term monitoring at a high temporal resolution remains limited, especially in Asia. Therefore, in this study, we measured the radioactivity of the ^7Be and ^{210}Pb in surface aerosols collected on a weekly basis in a coastal city (Xiamen) in southeastern China from 2013 to 2015 (110 samples in total). The activity of the ^7Be and ^{210}Pb ranged from 0.17 to 9.84 mBq m^{-3} (mean: $4.37 \pm 2.65 \text{ mBq m}^{-3}$) and from 0.17 to 3.31 mBq m^{-3} (mean: $1.26 \pm 0.78 \text{ mBq m}^{-3}$), respectively. Compared to reports from other regions, the ^{210}Pb activity, on average, was high, which may be related to the elevated ^{226}Ra activity in the soil in southeastern China. Also, the annual mean of the ^7Be activity was significantly correlated with latitude in the coastal region. Despite the difference in origin, the weekly ^7Be and ^{210}Pb activity was significantly correlated ($r = 0.679$, $p < 0.001$, $n = 110$) and showed similar temporal variations, with higher values during the cold dry season. The activity of both radionuclides was negatively correlated with the temperature and precipitation and positively correlated with the fine particle ($\text{PM}_{2.5}$) concentration. The combined effective dose of the ^7Be and ^{210}Pb is approximately 5.7% of the limit for humans; thus, natural radioactivity should be considered as a potential threat to human health, especially in regions with high $\text{PM}_{2.5}$ concentrations.

Keywords: ^7Be ; ^{210}Pb ; Aerosol; Coastal city; Environmental radioactivity.

INTRODUCTION

Natural airborne radionuclides (^7Be and ^{210}Pb) serve as powerful tracers for identifying and quantifying several atmospheric processes, such as the source, transport, and mixing of air masses; air mass exchanges between various atmospheric layers; and the residence times of atmospheric gasses and pollutants (Beks *et al.*, 1998; Heikkilä *et al.*, 2008; Papastefanou, 2009b; Poschl *et al.*, 2010; Baskaran, 2011; Lal and Baskaran, 2012; Du *et al.*, 2015; Zhang *et al.*, 2015). Therefore, it is important to understand the temporal and spatial variations of natural airborne radionuclides and influencing factors.

Cosmogenic ^7Be is formed primarily from the cosmic-ray spallation of oxygen and nitrogen in the stratosphere, troposphere, and surface of the earth (Kaste *et al.*, 2002).

^7Be is a particle-reactive nuclide that has a constant source with suitable activity. This nuclide has been widely used to trace the transport of suspended particles in the atmosphere and in estuaries and the open ocean (Baskaran *et al.*, 1993; Su *et al.*, 2003; Huang *et al.*, 2013; Du *et al.*, 2015). ^{210}Pb ($\tau = 22.1 \text{ a}$) is continuously produced from ^{222}Rn in the atmosphere, and ^{222}Rn emanates primarily from the land surface. ^{210}Pb may rapidly attach to aerosol particles, which is mainly accomplished via washout by precipitation from the atmosphere (Baskaran, 2011; Pham *et al.*, 2012; Du *et al.*, 2015). ^7Be and ^{210}Pb can be widely used to trace the sources, transport processes, and mixing of aerosols, as ^7Be is produced in the stratosphere and upper troposphere and ^{210}Pb is produced in the lower troposphere.

Earlier studies have found that ^{210}Pb is associated with fine particles (Schneider *et al.*, 1983; Winkler *et al.*, 1998). Compared to coarse particles, fine particles have a larger influence on human health, especially particles with an aerodynamic diameter of $< 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) (Chen *et al.*, 2018; Lu *et al.*, 2019). Long-term exposure to $\text{PM}_{2.5}$ can increase the risk of respiratory and cardiovascular diseases (Wang *et al.*, 2018). Some pollutants (e.g., ^{210}Pb , metals,

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sulfates, and polycyclic aromatic hydrocarbons) may be transported with fine atmospheric particles (Schneider *et al.*, 1983; Hu *et al.*, 2002; Hu *et al.*, 2012; Zhang *et al.*, 2018). ^{210}Pb and ^{210}Po are significant contributors to internal irradiation in humans by natural alpha emitters (Winkler and Rosner, 2000; IAEA, 2017). Therefore, understanding the factors influencing the temporal variations in ^{210}Pb and ^7Be also has important implications for public health.

One important aspect is the large temporal variability of these natural radionuclides (Preiss *et al.*, 1996). The wet atmospheric deposition fluxes of ^7Be and ^{210}Pb in Xiamen were reported in 2001–2013, and the temporal variation was assessed (Jia *et al.*, 2003; Yi *et al.*, 2007; Wang *et al.*, 2014; Zhang *et al.*, 2015; Chen *et al.*, 2016). Although a large database of the atmospheric deposition of ^7Be or ^{210}Pb around the world is available, data are scarce in Asia, especially data on the factors influencing the temporal variation of ^7Be and ^{210}Pb in aerosols. Here, we present weekly variations in ^7Be and ^{210}Pb in aerosol particles in a coastal city in southeastern China. Our objectives were to characterize the temporal variation in radioactivity and its influencing factors. We further calculated the effective doses and evaluated their influence on public health.

MATERIALS AND METHODS

Study Area

Xiamen is a city located on the southeastern coast of China. Xiamen features a subtropical monsoon climate characterized as Cfa by the Köppen climate classification (Kottek *et al.*, 2006). The summer is hot and humid, while the winter is mild and dry. Northeastern winds from land prevail in the winter, and southeastern winds from the ocean prevail in the summer (Bao *et al.*, 2018). The average annual temperature is 20.8°C, and the annual precipitation

has been approximately 1,200 mm during the past 50 years.

Meteorological data (including daily rainfall amount, daily maximum temperature (Tmax) and daily minimum temperature (Tmin)) were obtained from <https://rp5.ru/>, while daily air quality data (including $\text{PM}_{2.5}$ and PM_{10}) were obtained from <https://www.aqistudy.cn/historydata/>. Detailed information is provided in Supplementary Fig. S1.

Sampling and Measurement

The aerosol particles were collected on the roof of the isotopic building at the Third Institute of Oceanography in Xiamen (approximately 15 m above the ground; Fig. 1). The building is located at a distance of 50 m from Xiamen Bay, which is part of the coastline of the Taiwan Strait.

The aerosol particles for the radioactivity assessment were collected using a super high-volume sampler (MDS-600; TRACERLAB GmbH). The air was filtered through a 60×60 cm Petrianov FPP-15-1.5 filter. The sampling time ranged from 14 h to 24 h, and the average flow rate was $800 \text{ m}^3 \text{ h}^{-1}$. Therefore, the total sample volume in a filter was 11,000–19,000 m^3 , with an average value of 14,000 m^3 .

The activity of nuclides in the filter was directly determined with an HPGe detector (BE6530; Canberra), with a 60% counting efficiency and energy resolution of 2.2 keV (at 1332 keV). The activity of nuclides ^{210}Pb (46.5 keV) and ^7Be (477.6 keV) was determined for 2–3 h since most background nuclides (^{214}Pb , ^{214}Bi , etc.) decay sharply after 1 week (Wang *et al.*, 2012). The efficiency curve was obtained by LabSOCS (Lépy *et al.*, 2001; Bronson, 2003; Du *et al.*, 2008). The ^7Be activities were corrected for radioactive decay from the middle of the collection time to the middle of the counting time (Kim *et al.*, 1998; Du *et al.*, 2015). In addition, the minimum detection levels (MDLs) for ^7Be and ^{210}Pb in the aerosols were 0.03 mBq m^{-3} .

Fig. 1. Sampling location in Xiamen (southeastern coast of China). The figure was drawn using ODV software (Schlitzer, 2015).

Statistical Analysis

Pearson's correlation was performed to examine the correlation between radionuclide activity and meteorological parameters. All analyses were performed using MYSTAT.

RESULTS

Meteorological Conditions during the Sampling Period

The average monthly temperature ranged from 12.7–29.4°C from September 2013 to December 2015, and the maximum and minimum temperatures were in July and February, respectively. The average precipitation was 0.1–469.0 mm month⁻¹ during the sampling period. The maximum monthly precipitation occurred in August 2015, while the minimum monthly precipitation occurred in January 2014 (Supplementary Fig. S1).

During our sampling period in 2013–2015, the mean wind direction was from the north or northeast from October to December (Supplementary Fig. S2), from the east from January to March, and from the southwest or southeast from May to August.

Temporal Variations in the Activities of ⁷Be and ²¹⁰Pb

The weekly activities of ²¹⁰Pb and ⁷Be in aerosols ranged from 0.17 to 3.31 mBq m⁻³ (mean: 1.26 ± 0.78 mBq m⁻³) and from 0.17 to 9.84 mBq m⁻³ (mean: 4.37 ± 2.65 mBq m⁻³), respectively, from Oct. 2013 to Dec. 2015 (Figs. 2(a) and 2(b)). As shown in Fig. 2, the highest and lowest activity values for ⁷Be appeared on Oct. 8, 2014, and Nov. 9, 2015, respectively, while the highest and lowest activity values for ²¹⁰Pb occurred on Jan. 2, 2014, and May 23, 2014,

respectively.

Based on the weekly activities of ⁷Be and ²¹⁰Pb, the average monthly activities of ⁷Be and ²¹⁰Pb ranged from 1.18 to 7.62 mBq m⁻³ and from 0.34 to 2.57 mBq m⁻³, respectively. The highest monthly ⁷Be (7.62 ± 0.97 mBq m⁻³) and ²¹⁰Pb (2.57 ± 0.49 mBq m⁻³) activities were observed in Oct. 2013 and Dec. 2013, respectively. The monthly ⁷Be activity decreased from October to September, while the monthly variation in ²¹⁰Pb showed a clear “U” shape, with the lowest value appearing in June–July (Fig. 3). A similar pattern was observed in other coastal regions (Vecchi *et al.*, 2005; Dueñas *et al.*, 2011).

The ratio of ⁷Be/²¹⁰Pb ranged from 2.19 to 8.17, with an average value of 4.00 (Figs. 2(c) and 3). More than half of the samples had a ⁷Be/²¹⁰Pb ratio in the range of 2–4. No significant seasonal trend was observed for this ratio.

DISCUSSION

The ⁷Be and ²¹⁰Pb Activity Levels in Xiamen: A Comparison with Other Regions

The ²¹⁰Pb activity in aerosols may be controlled by the presence of significant land masses within the prevailing wind direction, resuspension of dust, and the wet deposition and vertical mixing of air (IAEA, 2017). Preiss *et al.* (1996) collected ²¹⁰Pb activities in surface air around the world, and the annual average activity of ²¹⁰Pb was 0–1.0 mBq m⁻³. Due to the large land masses, the highest ²¹⁰Pb activities were observed in the subtropical and temperate latitudes of the Northern Hemisphere (IAEA, 2017). Table 1 summarizes the ²¹⁰Pb activity observed in

Fig. 2. Weekly variations in (a) ⁷Be activity, (b) ²¹⁰Pb activity, and (c) ⁷Be/²¹⁰Pb ratio in aerosols in Xiamen.

Fig. 3. Monthly variations in ^7Be and ^{210}Pb activity and the $^7\text{Be}/^{210}\text{Pb}$ ratio in aerosols in Xiamen.

Table 1. Variations in ^{210}Pb activities (mBq m^{-3}) in the surface air around the world.

Location	Activity range	Average activity	Sample time	Data source
Xiamen	0.17–3.31	1.26 ± 0.78	2013–2015	This study
Detroit	0.30–4.22	1.2	1999–2001	(McNeary and Baskaran, 2003)
Belgrade	0.30–3.17	1.2	1985–1996	(Todorovic <i>et al.</i> , 2000)
Málaga, Spain	0.28–0.92	0.52	1992–1999	(Dueñas <i>et al.</i> , 2005)
Málaga, Spain	0.24–1.44	0.54	2000–2006	(Dueñas <i>et al.</i> , 2009)
Granada, Spain	0.2–1.1	0.57	1993–1997	(Azahra <i>et al.</i> , 2004)
Milan, Italy	0.22–1.31	0.70–0.82	2000–2001	(Vecchi <i>et al.</i> , 2005)
Tsukuba, Japan	0.2–0.8	0.45	1988–1992	(Sato <i>et al.</i> , 1994)
Palermo, Italy	0.136–3.390	0.98	1995–1996	(Cannizzaro <i>et al.</i> , 1999)
South Germany	0.38–0.72	0.57	1972–1999	(Winkler and Rosner, 2000)
Grenade	0.2–1.1	N.A.	1993–1997	(Azahra <i>et al.</i> , 2004)
Lisbon	0.036–0.524	0.181 ± 0.111	1986–1989	(Carvalho, 1995)
Svalbard, Finland	0.011–0.62	N.A.	1991–2000	(Paatero <i>et al.</i> , 2003)
Mangalore, India	0.13–3.4	1.0 ± 0.73	2014–2017	(Mohan <i>et al.</i> , 2018)
Kaiga, India	0.3–3.4	1.3 ± 0.73	2014–2017	(Mohan <i>et al.</i> , 2018)

N.A.: not available.

some previous studies. The ^{210}Pb activity in Xiamen was comparable with that in Detroit and Belgrade and higher than the values reported for other regions. The high activity of ^{210}Pb may be related to local sources. The ^{226}Ra (parent of ^{222}Rn) activity in Fujian Province (Xiamen is one coastal city of Fujian Province) in the surface soil (54 Bq kg^{-1}) is especially high in China (36.6 Bq kg^{-1}) (MEP, 2014), which is related to the magmatic bedrock in Fujian Province (Zhuo *et al.*, 2008a; MEP, 2014; Huang and Yu, 2017). Corresponding to the higher ^{226}Ra activities in the soil in southeastern China, the ^{222}Rn flux in southeastern China is generally higher than the average flux for all of China and around the world (UNSCEAR, 2000; Zhuo *et al.*, 2008b).

The production rates of ^7Be vary with latitude, as the transport of cosmogenic particles, production rates, and

their transport pathways are affected by the intensity of the geomagnetic field (Liu *et al.*, 2001; Papastefanou, 2009a). Du *et al.* (2015) concluded that wet ^7Be depositional fluxes increase with latitude. The depositional fluxes of ^7Be at 23 stations around the world are summarized in Fig. 4. A significant relationship between the annual mean activity of ^7Be and latitude can be observed in the global samples ($R^2 = 0.21$, $n = 21$ (excluding Waliguan and Edinburgh), $p < 0.01$; Fig. 4(a)). However, due to large differences in geographical and meteorological conditions among those stations, the correlation coefficient suggests that latitude explains approximately 20% of the variation. To better elucidate the influence of latitude on the ^7Be activity, the ^7Be activity data from 8 coastal stations with similar elevations and geomagnetic fields along the eastern coast of

Fig. 4. The latitudinal variation in annual depositional fluxes of ^7Be (mBq m^{-3}) at (a) stations around the world and (b) stations in coastal cities in China. The stations are (1) Beijing (Zhu *et al.*, 2014); (2) Qingdao (Yang *et al.*, 2013); (3) Haiyan (Jiang, 1995); (4) Hangzhou (Jiang, 1994); (5) Xiamen (this study); (6) Guangzhou (Yang *et al.*, 2011); (7) Shenzhen; (8) Shenzhen (Song *et al.*, 2003); (9) Edinburgh (Likuku, 2006); (10) Waliguan (Zheng *et al.*, 2005); (11) Palermo (Cannizzaro *et al.*, 2004); (12) Yamagata (Kikuchi *et al.*, 2009); (13) Granada (Azahra *et al.*, 2004); (14) El Arenosillo, El Carmen, and La Rabida (Lozano *et al.*, 2011); (15) Lanzhou (Wu *et al.*, 2011); (16) Xi'an (Chang *et al.*, 2008); (17) Málaga (Gordo *et al.*, 2015); (18) Daejeon (Chae *et al.*, 2011); (19) Islamabad (Ali *et al.*, 2011); (20) Kuwait (Al-Azmi *et al.*, 2001); and (21) Guiyang (Lee *et al.*, 2004).

China were selected. As shown in Fig. 4(b), the relationship between the depositional flux of ^7Be and latitude along the eastern coast of China was much more significant than that observed globally ($R^2 = 0.89$, $p < 0.001$, $n = 8$), suggesting that the overall ^7Be deposition in coastal regions is strongly controlled by latitude.

The $^7\text{Be}/^{210}\text{Pb}$ activity ratios in aerosols are significantly lower than those in bulk precipitation samples ($2.06\text{--}40.0$, averaging 10.9 ± 2.3) (Chen *et al.*, 2016). First, this may be attributed to the difference in the scavenging functions of ^7Be and ^{210}Pb . Most of the ^7Be is removed by precipitation at ground level, while larger amounts of ^{210}Pb are produced from the decay of ^{222}Rn , which can attach to aerosols and be removed by the dry depositional process (McNeary and Baskaran, 2003).

Factors Influencing the Temporal Variations in ^7Be and ^{210}Pb Activities

During our sampling period, the weekly ^7Be and ^{210}Pb activities varied by a factor of 59 and 19, respectively. This variation is much larger than that in earlier observations in Granada, Spain (Azahra *et al.*, 2004). As shown in Fig. 2, the variations in ^7Be and ^{210}Pb in some months (e.g., May 2014, Sep. 2014, and Sep. 2015) were comparable to their annual variations, suggesting that ^7Be and ^{210}Pb are highly dynamic. The activities of ^{210}Pb and ^7Be were significantly correlated during our sampling period (Fig. 5). A significant correlation between ^7Be and ^{210}Pb ($R^2 = 0.53$) was also observed during wet deposition (Chen *et al.*, 2016), which indicates that to some degree the variations in ^7Be and ^{210}Pb are controlled by similar processes. However, the correlation coefficient between the weekly ^7Be and ^{210}Pb values in our samples ($R^2 = 0.46$) suggests that they were

also affected by different factors related to differences in their sources.

Overall, the temporal distributions of ^7Be and ^{210}Pb in the surface air are determined by the source and scavenging processes in the air, which are in turn influenced by several factors, such as regional precipitation, humidity, and air temperature. Here, we correlated the ^7Be and ^{210}Pb activities with environmental parameters (e.g., total suspended particulate concentration (TSP), $\text{PM}_{2.5}$, PM_{10} , Tmax, Tmin, and precipitation) to explore the factors influencing the temporal variations in ^7Be and ^{210}Pb .

Factors Influencing the Weekly Variation in ^{210}Pb Activities

Variation in ^{210}Pb activity can be produced by variations in the local radon emanation rates, the height of the atmospheric boundary layer, meteorological parameters, temperature inversions, precipitation, and soil moisture content (Suzuki *et al.*, 1999; Wan *et al.*, 2005; Du *et al.*, 2008; Baskaran, 2016). Significant correlations were found between ^{210}Pb and temperature, TSP, $\text{PM}_{2.5}$, and PM_{10} (Fig. 5).

Because both ^7Be and ^{210}Pb are particle-reactive radionuclides, they should in theory be affected by particle concentrations. As shown in Fig. 5, weekly ^{210}Pb was significantly correlated with $\text{PM}_{2.5}$ and PM_{10} . This correlation has not been reported before. The correlation coefficient suggests that $\text{PM}_{2.5}$ can explain more than 50% of the variation in ^{210}Pb in aerosols. Interestingly, the correlation was more significant between ^{210}Pb and $\text{PM}_{2.5}$ (and PM_{10}) than between ^{210}Pb and TSP, which is consistent with an earlier study that indicated that the ^{210}Pb activity is higher in fine particles than in coarse particles (Winkler *et al.*, 1998).

Fig. 5. Linear correlation coefficients of weekly ${}^7\text{Be}$ and ${}^{210}\text{Pb}$ activities with PM_{2.5}, PM₁₀ and temperature. All the correlations are significant at the 0.01 level (2-tailed).

A significant negative correlation was observed between weekly ${}^{210}\text{Pb}$ and temperature (Fig. 5). This finding contrasts with observations in an inland region (Azahra *et al.*, 2004) and is consistent with an earlier study in a coastal region (Wan *et al.*, 2005), which further suggests that temperature plays an important role in affecting the atmospheric deposition of ${}^{210}\text{Pb}$ along coasts. On the one hand, the release of ${}^{222}\text{Rn}$ is normally low in June–August when the temperature is high, whereas it is high in December and January when temperatures are low in the Northern Hemisphere (Cheng *et al.*, 2001; Zahorowski *et al.*, 2005). On the other hand, the scavenging process may also play a role. Wet deposition (i.e., rainout and washout) is the

predominant mechanism contributing to the total deposition (and scavenging) (Kikuchi *et al.*, 2009; Laguionie *et al.*, 2014). An earlier study found that the wet deposition fluxes of ${}^{210}\text{Pb}$ were positively correlated with rainfall precipitation at the same location (Wang *et al.*, 2014; Chen *et al.*, 2016). The distribution of rainfall has distinct wet and dry periods. The wet period is from May to October, with higher temperatures. As rainfall increases, more ${}^{210}\text{Pb}$ may be scavenged, and the activity of ${}^{210}\text{Pb}$ in aerosols decreases. In our study, average ${}^{210}\text{Pb}$ showed a significant negative relationship with average precipitation (Fig. 6(a)) on the monthly scale, which further indicates that the scavenging process also affects ${}^{210}\text{Pb}$ in aerosol particles.

Temperature also explained the lower ^{210}Pb observed in Nov. and Dec. 2015 compared to that during the same months in 2013 and 2014, as the maximum temperature was much higher than that in 2013 and 2014 (Supplementary Fig. S1). Overall, compared to the fine particle concentration, temperature and precipitation played less significant roles in the dry deposition of ^{210}Pb .

The temporal variation in ^{210}Pb activities in aerosols may also be related to the wind direction. From October to December in 2014–2015, a large fraction of wind was from the north (northeastern China). From April to September, the winds were southeasterly and derived from the South China Sea and tropical oceans (Supplementary Fig. S2). Then, from October to December, the study area was primarily affected by air masses transported from northeastern China (land). ^{210}Pb is produced from ^{222}Rn , which primarily emanates from the land surface. Therefore, the higher ^{210}Pb activities from October to December than from April to September (Fig. 3) could also be partly attributed to differences in the source of the aerosols.

Factors Influencing the Weekly Variation in ^7Be Activities

The temporal variations in ^7Be activities in air samples depend upon three processes: 1) the transport of stratospheric air into the troposphere during the late winter and early spring seasons, 2) the increased vertical transport rate of ^7Be in warmer months (from the upper troposphere to the middle and lower troposphere and into the surface air), and 3) the variation in the rate of washout for aerosols (McNeary and Baskaran, 2003).

A significant correlation was also found between ^7Be and $\text{PM}_{2.5}$ (and PM_{10}), although with a lower correlation coefficient than that with ^{210}Pb . Since ^7Be is also a particle-reactive radionuclide, the particle concentration is expected to influence ^7Be , and the weaker significant correlation might

be because ^7Be has different sources than ^{210}Pb .

In contrast to ^{210}Pb , the variation in ^7Be was more strongly related to temperature (Fig. 5). In other regions, the stratosphere-troposphere exchange of air masses was found to increase with decreasing temperature (Feely *et al.*, 1989; Baskaran, 1995; Du *et al.*, 2015), and the deposition of ^7Be was high in winter and spring. In Xiamen, the monthly ^7Be activity in winter and spring (October–April) was higher than that in summer and autumn (May–September) because of the intense vertical exchange of air masses in winter and spring. In addition, the correlation between ^7Be and temperature may also be related to the seasonal changes in the wind direction and the wet scavenging process (i.e., precipitation). From October to April of the following year, the winds are northeasterly and derive from high-latitude regions of the northern Asian continent (e.g., northern China, the Korean Peninsula, and Japanese Islands) (Supplementary Fig. S2); from May to September, the winds are southeasterly and derive from lower-latitude regions in southwestern China and the South China Sea (Supplementary Fig. S2). Correspondingly, higher ^7Be activity was observed from October to April of the following year, which is mainly due to the northeastern monsoon. Conversely, lower ^7Be activity was observed from May to September, which is mainly due to the southeastern monsoon. Variations in the rate of aerosol washout may also affect the temporal variations in ^7Be activities. The negative correlation between monthly ^7Be and precipitation is also significant (which further confirms the influence of the scavenging process on ^7Be in aerosols; Fig. 6(b)).

Environmental Implications

As observed in our study, both ^7Be and ^{210}Pb showed a significant correlation with $\text{PM}_{2.5}$. The average breathing rate for adults is $22.2 \text{ m}^3 \text{ d}^{-1}$ (General Administration of

Fig. 6. The relationship (a) between monthly ^{210}Pb activities (mBq m^{-3}) and monthly precipitation (mm) and (b) between monthly ^7Be activities (mBq m^{-3}) and precipitation (mm).

Quality Supervision of the People's Republic of China, 2000). The effective dose coefficients for the ingestion of ^7Be and ^{210}Pb for members of the public were 5.5×10^{-11} and 5.6×10^{-6} Sv/Bq, respectively (Eckerman et al., 2012). The committed effective doses of ^7Be and ^{210}Pb for Xiamen citizens were 1.9×10^{-3} and $5.7 \times 10^1 \mu\text{Sv}$, respectively. Most internal irradiation doses via ^{210}Pb inhalation exist on bone surfaces and lungs. Fine atmospheric particles may be deposited within the lungs. Although the effective dose only accounts for 5.7% of the effective dose limit (1 mSv yr^{-1}), the effective dose needs to be considered when evaluating the air quality since only two radionuclides were considered here. The significant correlations of ^{210}Pb and ^7Be with atmospheric particles suggest that radionuclides can also be pollutants impacting human health and should be considered in air quality models, especially in regions and seasons with higher $\text{PM}_{2.5}$ levels.

CONCLUSIONS

The atmospheric deposition of radionuclides has significant implications for the environment. By monitoring radionuclides in surface aerosols in Xiamen, a coastal city in southeastern China, we discovered a high level of ^{210}Pb activity, as well as a strong correlation between ^7Be activity and latitude in the coastal region. The temporal variations in both radionuclides were influenced by their sources and scavenging processes. Overall, the ^{210}Pb activity exhibited a significant positive correlation with the $\text{PM}_{2.5}$ concentration and a weaker negative correlation with the air temperature (due to the release of ^{222}Rn) and precipitation (scavenging). The ^7Be activity, on the other hand, was primarily influenced by the temperature (specifically, in mid-latitude regions, the stratosphere-troposphere exchange of air masses increases as the temperature decreases and as the northeasterly wind from high-latitude regions strengthens) and precipitation.

The effective dose coefficient for ingested ^7Be and ^{210}Pb was estimated to account for approximately 5.7% of the dose limit in Xiamen. The relationship between ^{210}Pb and $\text{PM}_{2.5}$ (and to a lesser extent, between ^7Be and $\text{PM}_{2.5}$) suggests that radionuclides should be considered in air quality models, especially for areas and seasons with high $\text{PM}_{2.5}$ concentrations as well as for regions at high latitudes.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be

found in the online version at <http://www.aaqr.org>.

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