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Climate change - mediated atmospheric ²¹⁰Po and ²¹⁰Pb distribution: How significant can it be for the inhalation dose to humans?

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Abstract

The concentration of ²¹⁰Po and ²¹⁰Pb in vegetation, and their transfer from soil to vegetation and via aerosol deposited on foliage are well established. The available data show significantly higher levels of these radionuclides in ash from forest fires and aerosols downwind from industrial sites. The climate change-induced hot and dry conditions promote the spread of forest fires, which burn huge areas. On average, over 10 million hectares are reportedly lost annually. Large-scale forest fires and fossil-fuel and coal-operated Power and Desalination Plants are very likely to result in the dispersion of ²¹⁰Pb and ²¹⁰Po into the regional aerosol; such an effect has already been observed due to fires in Ukraine, Belarus, and Russia, which have led to the dispersion of ¹³⁷Cs over large parts of Europe. We have measured elevated levels in Kuwait, and similar observations have been reported from Portugal. The higher levels of ²¹⁰Po in PM_{2.5} raise a serious concern about an increased inhalation dose humans could receive. Our estimate shows that humans in areas affected by forest fires might receive a dose equivalent to 2 μ Sv d⁻¹, which is significantly higher than 0.099 μ Sv d⁻¹, the dose a person gets from smoking a packet of cigarettes daily. We propose that size-fractionated aerosol sampling should be taken up in regions affected by forest fires and industrial activities that add ²¹⁰Po to the atmosphere in order to obtain a robust inhalation dose assessment and issue informed advisories to the public.

Keywords: Forest fires, ²¹⁰Po, ²¹⁰Pb, size-fractionated aerosol, inhalation, dose, PM_{2.5}



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INTRODUCTION

The ubiquitous presence of ²³⁸U and ²³²Th in the environment and vegetation has been reported. Polonium-210 and lead-210 are naturally occurring radioactive isotopes and are part of the uranium radioactive decay series. Polonium-210 has a 138-day half-life, while radioactive lead-210 has a much longer half-life of 22.2 years. Both ²¹⁰Po and ²¹⁰Pb are produced as part of the decay chain of radon gas (²²²Rn), which itself has a half-life of 3.8 days^[1]. Radon, a noble gas, has a neutral electric charge, but its radioactive daughters, ²¹⁰Po and ²¹⁰Pb, are positively charged ions. These ions are highly reactive and quickly attach to airborne particles. Polonium-210 ions in the atmosphere rapidly become attached to aerosol particles within a relatively short time frame, ranging from 40 to 180 seconds after their formation from the radioactive decay of precursor radon^[2]. This attachment to particles is a key factor in their atmospheric dispersion. Dry and wet atmospheric depositions continuously remove radon daughters from the atmosphere. This removal process prevents the establishment of a secular radioactive equilibrium between radon and its progeny, including ²¹⁰Po and ²¹⁰Pb. As a result, there is a significant radioactive disequilibrium between ²¹⁰Po and ²¹⁰Pb in the environment.

The ²¹⁰Po/²¹⁰Pb ratio in the aerosols is generally much lower than 0.1 due to the ongoing removal of radon daughters from the atmosphere^[3,4]. Consequently, the concentration of ²¹⁰Po is typically much lower than that of ²¹⁰Pb in aerosol samples. This aspect highlights the dynamic behavior of these radionuclides in the atmosphere and their connection to the decay of radon gas, leading to a significant radioactive disequilibrium between ²¹⁰Po and ²¹⁰Pb in natural settings^[5]. This disequilibrium is vital to consider when studying environmental radioactivity, including the mean residence time of aerosols (²¹⁰Bi/²¹⁰Pb ratios for recent air mass up to a few days^[5,6], and ²¹⁰Po/²¹⁰Pb for older air mass of a month or more^[7,8]) and their potential health effects^[9,10].

While the radioactive decay of atmospheric radon is one source of ²¹⁰Po and ²¹⁰Pb, later research has identified additional sources, including volcanic emissions, industrial facilities, forest fires, coal burning, and nuclear weapons tests^[11-17]. These sources can release significant quantities of ²¹⁰Po and sometimes ²¹⁰Pb into the atmosphere. Fossil fuel and coal-based Power and Desalination plants and Oil refineries are known to contribute to significantly higher concentrations of ²¹⁰Po and ²¹⁰Pb^[18,19]. Importantly, these additional sources can significantly increase the ²¹⁰Po/²¹⁰Pb ratios in the atmosphere^[14,17]. Both ²¹⁰Po and ²¹⁰Pb can be inhaled when they are adhered to ultra-fine particles in the air. This type of exposure to these radionuclides can result in internal radiation doses to human beings [Figure 1], particularly from ²¹⁰Po, which is generally higher than other naturally occurring radionuclides, except for radon^[20]. The activity-to-dose conversion factor is 2.2 μ Sv/Bq for inhaled ²¹⁰Po^[21], which is higher than other naturally occurring radionuclides, including ²¹⁰Pb.

The redistribution of ¹³⁷Cs was first noticed in Europe after the extensive forest fires in Ukraine, Belarus, and Russia during $2010^{[22]}$. However, not much attention has been given to natural radionuclides associated with vegetation that are released into the atmosphere during forest fires^[14,23]. Given the potential health risks associated with exposure to ²¹⁰Po and ²¹⁰Pb, monitoring their presence and redistribution in the environment consequent to forest fires is crucial. With an increase in the frequency of forest fires globally, mainly due to climate change, about 9.3 × 10⁶ hectares of tree cover were lost in 2021, and Russia alone lost 5.4 × 10⁶ hectares of tree cover to fire in $2021^{[24]}$. The more recent statistics are even more striking; the Forest Fire Centre, Canada estimated an area of 9.5 × 10⁶ hectares was burned in the seven months of 2023, between January and July, keeping in view the recurrence and increasing spatial scale of the forest fires, it is quite likely that the activity concentration of ²¹⁰Po, ²¹⁰Pb and other radionuclides could be considerably enhanced



Figure 1. Graphical representation of ²¹⁰Po and ²¹⁰Pb sources and a likely inhalation dose.

in the surface air over areas beyond the charred forests.

RESULTS AND DISCUSSION

Certain investigations have documented ²¹⁰Po/²¹⁰Pb ratios surpassing one. These escalated ratios are frequently linked to the release of ²¹⁰Po from human-made sources involving high temperatures, such as metal smelters, ceramic kilns, incinerators, and forest fires^[2,3,10,17,25-27]. Studies analyzing radionuclides in aerosols have revealed that a significant amount of polonium activity is associated with fine and ultrafine aerosol particles. In Japan, over 70% of ²¹⁰Po activity in aerosols was detected in particles smaller than 0.7 μ m^[28]. In Poland, 82% of ²¹⁰Po found in aerosols was measured within the particle size range of 0.1 - 0.3 μ m, primarily attributed to emissions from industrial sources^[27]. Similarly, in Portugal, research on smoke from vegetation and forest fires indicated that most of the ²¹⁰Po in aerosols were linked to particles smaller than 1 μ m. Kuwait has also reported relatively high levels of ²¹⁰Po in aerosols countrywide. The major fraction of this activity was identified in the fine fraction of aerosol particulates, specifically in the size range of 0.39 - 2.5 μ m^[18,19,29], consistent with observations in other studies^[2,3,10,14-16,19,27,30-36].

Several studies have highlighted the concentration of ²¹⁰Po and ²¹⁰Pb in vegetation [Table 1] and aerosols [Table 2]. The concentration in vegetation samples exhibited ²¹⁰Pb concentrations ranging from 0.98 to 20.27 Bq kg⁻¹ and ²¹⁰Po concentrations ranging from 0.97 to 49.4 Bq kg⁻¹, where the aerosol-containing combusted particles showed a significant increase in ²¹⁰Po and ²¹⁰Pb concentrations. A significant variation in ²¹⁰Po levels was observed in non-fire impacted aerosol in which the ²¹⁰Po on the filter sample was 111 Bq kg^{-1[17]}, while in fly ash collected on filters of an aerosol sampler, concentrations varied between 3,604 - 7,255 Bq kg⁻¹ and was 1,115 Bq kg⁻¹ in ground ash from forest fires. The enhanced concentration of ²¹⁰Po in fly ash was a result of forest fire-contributed aerosol.

Since ²¹⁰Po and ²¹⁰Pb are non-essential for any growth and metabolic functions in plants, a detailed study has provided data to underpin the hypothesis that both ²¹⁰Po and ²¹⁰Pb are taken up by plants from soil^[37]. In spite of the restrictive uptake of potentially toxic elements by plants in metalliferous soils, ²¹⁰Po and ²¹⁰Pb accumulation has been observed in both metal-tolerant and non-tolerant plants^[38]. ²¹⁰Pb and ²¹⁰Po enter the vegetation through root uptake and aerial deposition on foliage^[39].

Country	Sample	²¹⁰ Pb	²¹⁰ Po	Reference	
Viseu region, North Portugal, (late	Citrus bushes	9.90 ± 0.35	12.0 ± 2.4	[16]	
summer 2012)	Oak tree trunk wood	3.27 ± 0.16	5.51 ± 0.02		
	Oak tree, leaves	17.2 ± 0.4	30.8±1.2		
	Eucalyptus, trunk wood	0.98 ± 0.03	1.68 ± 0.05		
	Eucalyptus bark	1.88 ± 0.09	2.60 ± 0.06		
	Eucalyptus leaves	10.3 ± 0.4	49.4 ± 2.3		
	Acacia tree, trunk wood	2.04 ± 0.05	4.05 ± 0.15		
	Acacia tree, leaves	20.27 ± 0.47	8.61±0.33		
	Pine tree trunk wood	1.43 ± 0.13 to 1.98 ± 0.09	0.97 ± 0.003 to 1.53 ± 0.006		
	Pine tree, bark	2.80 ± 0.08	2.87 ± 0.06		
	Pine tree, needle (leaves)	10.36 ± 0.31	3.10 ± 0.08		
	Ashes from the ground after forest fire	402±6	1115 ± 66		
	Size fractionated aerosol (Fly ash)	923 ± 53 to 2070 ± 88	3604 ± 148 to 7255 ± 285		
	Aerosol (without fire smoke)	5895 ± 218	114 ± 7		
Wyoming, USA	Soil	0.1073 ± 0.02 to 3.108 ± 0.24	0.078 ± 0.009 to 2.997 ± 0.333	[38]	
	Sagebrush	0.016 ± 0.006 to 0.051 ± 0.034	0.022 ± 0.003 to 0.198 ± 0.107		
	Mixed grasses	0.020 ± 0.008 to 0.481 ± 0.159	0.020 ± 0.004 to 0.355 ± 0.112		
	Mixed Forbs	0.031 ± 0.003 to 0.322 ± 0.199	0.008 ± 0.001 to 0.777 ± 0.249		
	All plants	0.021 ± 0.003 to 0.444 ± 0.126	0.017 ± 0.003 to 0.577 ± 0.145		
Portugal	Cabbage leaves	0.435	0.044	[16]	
	Maize aerial parts	0.304	0.217		
	Olive tree leaves	22.381	2.50		
	Olive tree trunk wood	10.24	0.333		
	Olive tree roots	3.333	2.619		
	Palm tree leaves	12.857	2.548		
	Palm Tree bark	0.786	0.214		
	Tobacco leaves (cured)	11.90	11.19		
	Soil (0 - 30 cm)	100	100		

Table 1.	²¹⁰ Pb and ²¹⁰ Po	concentration	(in Ba kg ⁻¹	drv weight)	in various	plants.	and soil
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The evidence of the accumulation of these radionuclides in vegetation is explicit. The edibles (fruits and vegetables) are likely to contribute to the internal radiation dose to consumers. The data are compelling that ²¹⁰Po and ²¹⁰Pb are significantly incorporated in these fruits and vegetables, which follow a non-linear uptake pattern mathematically. Plant concentration for ²¹⁰Pb is expressed as

Vegetation Concentration = $0.74 \left(1 - e^{-1.4 \text{ concentration in substrate}}\right) + 0.16_{\text{concentration in substrate}}$

while for ²¹⁰Po, the concentration is expressed as:

 $\textit{Vegetation Concentration} = 70.0 ~\times~ 1.08^{-350.0 ~ x ~ 1.08^{-0.4 \textit{concentration in substrate}} + 1.2$

Table 2. ²¹⁰Pb and ²¹⁰Po concentration (in Bq kg⁻¹ dry weight) in aerosols

Mean region, North Portugal, (late summer 2017) Size fractionation sensol (F) Aerosol (Without fire smoke) 203 ± 33 to 2070 = 88 2002 ± 218 104 = 7 Kowait, January 2018 - November 2019 Aerosol (Ma ₁₀ (S, S) Aerosol (Ma ₁₀ (S, S) Aerosol (Ma ₁₀ (S, L) Aerosol (Ma	Country	Sample	²¹⁰ Pb	²¹⁰ Po	Reference
Arcsol (without fire smoke)5895 ±2814±7Kuwait, January 2018 - November 2019Acrosol PMA to (Su)228 - 279[9, 28, 1]Arcsol PMA to (Su)370 - 406370 - 406Acrosol PMA to (Su)99 - 210370 - 406Arcsol PMA to (Su)019 - 210370 - 406Acrosol PMA to (Su)011 - 344370 - 406Arcsol PMA to (Qu)113 - 344313 - 190Acrosol PMA to (Qu)133 - 190470 - 198Acrosol PMA to (Qu)583 - 501570 - 486Acrosol PMA to (Qu)590 - 503 - 506570 - 486Acrosol PMA to (Qu)505 - 356570 - 486Acrosol PMA to (Qu)505 - 356570 - 486Acrosol PMA to (Qu)505 - 356570 - 486Acrosol PMA to (Qu)590 - 578570 - 486Acrosol PMA to (Qu)590 - 578596 - 411Acrosol PMA to (Qu)590 - 578596 - 411Acrosol PMA to (Qu)592 - 578596 - 596 -	Viseu region, North Portugal, (late summer 2012)	Size fractionated aerosol (Fly 923 ± 53 to $2070 \pm$ ash) 88		3604 ± 148 to 7255 ± 285	[16]
Kuwait, January 2018 - November 2019 Aerosol PM sp (0, 5u) 282 - 298 [19, 29, 41] Aerosol PM sp (0, 5u) 301 - 406 311 - 344 Aerosol PM sp (0, Au) 311 - 344 313 - 344 Aerosol PM sp (0, VN) 283 - 301 313 - 344 Aerosol PM sp (0, VN) 288 - 301 313 - 344 Aerosol PM sp (0, VN) 288 - 301 313 - 344 Aerosol PM sp (0, Sp) 705 - 193 305 - 336 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 342 314 - 344 Aerosol PM sp (0, Sp) 303 - 335 335 - 343 Aerosol PM sp (0, Sp) 303 - 335 335 - 343 Aerosol PM sp (0, Sp) 352 - 403		Aerosol (without fire smoke)	5895 ± 218	114 ± 7	
Aerosol PM ₃ (0, 5ω) 252 - 288 Aerosol PM ₃ (0, 6ω) 370 - 406 Aerosol PM ₃ (0, 6ω) 207 - 245 Aerosol PM ₃ (0, 4ω) 311 - 344 Aerosol PM ₃ (0, 4ω) 333 - 190 Aerosol PM ₃ (0, 4ω) 333 - 190 Aerosol PM ₃ (0, 5p) 363 - 301 Aerosol PM ₄ (0, 5p) 365 - 336 Aerosol PM ₄ (0, 5p) 303 - 342 Aerosol PM ₄ (0, 5p) 288 - 301 Aerosol PM ₄ (0, 5p) 288 - 301 Aerosol PM ₄ (0, 5p) 288 - 306 Aerosol PM ₄ (0, 5p) 288 - 326 Aerosol PM ₄ (1, 6u) 294 - 451 Aerosol PM ₄ (1, 6u) 294 - 451 Aerosol PM ₄ (1, 6u) 292 - 281 Aerosol PM ₄ (1, 6u) 310 - 391 Aerosol PM ₄ (1, 6u) 310 - 391 Aerosol PM ₄ (2, 0) 310 - 391	Kuwait, January 2018 - November 2019	Aerosol PM ≥ 10 (R,Su)		228 - 279	[19, 29, 41]
Aeroad PM sp0 (1, 5u) 370 - 406 Aeroad PM sp0 (1, 4u) 199 - 210 Aeroad PM sp0 (1, 4u) 311 - 344 Aeroad PM sp0 (1, 4u) 313 - 344 Aeroad PM sp0 (1, 4u) 288 - 301 Aeroad PM sp0 (1, 5p) 288 - 301 Aeroad PM sp0 (1, 5p) 305 - 133 Aeroad PM sp0 (1, 5p) 305 - 336 Aeroad PM sp0 (1, 5p) 303 - 342 Aeroad PM sp0 (1, 5p) 304 - 311 Aeroad PM sp0 (1, 5u) 765 - 178 Aeroad PM sp0 (1, 5u) 304 - 311 Aeroad PM sp0 (1, 5u) 304 - 311 Aeroad PM sp1 (1, 5u) 304 - 337 Aeroad PM sp1 (1, 5u) 304 - 331 Aeroad PM sp1 (1, 5u) 304 - 335 Aeroad PM sp1 (1, 5u) 304 - 331 Aeroad PM sp1 (1, 5u) 304 - 351		Aerosol PM ≥ 10 (U, Su)		252 - 288	
Aerosol PM s ₁₀ (R, Au) 99-200 Aerosol PM s ₁₀ (L, Au) 207 - 245 Aerosol PM s ₁₀ (L, Au) 13.44 Aerosol PM s ₁₀ (R, Wi) 33.190 Aerosol PM s ₁₀ (W) 55 - 193 Aerosol PM s ₁₀ (W) 55 - 193 Aerosol PM s ₁₀ (V, Vi) 203 - 336 Aerosol PM s ₁₀ (L, Sp) 203 - 336 Aerosol PM s ₁₀ (L, Sp) 288 - 326 Aerosol PM s ₁₀ (L, Sp) 288 - 326 Aerosol PM s ₁₀ (L, Sp) 288 - 326 Aerosol PM s ₁₀ (L, Sp) 288 - 326 Aerosol PM s ₁₀ (L, Sp) 288 - 326 Aerosol PM s ₁₀ (L, Sp) 288 - 326 Aerosol PM s ₁₀ (L, Sp) 294 - 451 Aerosol PM s ₁₀ (L, Wi) 294 - 451 Aerosol PM s ₁₀ (L, Wi) 252 - 284 Aerosol PM s ₁₀ (L, Sp) 303 - 335 Aerosol PM s ₁₀ (L, Sp) 302 - 336 Aerosol PM s ₁₀ (L, Sp) 302 - 326 Aerosol PM s ₁₀ (L, Sp) 303 - 335 Aerosol PM s ₁₀ (L, Sp) 303 - 335 Aerosol PM s ₁₀ (L, Sp) 303 - 335 Aerosol PM s ₁₀ (L, Sp) 303 - 335 Aerosol PM s ₁₀ (Aerosol PM ≥ 10 (I, Su)		370 - 406	
Aerosol PM sign (1, Au) 207-343 Aerosol PM sign (1, Au) 311-344 Aerosol PM sign (2, Wo) 121-176 Aerosol PM sign (2, Wo) 288-306 Aerosol PM sign (3, Sp) 288-301 Aerosol PM sign (5, Sp) 105-193 Aerosol PM sign (5, Sp) 003-342 Aerosol PM sign (5, Sp) 032-342 Aerosol PM sign (3, Sp) 033-422 Aerosol PM sign (2, Sp) 288-326 Aerosol PM sign (2, Sp) 294-451 Aerosol PM sign (2, Sp) 294-451 Aerosol PM sign (2, Sp) 294-451 Aerosol PM sign (2, Sp) 292-284 Aerosol PM sign (2, Sp) 202-281 Aerosol PM sign (2, Sp) 222-284 Aerosol PM sign (2, Sp) 244-960		Aerosol PM ≥10 (R, Au)		199 - 210	
Aerosol PM as (0, Au) 311-344 Aerosol PM as (0, W) 121-176 Aerosol PM as (0, W) 331-190 Aerosol PM as (0, Sp) 288-301 Aerosol PM as (0, Sp) 055-336 Aerosol PM as (0, Sp) 303-342 Aerosol PM as (0, Sp) 303-342 Aerosol PM as (0, Sp) 303-342 Aerosol PM as (0, Sp) 306-314 Aerosol PM as (0, Sp) 307-335 Aerosol PM as (0, Sp) 307-346 Aerosol PM as (0, Sp) 307-346 Aerosol PM as (0, Sp) 317-36<		Aerosol PM ≥10 (U, Au)		207 - 245	
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Aerosol PM ₁₀ (0, Sp) 155 - 193 Aerosol PM ₂₀ (0, Sp) 305 - 336 Aerosol PM _{25,10} (0, Su) 303 - 342 Aerosol PM _{25,10} (0, Su) 288 - 326 Aerosol PM _{25,10} (0, Su) 265 - 278 Aerosol PM _{25,10} (0, Au) 265 - 278 Aerosol PM _{25,10} (0, Au) 294 - 451 Aerosol PM _{25,10} (0, Au) 90 - 223 Aerosol PM _{25,10} (0, Wi) 90 - 223 Aerosol PM _{25,10} (0, Wi) 303 - 335 Aerosol PM _{25,10} (1, Wi) 252 - 284 Aerosol PM _{25,10} (1, Sp) 30 - 335 Aerosol PM _{25,10} (1, Sp) 322 - 284 Aerosol PM _{25,10} (1, Sp) 52 - 403 Aerosol PM _{25,10} (1, Sp) 90 - 323 Aerosol PM _{25,10} (1, Sp) 91 - 502 Aerosol PM _{25,10} (1, Sp) 93 - 335 Aerosol PM _{25,12} (1, Su) 93 - 913 Aerosol PM _{25,12} (2, Au) 90 - 91 Aerosol PM _{25,12} (2, Au) 93 - 913 Aerosol PM _{25,12} (2, Au) 93 - 913		Aerosol PM ≥10 (I, Wi)		288 - 301	
Aerosol PM 200 (J, 5p) 70 - 198 Aerosol PM 200 (J, 5p) 305 - 336 Aerosol PM 25-10 (R, 5u) 288 - 326 Aerosol PM 25-10 (J, 5u) 288 - 326 Aerosol PM 25-10 (J, 5u) 265 - 778 Aerosol PM 25-10 (J, 5u) 264 - 451 Aerosol PM 25-10 (J, Au) 294 - 451 Aerosol PM 25-10 (J, Wi) 303 - 335 Aerosol PM 25-10 (J, Wi) 303 - 335 Aerosol PM 25-10 (J, Wi) 303 - 335 Aerosol PM 25-10 (J, Sp) 202 - 251 Aerosol PM 25-10 (J, Sp) 222 - 284 Aerosol PM 25-10 (J, Sp) 252 - 284 Aerosol PM 25-10 (J, Sp) 252 - 284 Aerosol PM 25-10 (J, Sp) 55 - 596 Aerosol PM 25-10 (J, Sp) 55 - 596 Aerosol PM 25-10 (J, Sp) 55 - 596 Aerosol PM 25-10 (J, Sp) 51 - 596 Aerosol PM 25-10 (J, Sp) 51 - 596 Aerosol PM 25-10 (J, Sp) 51 - 596 Aerosol PM 25-20 (J, Au) 631 - 698 Aerosol PM 25-20 (J, Au) 631 - 698 Aerosol PM 25-20 (J, Mu) 631 - 698 Aerosol PM 25-20 (J, Mu) 53 - 661 Aerosol PM		Aerosol PM ≥10 (R, Sp)		155 - 193	
Aerosol PM aerosol PM pison (R Su)305 - 336Aerosol PM pison (R Su)303 - 342Aerosol PM pison (R Su)406 - 411Aerosol PM pison (R Au)265 - 278Aerosol PM pison (R Au)294 - 451Aerosol PM pison (R Au)99 - 323Aerosol PM pison (R W)90 - 223Aerosol PM pison (R W)502 - 284Aerosol PM pison (R Sp)522 - 284Aerosol PM pison (R Sp)522 - 284Aerosol PM pison (R Sp)522 - 284Aerosol PM pison (U, Sp)522 - 403Aerosol PM pison (U, Sp)515 - 596Aerosol PM pison 2(U, Su)515 - 596Aerosol PM pison 2(U, Su)631 - 698Aerosol PM pison 2(U, Su)631 - 698Aerosol PM pison 2(U, Su)631 - 698Aerosol PM pison 2(U, Su)632 - 904Aerosol PM pison 2(U, Su)52 - 661Aerosol PM pison 2(U, Sp)52 - 661Aerosol PM pison 2(U, Sp)66 - 479Aerosol PM pison 2(U, Sp)66 - 700Aerosol PM pison 2(U, Sp)56 - 602Aerosol PM pison 2(U, Sp)56 - 603Aerosol PM pison 2(U, Sp)66		Aerosol PM ≥10 (U, Sp)		170 - 198	
Aerosol PM25-10 (R,Su) 303 - 342 Aerosol PM25-10 (J, Su) 288 - 326 Aerosol PM25-10 (J, Su) 265 - 71 Aerosol PM25-10 (R, Au) 265 - 72 Aerosol PM25-10 (R, Au) 349 - 387 Aerosol PM25-10 (R, Wi) 294 - 451 Aerosol PM25-10 (R, Wi) 252 - 284 Aerosol PM25-10 (R, Wi) 303 - 335 Aerosol PM25-10 (R, Wi) 303 - 335 Aerosol PM25-10 (R, Wi) 252 - 284 Aerosol PM25-10 (R, Sp) 220 - 251 Aerosol PM25-10 (R, Sp) 55 - 596 Aerosol PM25-10 (R, Sp) 55 - 596 Aerosol PM25-10 (R, Sp) 515 - 596 Aerosol PM25-10 (R, Sp) 515 - 596 Aerosol PM25-10 (R, Sp) 515 - 596 Aerosol PM25-10 (R, Sp) 631 - 698 Aerosol PM26-22 (R, Su) 631 - 698 Aerosol PM26-22 (R, Su) 52 - 264 Aerosol PM26-22 (R, Su) 52 - 364 Aerosol PM26-22 (R, Su) 631 - 698 Aerosol PM26-22 (R, Su) 53 - 536 Aerosol PM26-22 (R, Su) 52 - 646 Aerosol PM26-22 (R, Su) 52 - 646 Aerosol PM26-22 (R, Su)		Aerosol PM ≥10 (I, Sp)		305 - 336	
Aerosol PM2510 (U, Su) 288 - 326 Aerosol PM2510 (Su) 406 - 411 Aerosol PM2510 (Su) 244 - 51 Aerosol PM2510 (U, Au) 349 - 387 Aerosol PM2510 (U, Wi) 522 - 284 Aerosol PM2510 (N, Sp) 252 - 284 Aerosol PM2510 (N, Sp) 252 - 284 Aerosol PM2510 (N, Sp) 252 - 284 Aerosol PM2510 (N, Sp) 552 - 576 Aerosol PM2520 (N, Sp) 944 - 960 Aerosol PM2520 (N, Sp) 481 - 502 Aerosol PM25922 (N, Su) 512 - 561 Aerosol PM25922 (N, Wi) 563 - 904 Aerosol PM25922 (N, Wi) 564 - 370 Aerosol PM25922 (N, Sp) 666 - 700 Aerosol PM25922 (N, Sp) 666 - 700 Aerosol PM25922 (N, Sp) 566 - 700 Aerosol PM25922 (N, Sp) 566 - 700 <td< td=""><td></td><td>Aerosol PM_{2.5 - 10} (R,Su)</td><td></td><td>303 - 342</td></td<>		Aerosol PM _{2.5 - 10} (R,Su)		303 - 342	
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Aerosol PM25-10 (R, Au) 265 - 278 Aerosol PM25-10 (U, Au) 294 - 451 Aerosol PM25-10 (U, Au) 349 - 357 Aerosol PM25-10 (R, W) 50 - 223 Aerosol PM25-10 (U, Wi) 300 - 335 Aerosol PM25-10 (U, Wi) 300 - 335 Aerosol PM25-10 (U, Sp) 220 - 251 Aerosol PM25-10 (U, Sp) 252 - 284 Aerosol PM25-10 (U, Sp) 252 - 203 Aerosol PM25-10 (U, Sp) 515 - 596 Aerosol PM25-10 (U, Sp) 515 - 596 Aerosol PM25-10 (U, Sp) 515 - 596 Aerosol PM29-25 (U, Su) 705 - 746 Aerosol PM29-25 (U, Su) 515 - 596 Aerosol PM29-25 (U, Su) 513 - 698 Aerosol PM29-25 (U, Su) 513 - 698 Aerosol PM29-25 (U, Su) 513 - 698 Aerosol PM29-25 (U, Su) 522 - 661 Aerosol PM29-25 (U, Su) 663 - 790 Aerosol PM29-25 (U, Sp) 666 - 790 Aerosol PM29-25 (U, Sp) 666 - 790 Aerosol PM29-25 (U, Sp) </td <td></td> <td>Aerosol PM_{2.5 - 10} (I, Su)</td> <td></td> <td>406 - 411</td>		Aerosol PM _{2.5 - 10} (I, Su)		406 - 411	
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Aerosol PM25-10 (R,Wi)190-223Aerosol PM25-10 (U,Wi)252-284Aerosol PM25-10 (U,Sp)200-251Aerosol PM25-10 (U,Sp)252-284Aerosol PM25-10 (U,Sp)252-284Aerosol PM25-10 (U,Sp)552-403Aerosol PM25-10 (U,Sp)552-403Aerosol PM25-10 (U,Sp)515-596Aerosol PM25-10 (U,Sp)705-746Aerosol PM039-25 (U,Su)944-960Aerosol PM039-25 (U,Su)944-960Aerosol PM039-25 (U,Su)944-960Aerosol PM039-25 (U,Su)944-960Aerosol PM039-25 (U,Su)931-613Aerosol PM039-25 (U,Su)931-613Aerosol PM039-25 (U,Su)931-63Aerosol PM039-25 (U,Su)863-897Aerosol PM039-25 (U,Su)164-100Aerosol PM039-25 (U,Su)164-100Aerosol PM0304 (230.41996)345.03		Aerosol PM _{2.5 - 10} (I, Au)		349 - 387	
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Aerosol PM250330 - 335Aerosol PM250220 - 251Aerosol PM250522 - 284Aerosol PM250552 - 403Aerosol PM250555 - 596Aerosol PM039.25705 - 746Aerosol PM039.25944 - 960Aerosol PM039.25944 - 960Aerosol PM039.25944 - 960Aerosol PM039.25631 - 698Aerosol PM039.25933 - 933Aerosol PM039.25933 - 934Aerosol PM039.25646 - 79Aerosol PM039.25946 - 897Aerosol PM039.25946 - 897Aerosol PM039.25954 - 046Aerosol PM039.2575 - 04Aerosol PM039.25954 - 046Aerosol PM039.25954 - 046Aerosol PM039.25954 - 046Aerosol PM039.25954 - 046Aerosol PM039.2514 - 107Aerosol PM039.2515 - 047Aerosol PM039.2514 - 107Aerosol PM039.2515 - 047Aerosol PM039.32		Aerosol PM _{2.5 - 10} (U, Wi)		252 - 284	
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Aerosol PM25-10 (1, Sp)352 - 403Aerosol PM033-25 (R, Su)515 - 596Aerosol PM033-25 (U, Su)705 - 746Aerosol PM033-25 (U, Su)944 - 960Aerosol PM033-25 (R, Au)481 - 502Aerosol PM033-25 (R, Au)631 - 698Aerosol PM033-25 (U, Au)903 - 913Aerosol PM033-25 (U, Au)903 - 913Aerosol PM033-25 (U, Au)352 - 466Aerosol PM033-25 (U, Au)722 - 661Aerosol PM033-25 (U, Vi)572 - 661Aerosol PM033-25 (U, Sp)666 - 479Aerosol PM033-25 (U, Sp)666 - 479Aerosol PM033-25 (U, Sp)666 - 479Aerosol PM033-25 (U, Sp)896 - 897Aerosol PM033-25 (U, Sp)504Aerosol PM033-25 (U, Sp)154 0.17Aerosol PM033-25 (U, Sp)385 4.03Aerosol PM033-25 (U, Sp)385 4.03Aerosol PM033-25 (U, Sp)154 0.17Aerosol PM033-26 (U, Sp)385 4.03Aerosol PM1224 (23.04.1996)385 4.03 <trr>Aerosol PM1</trr>		Aerosol PM _{2.5 - 10} (U, Sp)		252 - 284	
Aerosol PM0039-25 (R,Su) 515-596 Aerosol PM0039-25 (L,Su) 705-746 Aerosol PM0039-25 (L,Su) 944-960 Aerosol PM0039-25 (L,Au) 481-502 Aerosol PM0039-25 (L,Au) 631-698 Aerosol PM0039-25 (L,Au) 903-913 Aerosol PM0039-25 (L,SP) 666-9700 Aerosol PM0039-25 (L,Sp) 896-897 Aerosol PM0039-25 (L,SP) 896-897 Aerosol PM013-03 (23.04.1996) 17.4 ± 0.7 18.4 ± 0.17 Aerosol PM013-03 (23.04.1996) 17.4 ± 0.7 18.4 ± 0.17 Aerosol PM013-03 (23.04.1996) 17.4 ± 0.7 18.4 ± 0.17 Aerosol PM013-03 (23.04.1996) 17.4 ± 0.7 18.4 ± 0.17 Aerosol PM013-03 (23.04.1996) 18.4 ± 0.17 19.4 ± 0.17 Aerosol PM013-03 (23.04.1996) 18.4 ± 0.7 18.4 ± 0.17 <td< td=""><td></td><td>Aerosol PM_{2.5 - 10} (I, Sp)</td><td></td><td>352 - 403</td><td></td></td<>		Aerosol PM _{2.5 - 10} (I, Sp)		352 - 403	
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Aerosol PM _{0.39-2.5} (R, Wi) 435 - 436 Aerosol PM _{0.39-2.5} (U, Wi) 572 - 661 Aerosol PM _{0.39-2.5} (I, Wi) 863 - 904 Aerosol PM _{0.39-2.5} (R, Sp) 466 - 479 Aerosol PM _{0.39-2.5} (U, Sp) 606 - 700 Aerosol PM _{0.39-2.5} (I, Sp) 896 - 897 Vienna, Austria* Aerosol PM _{0.39-2.5} (I, Sp) 896 - 897 Aerosol PM _{0.39-2.5} (I, Sp) 15 ± 0.17 [42] Aerosol PM _{0.39-2.5} (I, Sp) 16 ± 1.01 2.2 ± 0.2 Aerosol PM _{0.39-2.5} (I, Sp) 16 ± 1.01 2.2 ± 0.2 Aerosol PM _{0.412} (23.04.1996) 17.4 ± 0.7 18 ± 0.17 Aerosol PM _{0.612} (23.04.1996) 1.9 ± 0.2 1.2 ± 0.2 Aerosol PM _{0.612} (23.04.1996) 1.9 ± 0.2 1.2 ± 0.2 Aerosol PM _{0.612} (23.04.1996) 1.9 ± 0.2 1.2 ± 0.2 Aerosol PM _{0.612} (23.04.1996) 1.9 ± 0.2 1.9 ± 0.2 Aerosol PM _{0.612} (23.04.1996) 0.88 ± 0.1 1.9 ± 0.2 Aerosol PM _{0.615.03} (12.06.1996) 9.3 ± 0.5 0.55 ± 0.08 Aerosol PM _{0.30-6} (12.06.1996) 1.9 ± 0.7 0.5 ± 0.08 Aerosol PM _{0.612} (12.06.1996)		Aerosol PM _{0.39 -2.5} (I, Au)		903 - 913	
Aerosol PM0.39-2.5(U,Wi) 572 - 661 Aerosol PM0.39-2.5(I,Wi) 863 - 904 Aerosol PM0.39-2.5(R,Sp) 466 - 479 Aerosol PM0.39-2.5(U,Sp) 606 - 700 Aerosol PM0.39-2.5(I,Sp) 896 - 897 Vienna, Austria* Aerosol PM0.15-03 (23.04.1996) 7.5 ± 0.4 1.5 ± 0.17 [42] Aerosol PM0.30.6 (23.04.1996) 7.5 ± 0.4 1.8 ± 0.17 [42] Aerosol PM0.30.6 (23.04.1996) 17.4 ± 0.7 1.8 ± 0.17 [42] Aerosol PM0.30.6 (23.04.1996) 17.4 ± 0.7 1.8 ± 0.17 [42] Aerosol PM0.30.6 (23.04.1996) 14.6 ± 1.0 2.2 ± 0.2 [42] Aerosol PM0.30.6 (23.04.1996) 1.9 ± 0.2 [42] [42] Aerosol PM0.30.6 (23.04.1996) 1.8 ± 0.17 [42] [42] Aerosol PM0.30.6 (23.04.1996) 1.8 ± 0.17 [42] [42] Aerosol PM0.30.6 (23.04.1996) 1.9 ± 0.2 [42] [42] Aerosol PM0.30.6 (23.04.1996) 0.88 ± 0.1 [42] [42] Aerosol PM0.30.6 (12.06.1996) 0.88 ± 0.1 [51] [51] Aerosol PM0.30.6 (12.06.1996) 1.9 ± 0.2 [51] [51] <td></td> <td>Aerosol PM_{0.39 - 2.5}(R, Wi)</td> <td></td> <td>435 - 436</td> <td></td>		Aerosol PM _{0.39 - 2.5} (R, Wi)		435 - 436	
Aerosol PM _{0.39-25} (l, Wi) 863 - 904 Aerosol PM _{0.39-25} (R, Sp) 466 - 479 Aerosol PM _{0.39-25} (l, Sp) 606 - 700 Aerosol PM _{0.39-25} (l, Sp) 896 - 897 Vienna, Austria* Aerosol PM _{0.39-0} (23.04.1996) 7.5 ± 0.4 1.5 ± 0.17 [42] Aerosol PM _{0.39-0.6} (23.04.1996) 7.5 ± 0.4 1.8 ± 0.17 [42] Aerosol PM _{0.39-0.6} (23.04.1996) 17.4 ± 0.7 1.8 ± 0.17 [42] Aerosol PM _{0.3-0.6} (23.04.1996) 14.6 ± 1.0 2.2 ± 0.2 [42] Aerosol PM _{0.4-1.2} (23.04.1996) 1.8 ± 0.17 [42] Aerosol PM _{0.3-0.6} (23.04.1996) 1.9 ± 0.2 [42] Aerosol PM _{0.4-5.0} (23.04.1996) 1.9 ± 0.2 [42] Aerosol PM _{0.15-03} (12.06.1996) 0.88 ± 0.1 [42] Aerosol PM _{0.15-03} (12.06.1996) 0.5 ± 0.08 [40] Aerosol PM _{0.15-03} (12.06.1996) 0.5 ± 0.08 [40] Aerosol PM _{0.15-03} (12.06.1996) 15 ± 0.7 0.5 ± 0.08		Aerosol PM _{0.39 - 2.5} (U, Wi)		572 - 661	
Aerosol PM _{0.39-25} (R, Sp) 466 - 479 Aerosol PM _{0.39-25} (U, Sp) 606 - 700 Aerosol PM _{0.39-25} (U, Sp) 896 - 897 Vienna, Austria* Aerosol PM _{0.15-0.3} (23.04.1996) 7.5 ± 0.4 1.5 ± 0.17 [42] Aerosol PM _{0.39-6} (23.04.1996) 17.4 ± 0.7 1.8 ± 0.17 [42] Aerosol PM _{0.6-1.2} (23.04.1996) 14.6 ± 1.0 2.2 ± 0.2 [42] Aerosol PM _{0.6-1.2} (23.04.1996) 14.6 ± 1.0 2.2 ± 0.2 [42] Aerosol PM _{0.6-1.2} (23.04.1996) 14.6 ± 1.0 2.2 ± 0.2 [42] Aerosol PM _{0.6-1.2} (23.04.1996) 18.5 ± 0.3 0.2 ± 0.03 [42] Aerosol PM _{0.6-1.2} (23.04.1996) 18.5 ± 0.3 0.2 ± 0.03 [42] Aerosol PM _{0.6-1.2} (23.04.1996) 19.5 ± 0.3 [2.5 ± 0.08 [42] Aerosol PM _{0.5-0} (23.04.1996) 0.88 ± 0.1 [42] [42] Aerosol PM _{0.5-0} (12.06.1996) 9.3 ± 0.5 0.55 ± 0.08 [42] Aerosol PM _{0.5-0} (12.06.1996) 15 ± 0.7 0.52 ± 0.08 [42]		Aerosol PM _{0.39 - 2.5} (I, Wi)		863 - 904	
Aerosol PM0,39-25 (U, Sp) 606 - 700 Vienna, Austria* 896 - 897 Aerosol PM0,15-03 (23.04.1996) 7.5 ± 0.4 15 ± 0.17 Aerosol PM0,03-0.6 (23.04.1996) 17.4 ± 0.7 1.8 ± 0.17 Aerosol PM0,03-0.6 (23.04.1996) 14.6 ± 1.0 2.2 ± 0.2 Aerosol PM0,04-12 (23.04.1996) 1.8 ± 0.17 4.8 ± 0.17 Aerosol PM0,04-12 (23.04.1996) 1.4 6 ± 1.0 0.2 ± 0.02 Aerosol PM0,24-20 (23.04.1996) 3.85 ± 0.3 0.2 ± 0.03 Aerosol PM0,24-50 (23.04.1996) 1.9 ± 0.2 1.9 ± 0.2 Aerosol PM0,24-50 (23.04.1996) 0.88 ± 0.1 1.9 ± 0.2 Aerosol PM0,15-03 (12.06.1996) 0.3 ± 0.5 0.55 ± 0.08 Aerosol PM0,05-03 (12.06.1996) 9.3 ± 0.5 0.5 ± 0.08 Aerosol PM0,05-03 (12.06.1996) 15 ± 0.7 0.5 ± 0.08		Aerosol PM _{0.39 - 2.5} (R, Sp)	I PM _{0.39 - 2.5} (R, Sp) I PM _{0.39 - 2.5} (U, Sp)		
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Vienna, Austria* Aerosol PM _{0.15-0.3} (23.04.1996) 7.5 ± 0.4 1.5 ± 0.17 [42] Aerosol PM _{0.3-0.6} (23.04.1996) 17.4 ± 0.7 1.8 ± 0.17 1.4 ± 0.7 1.8 ± 0.17 Aerosol PM _{0.6-1.2} (23.04.1996) 14.6 ± 1.0 2.2 ± 0.2 1.4 ± 0.7 1.4 ± 0.7 1.4 ± 0.7 1.4 ± 0.7 Aerosol PM _{0.6-1.2} (23.04.1996) 14.6 ± 1.0 2.2 ± 0.2 1.4 ± 0.7 1.4 ± 0		Aerosol PM _{0.39 - 2.5} (I, Sp)		896 - 897	
Aerosol PM 0.3-0.6 17.4 ± 0.7 1.8 ± 0.17 Aerosol PM 0.6-1.2 14.6 ± 1.0 2.2 ± 0.2 Aerosol PM 1.2-2.4 $23.04.1996$) 3.85 ± 0.3 0.2 ± 0.03 Aerosol PM 2.4-5.0 $23.04.1996$) 1.9 ± 0.2 1.9 ± 0.2 Aerosol PM 0.15-0.3 $0.23.04.1996$) 0.88 ± 0.1 0.55 ± 0.08 Aerosol PM 0.15-0.3 $12.06.1996$) 15 ± 0.7 0.55 ± 0.08 Aerosol PM 0.6-1.2 $12.06.1996$) 15.8 ± 0.7 0.52 ± 0.08	Vienna, Austria*	Aerosol PM _{0.15-0.3} (23.04.1996)	7.5 ± 0.4	1.5 ± 0.17	[42]
Aerosol $PM_{0.6-1.2}$ (23.04.1996)14.6 ± 1.02.2 ± 0.2Aerosol $PM_{1.2-2.4}$ (23.04.1996)3.85 ± 0.30.2 ± 0.03Aerosol $PM_{2.4-5.0}$ (23.04.1996)1.9 ± 0.2Aerosol $PM_{5.0-10}$ (23.04.1996)0.88 ± 0.1Aerosol $PM_{0.15-0.3}$ (12.06.1996)9.3 ± 0.50.55 ± 0.08Aerosol $PM_{0.3-0.6}$ (12.06.1996)15 ± 0.70.5 ± 0.08Aerosol $PM_{0.6-1.2}$ (12.06.1996)15.8 ± 0.70.52 ± 0.08		Aerosol PM _{0.3-0.6} (23.04.1996)	17.4 ± 0.7	1.8 ± 0.17	
Aerosol $PM_{1,2-2,4}$ (23.04.1996) 3.85 ± 0.3 0.2 ± 0.03 Aerosol $PM_{2,4-5,0}$ (23.04.1996) 1.9 ± 0.2 Aerosol $PM_{5,0-10}$ (23.04.1996) 0.88 ± 0.1 Aerosol $PM_{0,15-0,3}$ (12.06.1996) 9.3 ± 0.5 0.55 ± 0.08 Aerosol $PM_{0,3-0,6}$ (12.06.1996) 15 ± 0.7 0.52 ± 0.08 Aerosol $PM_{0,6-1,2}$ (12.06.1996) 15.8 ± 0.7 0.52 ± 0.08		Aerosol PM _{0.6-1.2} (23.04.1996)	14.6 ± 1.0	2.2 ± 0.2	
Aerosol $PM_{2.4-5.0}$ (23.04.1996) 1.9 ± 0.2 Aerosol $PM_{5.0-10}$ (23.04.1996) 0.88 ± 0.1 Aerosol $PM_{0.15-0.3}$ (12.06.1996) 9.3 ± 0.5 0.55 ± 0.08 Aerosol $PM_{0.3-0.6}$ (12.06.1996) 15 ± 0.7 0.5 ± 0.08 Aerosol $PM_{0.6-1.2}$ (12.06.1996) 15.8 ± 0.7 0.52 ± 0.08		Aerosol PM _{1.2-2.4} (23.04.1996)	3.85 ± 0.3	0.2 ± 0.03	
Aerosol $PM_{5.0-10}$ (23.04.1996) 0.88 ± 0.1 Aerosol $PM_{0.15-0.3}$ (12.06.1996) 9.3 ± 0.5 0.55 ± 0.08 Aerosol $PM_{0.3-0.6}$ (12.06.1996) 15 ± 0.7 0.5 ± 0.08 Aerosol $PM_{0.6-1.2}$ (12.06.1996) 15.8 ± 0.7 0.52 ± 0.08		Aerosol PM _{2.4-5.0} (23.04.1996)	1.9 ± 0.2		
Aerosol $PM_{0.15-0.3}$ (12.06.1996) 9.3 ± 0.5 0.55 ± 0.08 Aerosol $PM_{0.3-0.6}$ (12.06.1996) 15 ± 0.7 0.5 ± 0.08 Aerosol $PM_{0.6-1.2}$ (12.06.1996) 15.8 ± 0.7 0.52 ± 0.08		Aerosol PM _{5.0-10} (23.04.1996)	0.88 ± 0.1		
Aerosol $PM_{0.3-0.6}$ (12.06.1996) 15 ± 0.7 0.5 ± 0.08 Aerosol $PM_{0.6-1.2}$ (12.06.1996) 15.8 ± 0.7 0.52 ± 0.08		Aerosol PM _{0.15-0.3} (12.06.1996)	9.3 ± 0.5	0.55 ± 0.08	
Aerosol $PM_{0.6-1.2}$ (12.06.1996) 15.8 ± 0.7 0.52 ± 0.08		Aerosol PM _{0.3-0.6} (12.06.1996)	15 ± 0.7	0.5 ± 0.08	
		Aerosol PM _{0.6-1.2} (12.06.1996)	15.8 ± 0.7	0.52 ± 0.08	

Aerosol PM _{1.2-2.4} (12.06.1996)	3.15 ± 0.2	
Aerosol PM _{2.4-5.0} (12.06.1996)	0.95 ± 0.1	0.2 ± 0.04
Aerosol PM _{0.15-0.3} (12.08.1996)	12.4 ± 0.5	1.33 ± 0.15
Aerosol PM _{0.3-0.6} (12.08.1996)	13.7 ± 0.7	0.7 ± 0.1
Aerosol PM _{0.6-1.2} (12.08.1996)	6.5 ± 0.4	
Aerosol PM _{1.2-2.4} (12.08.1996)	1.7 ± 0.2	
Aerosol PM _{0.15-0.3} (2.10.1996)	3.3 ± 0.40	0.19 ± 0.12
Aerosol PM _{0.3-0.6} (2.10.1996)	5.5 ± 0.50	0.62 ± 0.15
Aerosol PM _{0.6-1.2} (2.10.1996)	4.8 ± 0.50	0.19 ± 0.12
Aerosol PM _{1.2-2.4} (2.10.1996)	0.7 ± 0.30	0.17 ± 0.13
Aerosol PM _{2.4-5.0} (2.10.1996)	0.25 ± 0.23	0.24 ± 0.14
Aerosol PM _{0.15-0.3} (13.11.1996)	7.5 ± 0.4	12.3 ± 0.5
Aerosol PM _{0.3-0.6} (13.11.1996)	10.5 ± 0.6	2 ± 0.2
Aerosol PM _{0.6-1.2} (13.11.1996)	10.2 ± 0.6	0.7 ± 0.1
Aerosol PM _{1.2-2.4} (13.11.1996)	1.2 ± 0.1	0.2 ± 0.04
Aerosol PM _{2.4-5.0} (13.11.1996)	1.9 ± 0.2	0.2 ± 0.04
Aerosol PM _{5.0-10} (13.11.1996)	0.7 ± 0.1	0.07 ± 0.02
Aerosol PM _{0.15-0.3} (17.12.1996)	10.8 ± 0.6	0.5 ± 0.2
Aerosol PM _{0.3-0.6} (17.12.1996)	25 ± 0.9	0.9 ± 0.2
Aerosol PM _{0.6-1.2} (17.12.1996)	38.8 ± 1.3	0.8 ± 0.2
Aerosol PM _{1.2-2.4} (17.12.1996)	20 ± 0.9	0.5 ± 0.1
Aerosol PM _{2.4-5.0} (17.12.1996)	1.2 ± 0.3	0.1 ± 0.1
Aerosol PM _{5.0-10} (17.12.1996)	5.8 ± 0.4	0.1 ± 0.1
Aerosol PM _{0.15-0.3} (12.02.1997)	4.8 ± 0.3	0.69 ± 0.1
Aerosol PM _{0.3-0.6} (12.02.1997)	7.7 ± 0.4	1.45 ± 0.15
Aerosol PM _{0.6-1.2} (12.02.1997)	5.8 ± 0.4	0.33 ± 0.05
Aerosol PM _{1.2-2.4} (12.02.1997)	1.3 ± 0.1	0.26 ± 0.05
Aerosol PM _{2.4-5.0} (12.02.1997)	1.1 ± 0.1	
Aerosol PM _{0.15-0.3} (11.03.1997)	6.4 ± 0.4	1.4 ± 0.2
Aerosol PM _{0.3-0.6} (11.03.1997)	11.8 ± 0.6	1.4 ± 0.2
Aerosol PM _{0.6-1.2} (11.03.1997)	7.2 ± 0.4	0.98 ± 0.18
Aerosol PM _{1.2-2.4} (11.03.1997)	1.7 ± 0.2	0.3 ± 0.05
Aerosol PM _{2.4-5.0} (11.03.1997)	0.4 ± 0.04	
Aerosol PM _{0.15-0.3} (29.04.1997)	3.6 ± 0.3	
Aerosol PM _{0.3-0.6} (29.04.1997)	5.9 ± 0.4	0.12 ± 0.03
Aerosol PM _{0.6-1.2} (29.04.1997)	3.3 ± 0.3	
Aerosol PM _{1.2-2.4} (29.04.1997)	1.2 ± 0.1	
Aerosol PM _{2.4-5.0} (29.04.1997)	1.8 ± 0.2	
Aerosol PM _{0.15-0.3} (21.05.1997)	3.3 ± 0.25	
Aerosol PM _{0.3-0.6} (21.05.1997)	5.9 ± 0.4	0.14 ± 0.03
Aerosol PM _{0.6-1.2} (21.05.1997)	4 ± 0.28	0.07 ± 0.02
Aerosol PM _{1.2-2.4} (21.05.1997)	0.8 ± 0.08	
Aerosol PM _{2.4-5.0} (21.05.1997)	0.2 ± 0.02	
Aerosol PM _{0.15-0.3} (09.01.1999)	9.5 ± 0.5	1.7 ± 0.2
Aerosol PM _{0.3-0.6} (09.01.1999)	7.9 ± 0.4	
Aerosol PM _{0.6-1.2} (09.01.1999)	4.7 ± 0.3	
Aerosol PM _{1.2-2.4} (09.01.1999)	0	
Aerosol PM _{0.15-0.3} (28.05.1999)	14.3 ± 0.6	0.85 ± 0.10
Aerosol PM _{0.3-0.6} (28.05.1999)	24.9 ± 0.9	1.04 ± 0.20
Aerosol PM _{0.6-1.2} (28.05.1999)	11.5 ± 0.6	0.76 ± 0.10
Aerosol PM _{12-2.4} (28.05.1999)	1.7 ± 0.1	

Badgastein, Austria*

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Stubnerkogel, Austria*	Aerosol PM _{0.15-0.3} (25.05.1999)	22.8 ± 0.9	4.1 ± 0.3
	Aerosol PM _{0.3-0.6} (25.05.1999)	11.3 ± 0.6	1.5 ± 0.2
	Aerosol PM _{0.6-1.2} (25.05.1999)	7.8 ± 0.5	1.2 ± 0.1
	Aerosol PM _{1.2-2.4} (25.05.1999)	1.1 ± 0.1	0.5 ± 0.1
	Aerosol PM _{0.15-0.3} (27.05.1999)	8.9 ± 0.5	1 ± 0.12
	Aerosol PM _{0.3-0.6} (27.05.1999)	10.5 ± 0.5	0.6 ± 0.08
	Aerosol PM _{0.6-1.2} (27.05.1999)	9 ± 0.5	0.6 ± 0.08
	Aerosol PM _{1.2-2.4} (27.05.1999)	0.9 ± 0.1	

R: Remote Site; U: Urban Site; I: downwind of Industrial Site; Su: Summer; Au: Autumn; Wi: winter; Sp: Spring; *: in mBq/100 m³ air.

The data depict that bioaccumulation takes place at even lower substrate concentrations and ²¹⁰Po accumulation exceeds ²¹⁰Pb by about a factor of 2^[37]. The much higher ²¹⁰Po and ²¹⁰Pb concentrations in aerosols emanating from forest fires, power and desalination plants, and oil installations highlight the considerable dose humans can get from inhalation. The issue is exacerbated given that frequent forest fires are linked to climate change. An extensive area is lost to forest fires year after year globally, most recently in Australia, Canada, Spain, Belarus, Russia, Portugal, and Turkiye. A very detailed spatial distribution of forest fires^[24] provides an overview of approximately 10 million hectares of forest lost yearly.

It will be quite imperative to conduct aerosol sampling and define the concentration of these radionuclides in size-fractionated aerosols. We have found a six-stage cascade impactor mounted on a high-volume air sampler to be very effective in determining radioactivity in respirable and inhalable fractions^[19,29,40,41]. The likelihood of volatilization of ²¹⁰Po in forest fires is relatively high as temperatures above 1,000 °C have been reported from forest fires^[17]. The considerable reduction of volume due to fire and the positive charge of gaseous ²¹⁰Po can result in the recapture of ²¹⁰Po and ²¹⁰Pb on ash particles, resulting in higher concentrations of these radionuclides in ash and aerosols.

The highest concentration of ²¹⁰Po in the vicinity of forest fires and downwind industrial sites is associated with $PM_{_{0.39-2.5}}$ and $PM_{_{2.5-10}}$ sizes. Considering an average breathing rate of 6 L min⁻¹, an adult breathes about 8.64 m³ daily. The ²¹⁰Po concentration in forest fires in Portugal was reported as 70 mBq m⁻³, resulting in an inhalation rate of 0.605 Bq d⁻¹. Using the dose conversion factor of 3.3×10^{-6} Sv Bq⁻¹, a 2 μ Sv d⁻¹ dose is interesting to put it in perspective: an individual who smokes a packet of cigarettes daily gets about 0.099 μ Sv d⁻¹, which is significantly lower than the population exposure during forest fires.

CONCLUSION

Forest fires play a significant role in the redistribution of ²¹⁰Po and ²¹⁰Pb. These fires not only release these isotopes into the atmosphere but also facilitate their transport over considerable distances. The combustion of organic matter during forest fires liberates substantial quantities of ²¹⁰Po and ²¹⁰Pb into the air, where they can attach to aerosol particles. Studies have shown that these isotopes often exhibit elevated concentration ratios in the aftermath of forest fires, surpassing unity in some instances.

The resultant aerosols, laden with ²¹⁰Po and ²¹⁰Pb, disperse throughout the atmosphere. Fine and ultrafine aerosol particles become carriers for a significant portion of these isotopes. Research has indicated that a substantial percentage, sometimes over 70%, of ²¹⁰Po activity in aerosols is associated with particles smaller than 2.5 μ m. The ultrafine particles are reported to have the highest levels of these isotopes post-forest fires. This pattern aligns with observations not only in forests but also in areas affected by other combustion sources, such as industrial emissions across different geographical locations. The highest concentrations are

observed in inhalable and respirable fractions of the aerosols that are more likely to enhance the radiation dose humans receive due to inhalation, i.e., the ~2 μ Sv d⁻¹ dose from forest fires and ~ 0.002 - 0.042 μ Sv d⁻¹ dose from industrial emissions. From the dose perspective, the climate change-mediated fires and increase in fossil fuel and coal-based power generation are likely to result in the redistribution of ²¹⁰Po and ²¹⁰Pb and impart a dose that is several orders of magnitude higher than the normal background doses and likely to significantly contribute to the 1 mSv permissible annual dose.

Understanding the dynamics of ²¹⁰Po and ²¹⁰Pb redistribution in the aftermath of forest fires is crucial for comprehending their environmental impact and potential implications for human health. Tracking the dispersion of these radionuclides and their attachment to aerosols can shed light on the broader implications of these natural events on atmospheric radioactivity and the subsequent exposure risks to ecosystems and populations downwind from these fire-affected regions.

DECLARATIONS

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Authors' contributions

Conceptualized and designed the study: Uddin S Performed data analysis: Gorgun AU, Behbehani M, Habibi N Helped with the interpretation: Fowler SW , Filizok I Done the data acquisition: Uddin S, Behbehani M. Provided the technical and material support: Fowler SW, Al-Murad M, Uddin S

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate Not applicable.

Consent for publication Not applicable.

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