Volume 12, Number 2, 2019. pp. 183-189

Jordan Journal of Physics

ARTICLE

Radiological Characterization of Settled Dust during a Severe Dust Episode in Jordan

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Received on: 25/9/2018; *Accepted on: 28/1/2019*

Abstract: An unusually massive dust storm influenced Jordan and neighboring countries on September 8th to 11th 2015. The dust from this storm was investigated for its radioactive content using gamma-ray spectroscopy. Such storms may carry a large amount of dust and radioactive content, which may impact human health. Samples were collected from different regions in Jordan. The activity concentrations of natural ^{232}Th (Thorium), ^{238}U (Uranium), ^{40}K (Potassium) and artificial ^{137}Cs (Cesium) radionuclides were measured. The activity concentrations (Bq kg^{-1}) had an average of (± Standard Deviation (SD)) 24.7 ± 10, 34.1 ± 13.3, 438 ± 124 and 15.7 ± 4.1 for ^{232}Th, ^{238}U, ^{40}K, and ^{137}Cs, respectively. The activity concentrations of natural and artificial radionuclides were analogous with results obtained from different studies with seasonal storms. The natural radionuclides were comparable to what was found in the local soil, while the activity concentration of ^{137}Cs was larger than that found in soil (2.4 ± 1.2 Bq kg^{-1}) and this is attributed to particle size effects. Dose assessment of ^{137}Cs showed that it does not contribute significantly to the internal dose of a human during inhalation. The correlation between ^{232}Th and ^{40}K activity concentration in the measured dust particles is a moderate correlation with a value which is in agreement with those found in other studies worldwide.

Keywords: Radioactivity, Gamma -ray spectrometry, Cesium-137, Unseasonal dust.
PACS number: 29.30.Kv.

1. Introduction

In the past decades, researchers were interested in studying the activities related to nuclear reactions and radioactivity concentrations and its correlated health hazards [1]. Humans are exposed to radionuclides from two main sources, natural and artificial, both of which enter the human body through the food and accumulate in specific organs. Natural radionuclides include the uranium decay series (^{235}U and ^{238}U), the thorium decay series (^{232}Th) and Potassium (^{40}K) [2]. The artificial radionuclides (^{137}Cs, ^{90}Sr, ^{239}Pu, …etc.) can be released to the environment due to accidents in nuclear reactors such as Chernobyl or from nuclear industry waste, fallout from atmospheric nuclear weapon testing and medical waste [3].

One of the most important artificial nuclides to study is ^{137}Cs (with a half-life of 30 years), since it moves easily through the environment

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similarly to rubidium and potassium. Its world-wide spread is related to the fallout from atmospheric nuclear weapon testing in the 1950s and 1960s [3]. Among other pathways, humans may directly inhale ^{137}Cs with dust and this pathway may have health consequences [4].

Eastern Mediterranean countries, including Jordan, are affected by seasonal dust storms during the spring season [5, 6]. Besides that, there are unseasonal dust storms that occur under specific weather conditions which meteorologists cannot sometimes predict [7]. These dust storms can affect both weather and human health [8].

A massive dust storm swept through the Middle East on September 8th, 2015, lasting four days, badly reducing visibility, killing at least twelve people and sending thousands of people to hospitals with breathing problems in several Middle Eastern states including Jordan [9, 10, 11]. Broadcast media talked in detail about this unusual event [12, 13, 14, 15]. Health authorities in the affected countries advised and warned people not to leave their homes [16]. Schools in Jordan and Lebanon were closed due to weather and several flights across the region were grounded due to poor visibility Even the combat was stopped in central Syria [17].

Storms like this are called Haboobs in Arabic culture, which means “violent winds”. Meteorologists were unable to foresee this dense dust storm, because of the unusual weather conditions that are attributed to such a “rare” metrological phenomenon [7]. These storms can travel for thousands of kilometers, even across the Pacific and can impact many parts of the world.

Papastefanou et al. (2001) studied the radioactivity of radioactive nuclides in colored rain dust samples. It was shown that ^{137}Cs remained after the Chernobyl reactor accident [18]. Papastefanou and Manolopoulou (1989) determined the radioactivity of colored rain in Thessaloniki, Greece by comparing the radioactivity of soil before and after the fall of colored rain. They identified the fission products ^{137}Cs, ^{134}Cs, ^{144}Ce, ^{106}Ru and ^{125}Sb, where all these radionuclides were related to the Chernobyl reactor accident which occurred two years before the study [19].

In Jordan, the first study to assess the radioactivity in seasonal dust storms was in 2015 [20]. The researchers measured the level of natural and artificial radionuclide from large seasonal dust storms in 2012 for samples that were collected from Northern Jordan using gamma- ray spectroscopy. They compared their results with soil samples from the same region.

Recently, a study was conducted to investigate the characteristics of the same unseasonal dust storm as in our present work, at Limassol, Cyprus. The researchers discussed their results based on satellite, lidar vertical profiling and *in situ* aerosol observations [21].

The goal of this study is to measure activity concentrations of natural and artificial radionuclides in this large unseasonal dust storm at different locations in Jordan. For comparison purposes, soil samples from the same regions are analyzed to determine the enrichment of radionuclides (especially ^{137}Cs) to compare the values in dust particles and soil particles.

2. Materials and Methods

Samples of unseasonal dust storm were collected from nine different countryside regions in Jordan which lie at different heights above sea level ranging from 380 to 1000 m based on Google maps [22], (Aqraba, ArRamtha, Huwara, Al Husun, Muhayyam Azmi Almofte, Assarih, Jerash, Jouza and Mo’ta). The study regions were covered with a thin layer of dust. The samples were collected off smooth flat surfaces in the areas (i.e., one sample was gathered from each region). In addition to the dust samples, different soil samples were collected from the same areas for comparison purposes at (0-10) cm depth level all over, packed in plastic bags, assembled in the laboratory and oven dried for at least 2 hrs. at 100^{o}C until a constant weight was reached. Then, the soil samples were sieved through 0.05 mm mesh to remove stones, pebbles and other impurities.

Samples of dust and soil were transferred to standard 100 ml cylindrical cups of 2 cm radius and 6 cm height and sealed. Thereafter, the samples were stored for at least 6 weeks before counting of gamma spectrometric analysis to ensure that secular equilibrium between ^{226}Ra and its decay products was reached.

The activity concentration measurements were performed using high-purity germanium detector (Canberra, Industries, Inc., USA). The detector was of a high resolution; 1.9 *keV* at 1.33

MeV of ^{60}Co gamma ray peak and a relative efficiency at the same energy peak of 25%. The background radiation was reduced by shielding the detector with a 100mm thick lead cylinder. The data was analyzed using Genie 2000 software containing peak search and nuclide identification modules. A multi-gamma ray reference standard (MGS-5.Canberra, USA) was used for calibration of energy and relative efficiencies for the detector which emits gamma rays of 60-1461 *keV*. The samples were counted for 86,000 s to reduce the statistical counting error with dead time smaller than 10%. Standard reference materials were used to perform quality control tests obtained from International Atomic Energy Agency (IAEA) (IAEA-375 soil and IAEA-315 marine sediment) in the same geometry as the measured samples. Under the same conditions, an empty cup measurements were also performed to determine the background counts.

The activity concentrations of ^{137}Cs and ^{40}K were directly defined *via* their gamma lines of (yields) 662 *keV* (0.85) and 1461 *keV* (0.11), respectively. On the other hand, the activity concentration of ^{232}Th was determined using the gamma line of its daughter (in the decay chain of radioactive substances it's the decay product of parent nuclide ; i.e., ^{232}Th in this case) ^{228}Ac using 911 *keV* (0.29). For ^{238}U, the activity concentration was determined using the weighted mean activity concentration of its first daughter ^{234}Th 63.3 *keV* (0.048). The minimum detectable activities for ^{137}Cs, ^{40}K, ^{238}U and ^{232}Th were 0.17, 8.2, 4.6 and 0.71 Bq kg^{-1}, respectively.

3. Results and Discussion

Fig. 1 shows the image of the dust storm over the Middle East (AFP photo), captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board the Aqua satellite [23]. The image shows that the dust storm affected large parts of Jordan on Tuesday, September 8th 2015. The maximum dust particle mass concentrations for this dust storm were in the order of 10000 µg/m^3 [21]. For more information about the characterization quantities of this dust storm, see Mamouri et al. (2016).

As shown in Table 1, the radionuclides ^{137}Cs, ^{40}K, ^{232}Th and ^{238}U were identified in all dust and soil sample regions. For dust samples, the activity concentration of ^{137}Cs was in the range of 10.9 ± 2.0 Bq kg^{-1} and 24.6 ± 4.5 Bq kg^{-1} with an average of (±SD) 15.7 ± 4.1 Bq kg^{-1}. This result is less than that of the other study (1000 ± 5.0 Bq kg^{-1}) [19], which can be related to the time period since the nuclear accidents and the weapon testing.

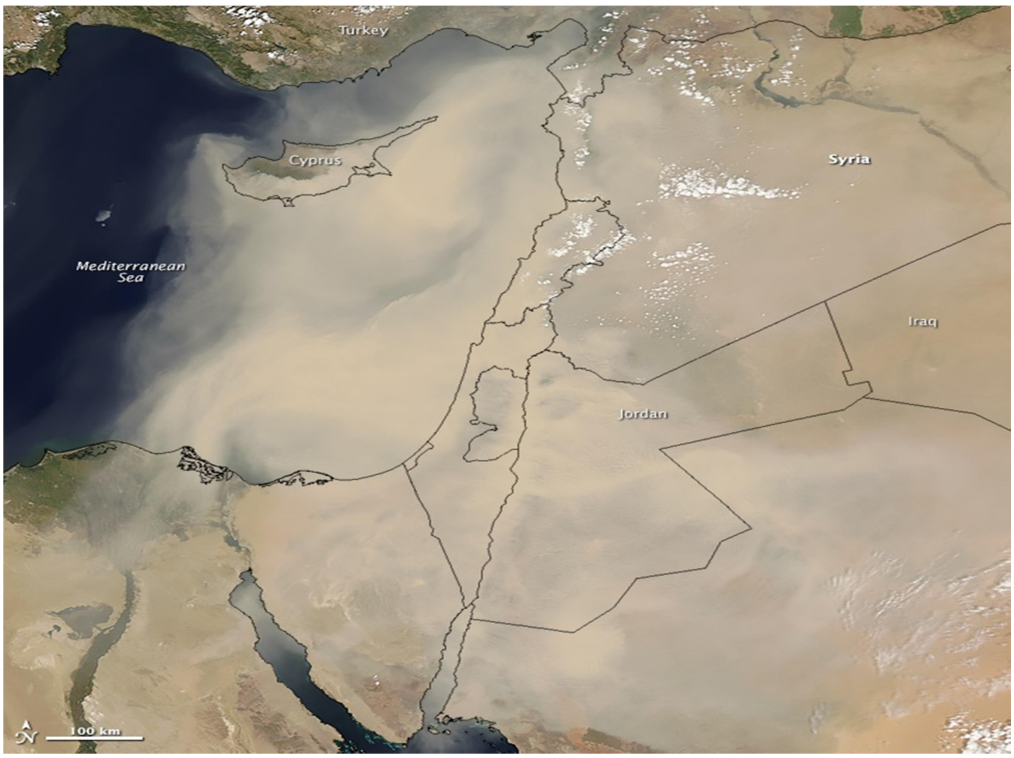

FIG. 1. The image of the dust storm over the Middle East (AFP photo), captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board the Aqua satellite on Tuesday, September 8th [23].

TABLE 1. Activity concentrations of measured radionuclides in dust samples and in local soil samples (all activity concentrations were decay corrected for September).

Region	Height above sea level (m) (Google maps)	Activity concentration of radionuclides (Bq kg^{-1})							
		Dust Samples				Soil Samples			
		^{137}Cs	^{40}K	^{232}Th	^{238}U	^{137}Cs	^{40}K	^{232}Th	^{238}U
Al Husun	600	14.6 ±1.1	404.6 ±34.0	22.1 ±3.2	25.8 ±4.3	0.5 ±0.1	315.9 ±3.9	45.7 ±6.4	39.5 ±6.1
ArRamtha	530	19.9 ±1.9	533.9 ±54.6	28.0 ±4.8	27.4 ±5.7	4.6 ±2.5	160.6 ±38	22.7 ±7.6	20.4 ±4.9
Assarih	700	17.4 ±1.4	417.8 ±39.0	21.2 ±3.7	25.4 ±4.8	1.4 ±0.4	324 ±26.3	29.9 ±3.2	29.7 ±3.0
Aqraba	380	12.8 ±1.3	320.5 ±33.9	23.9 ±4.0	20.8 ±4.6	2.3 ±1.6	172 ±21	26 ±3.7	21.4 ±4.4
Huwara	540	15.6 ±1.2	427.8 ±38.0	20.0 ±3.7	24.9 ±4.5	4.1 ±0.6	495.1 ±58.2	32 ±3.8	38.5 ±7.9
Jerash	700	11.80 ±1.5	402.9 ±46.3	17.2 ±4.5	52.6 ±9.6	2 ±0.6	218.4± 24.4	14.5 ±3.5	19.9 ±4.1
Jouza	800	24.6 ±4.5	751.5 ±14.0	51.7 ±12.3	58.7 ±17.3	2.6 ±0.4	211.9 ±16.5	28.9 ±2.4	20.3 ±3.0
Mo'ta	1000	10.9 ±2.0	385.0 ±6.3	21.7 ±7.1	45.3 ±11.3	1.9 ±0.3	313.5 ±25.2	39.5 ±3.3	29.2 ±4.5
Muhayyam Azmi Almofte	660	13.9 ±1.3	352.9 ±37.5	22.8 ±3.1	26.7 ±5.4	2.2 ±0.3	185.7 ±15.2	26.6 ±2.7	20.6 ±3.0
MIN.		10.9 ±2.0	320.5 ±33.9	17.2 ±4.5	20.8 ±4.6	0.5 ±0.1	160.6 ±38	14.5 ±3.5	19.9 ±4.1
MAX.		24.6 ±4.5	751.5 ±14.0	51.7 ±12.3	58.7 ±17.3	4.6 ±2.5	495.1 ±58.2	45.7 ±6.4	39.5 ±6.1
Average ± (SD)		15.7 ± 4.1	438 ±124	24.7 ±10.0	34.1 ±13.3	2.4 ±1.2	266.3 ± 111	29.5 ±10.8	26.6 ± 8.2

^{40}K which is naturally occurring had activity concentrations ranking between 321 ± 34 Bq kg^{-1} and 752 ± 14 Bq kg^{-1} with an average of 438 ± 124 Bq kg^{-1}. The activity concentrations of ^{232}Th ranged from 17.2 ± 4.5 Bq kg^{-1} to 51.7 ± 12.3 Bq kg^{-1} with an average of 24.7 ± 10 Bq kg^{-1} and for ^{238}U, the activity concentrations ranged from 20.8 ± 4.6 Bq kg^{-1} to 58.7 ± 17.3 Bq kg^{-1} with an average of 34.1 ± 13.3 Bq kg^{-1}. Table 2 compares the activity concentrations of ^{137}Cs, ^{40}K, ^{232}Th and ^{238}U in the present study and previous studies for dust samples.

For soil samples, the activity concentrations of ^{137}Cs were in the range of 0.5 ± 0.1 Bq kg^{-1} to 4.6 ± 2.5 Bq kg^{-1} with an average of (±SD) 2.4 ± 1.2 Bq kg^{-1}. This measured value is comparable with those of previous studies of (0.3 - 41) Bq kg^{-1} [24] and recent study of 2.3 ± 1.6 Bq kg^{-1} [20].

For ^{40}K, the activity concentrations were in the range from 160.6 ± 38 Bq kg^{-1} to 495.1 ± 58.2 Bq kg^{-1} with an average of (±SD) 266.3 ± 111 Bq kg^{-1}. For ^{232}Th, the activity concentrations were from 14.5 ± 3.5 Bq kg^{-1} to 45.7 ± 6.4 Bq kg^{-1} with an average of (±SD) 29.5 ± 10.8 Bq kg^{-1}. The activity concentrations of ^{238}U were in the range between 19.9 ± 4.1 Bq kg^{-1} and 39.5 ± 6.1 Bq kg^{-1} with an average of (±SD) 26.6 ± 8.2 Bq kg^{-1}.

TABLE 2. Activity concentrations of measured radionuclides in dust samples in the present work and in previous studies.

Radionuclides	Activity concentration of radionuclides (Bq kg^{-1}) (±SD)	
	Present study	Previous studies
^{137}Cs	15.7 ± 4.1	17.0 ± 2.0 [20] 26.6 ± 4.4 [18].
^{40}K	438 ± 124	402 [19] 488 [18] 547 ± 56 [20]
^{232}Th	24.7 ± 10	30.0 ± 4.9 [20]
^{238}U	34.1 ± 13.3	49.3 ± 14 [20]

The internationally reported average values for the natural radionuclides ^{238}U, ^{232}Th and ^{40}K are 40, 40 and 370 Bq kg^{-1}, respectively [3]. The obtained results of the present work in dust and soil samples are comparable with the worldwide average concentration values. The average activity concentration of ^{137}Cs in dust samples was about eight times its value in soil samples, where the activity concentration increases in the finer size of soil as reported in several studies [25, 26, 27]. The dust samples in the present work have an aerodynamic diameter smaller than 10 µm [21], which is classified as silt and clay with particle sizes of <63 µm according to ISO-14688-1 classification of soil [28].

In spite of the relatively large concentration of ^{137}Cs in the dust storm with respect to the concentration in soil, it's not large enough to affect the potential radiological impact on human health, since the effective dose coefficients for inhalation of ^{137}Cs are very small. Based on the ICRP Publication 119 [29], the dose equivalent coefficient of ^{137}Cs for adults is 4.8 x 10^{-9}, which would give rise to a dose of 0.08 µSv per kg of inhaled ^{137}Cs in the dust storm studied here. Assuming that the inhaled mass is in the order of milligrams, the expected dose will be in the range of nSv. In addition, the worldwide average effective dose based on UNSCEAR (2000) [3] is 0.22 µSv, which is around 2.7% of the total annual dose from artificial radionuclide.

The correlation between ^{232}Th and ^{40}K in dust samples is illustrated in Fig. 2. The correlation is moderate. While there is no theoretical basis for this correlation, this result agreed with those revealed other studies worldwide [30, 31, 32].

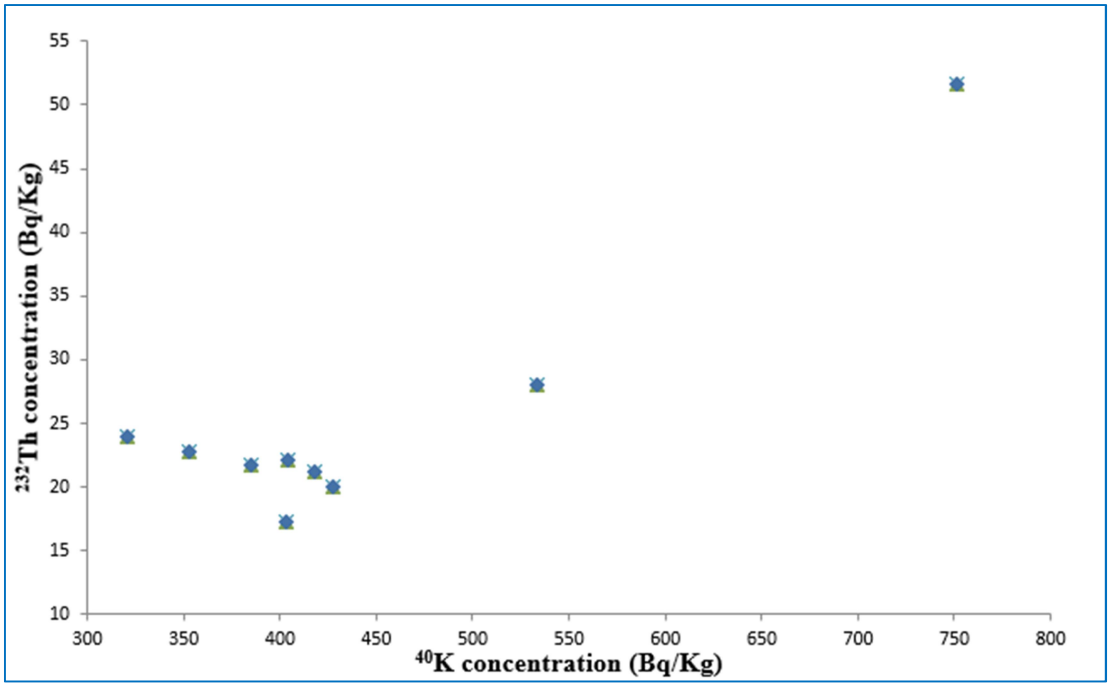

FIG. 2. Potassium *vs*. thorium concentration in dust samples.

4. Conclusions

A huge unusual dust storm swept through the Middle East on September 8th, 2015, for four days. The activity concentrations of dust and local soil samples were measured in different locations in Jordan using gamma-ray spectroscopy. Terrestrial radioisotopes (^{232}Th, ^{238}U and ^{40}K) and the artificial radioisotope ^{137}Cs were detected in the samples. In particular, the activity concentration of ^{137}Cs was (±SD) 15.7 ± 4.1 Bq kg^{-1}. This high value compared to that in soil (2.4 ± 1.2 Bq kg^{-1}) related to abundance of fine-sized particles, which is consistent with previous studies. The natural radionuclides in dust are comparable to what is found in soil. The dose assessment of ^{137}Cs inhalation from dust showed that ^{137}Cs contribution to additional effective dose will be negligible.

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