

Spatial Distribution of Total ^{210}Pb in the Marine Sediment of Peninsular Malaysia: Radioactivity Level Variations in the Sunda Shelf Seas

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Received: 26 February 2023, Revised: 26 March 2023, Accepted: 27 March 2023, Published: 26 April 2023

Abstract

Radiochemical separation techniques were applied to measure ^{210}Pb radioactivity in samples to determine spatial distribution of total ^{210}Pb radionuclide in surface sediments and water column for the main waters on the Sunda Shelf. The average ^{210}Pb radioactivity level recorded for the Malacca Strait (MS) is significantly higher than that of the southern South China Sea (sSCS); this is attributed to the supply of input from the Andaman Sea in its northern areas, and massive terrestrial processes from bordering land masses. The results reveal that the decreasing trend of total ^{210}Pb in Peninsular Malaysia's marine sediment starts with the north maritime zone of Malacca Strait (64.28 ± 5.97 Bq/kg) > south maritime zone of Malacca Strait (50.88 ± 6.15 Bq/kg) > east maritime zone of sSCS (41.01 ± 3.07 Bq/kg) > south maritime zone of sSCS (40.78 ± 3.16 Bq/kg). The Kelantan and Pahang Deltas have been identified as two of the main anthropogenic sources of input for total ^{210}Pb in the sSCS with atmospheric transboundary mobilization affecting total ^{210}Pb in the water column. In the Malacca Strait, however, the distribution of total ^{210}Pb might be influenced mainly by in situ processes of the strait's seafloor and sources origin of sediment.

Keywords: ^{210}Pb , Sediment, Malacca Strait, Southern South China Sea, Andaman

Introduction

Lead- 210 (^{210}Pb) is a naturally occurring radioisotope that is found throughout the natural ecosystem and originates from the Earth's crust and atmosphere. It is a member of the ^{238}U decay series and is produced by the decay of gaseous ^{222}Rn which attaches to fine aerosols in the atmosphere and contributes to atmospheric fallout. In marine sediments, ^{210}Pb can be categorized as supported, unsupported, or excess based on its sources. It has a wide range of applications in marine research including age dating for sediment cores, particle cycling and export processes in ocean surfaces, and as a tracer for atmospheric processes like continental dust and air mass transport time scales. ^{210}Pb has a short half-life of 22.2 years and is a valuable tool in understanding environmental changes and pollution history in various ecosystems.

Despite its recognized importance as geochemical tracers (ex: Source, transport, contaminant and removal tracers) in oceanic processes, knowledge regarding ^{210}Pb within Malaysia and other Southeast Asian waters is still limited concerning its source, sink, internal cycling and chemical speciation in marine environments.

The southward extension of mainland Southeast Asia is known as the Sunda Shelf, a stable continental shelf that is dominated by shallow seas and a number of busy maritime lanes such as the Java Sea, the sSCS, and the Singapore and Malacca Strait. Most geographical regions on the Sunda Shelf are commonly dominated by alternating monsoon systems known as the summer and winter monsoons with 2 prevailing but different and opposing wind directions, thus having a significant impact on ocean circulation. This meteorological characteristic and the addition of strong impacts from human activities thus makes the

marine ecosystem of the Sunda Shelf a subject of interest for researchers to study the sensitivity of physical and biogeochemical processes attributed to environmental and climate changes issues [1].

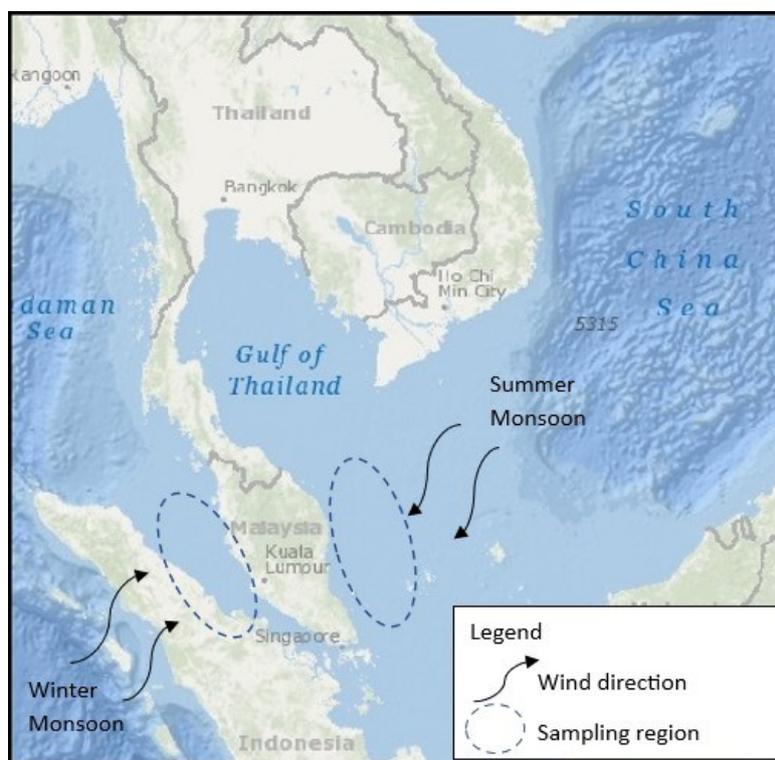


Figure 1 The area of sampling in Northern Malacca Straits affected by monsoonal season.

There are only a few studies conducted on or associated with natural radionuclide in this marine region [2-4]. The latest research relating to ^{210}Pb and its progeny, ^{210}Po by Sabuti and Mohamed [5], stated that there is a lack of information on the transport of these radionuclides from the atmosphere to seawater and eventually to the sediments of the Malaysian Sea. Most of the studies mentioned above have only covered the atmosphere (atmospheric deposition) and seawater phases (air-sea interaction) as atmospheric transport is known to act as an important vector for the transfer of anthropogenic materials from the continents to the open ocean. A further study covering the sediment-water boundary is required so that this radionuclide behaviour such as its transport pathways, internal cycling and its fate after being introduced into the ocean ecosystem can be fully understood and further evaluation and verification on its possible origin sources can be achieved. The main aim of this study is thus to determine the distribution and sources of ^{210}Pb radionuclide in surface sediments and the upper water column throughout Peninsular Malaysia's seas by focusing on the region within the sSCS, bordered by the Gulf of Thailand and within the northern Malacca Strait.

Materials and methods

Samples for this study were collected during the Universiti Kebangsaan Malaysia (UKM) Scientific Expedition Cruise conducted in September 2017 (end of the Southwest Monsoon) on the Universiti Malaysia Terengganu (UMT) Research Vessel, Discovery. A total of 78 sampling stations were selected from Peninsular Malaysia's water basin covering all of the possible Exclusive Economic Zone (EEZ) areas around the peninsular. The stations can be further divided into 2 areas; offshore stations (South China Sea and Malacca Straits) and nearshore stations (Kelantan and Pahang Deltas). For the classification, the station was divided into several zones. These major zones were named the eastern maritime region of sSCS (sSCS1), the southern maritime region of the sSCS (sSCS2), the northern maritime region of the Strait of Melaka (SM1), and the southern maritime region of the Strait of Malacca (SM2). sSCS1 and SM1 included stations located at latitudes above 5°N while sSCS2 and SM2 comprised stations located at latitudes below 5°N (Figure 2). Apart from offshore stations, a few samples were also collected at nearshore stations in the

Kelantan and Pahang Deltas (**Figure 3**) in order to determine where there is significant anthropogenic input to the sSCS from these areas.

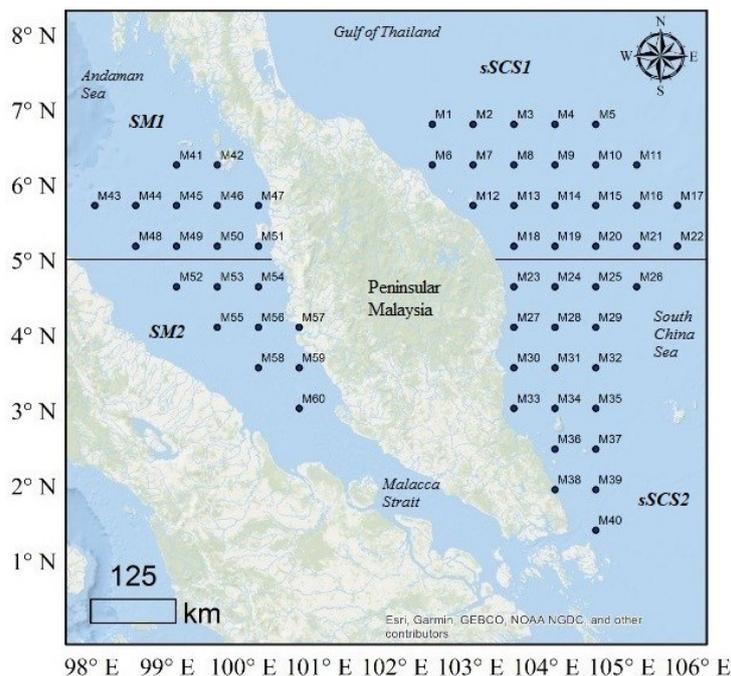


Figure 2 Offshore sampling stations with 4 major zones; eastern maritime region of sSCS (sSCS1), southern maritime region of sSCS (sSCS2), northern maritime region of Strait of Melaka (SM1), and southern maritime region of the Strait of Malacca (SM2).

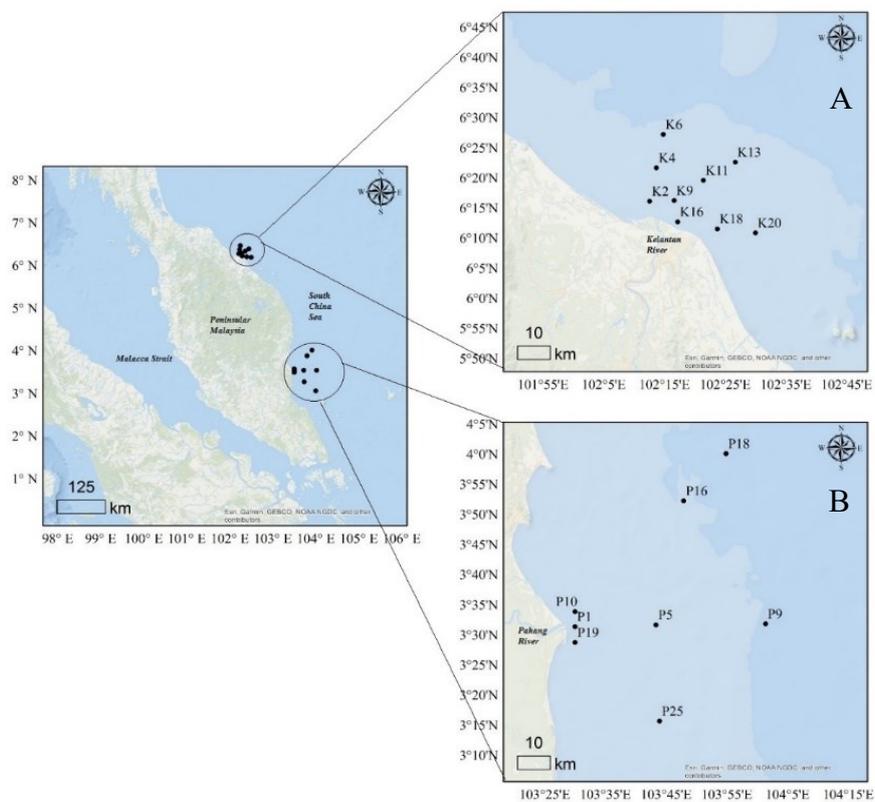


Figure 3 Nearshore sampling stations; (a) Kelantan Delta and (b) Pahang Delta.

Preparation of the sediment samples was based on Rahim *et al.* [6], consisting of processes of drying, grinding and sieving with a 63-micron sieve. About 1 g of fine sediment sample that had been thoroughly ground and sieved was then digested with 10 mL 8 M HNO₃ for 3 h. The volume of sample solution in the beaker was reduced using a drying technique to ascertain an appropriate amount before being filtered through a 0.25 µm filter paper. Afterwards, the sample was precipitated with NH₃ before moving to the electrodeposition phase.

For seawater samples, the procedures was based on the method of Saili and Mohamed [7]. Primarily, the seawater samples were combined with Pb(NO₃)₂ solution carrier and 2.5 mL Fe solution carrier before the addition of NH₃ and Na₂CO₃; turning the acidic sample to pH10 to form a white precipitate for collection, with the supernatant was discarded. The precipitate was re-dissolved with HNO₃ to pH 2 - 3 and 5 mL HClO₄ and heated for 2 h for CO₂ removal.

For radiochemical separation method by electrodeposition, the dissolved samples were electrodeposited at 2.3 - 2.5 V for 1 h (platinum gauze as anode and steel wire as cathode). Then, a platinum bucket was rinsed with a mixture of 3 M HNO₃ and 30 % H₂O₂. Next, the sample was heated until fully dried before dissolving it with 30 mL 0.5M HNO₃ and 1 mL H₂SO₄, so that white PbSO₄ appears. The measurement of ²¹⁰Pb radioactive emissions from PbSO₄ precipitates were performed after 25 days of electrodeposition (after the ²¹⁰Bi ingrowth period) using Gross Alpha-Beta Counters by Canberra, Inc., with Eclipse software. The average recovery yield percentage of Pb²⁺ from Pb(NO₃)₂ carrier for both sediment and seawater samples were 84 and 85 % respectively. The estimation from SRM4357 NIST (ocean sediment) also showed a convincing recovery yield percentage for the accuracy of this method, reaching 90.60 % (21.74 Bq/kg). All the data were calculated using a radioactivity formula to gain the real activity concentration of the sample on the sampling date at each station.

To determine the change and source of ²¹⁰Pb of coastal of Peninsular Malaysia, the excess ²¹⁰Pb was used as a tool to assess the changes occurred within the Peninsular Malaysia sea. ²²⁶Ra is important tracers in oceanographic studies on time-scales and recognized as a tracer for natural processes in the atmosphere and on the earth surface. As ²¹⁰Pb is daughter of ²²⁶Ra, the importance of being non-particle reactive, resulting a tool for detecting ocean mixing through ²²⁶Ra to be supplied and enriched along the water-sediment interface [8]. In this study, the activities of ²²⁶Ra were estimated using Eqs. (1) - (2) for the values of radium and their standard deviation, respectively [8,9].

$$Z = [y + 0.571]/1.734 \quad (1)$$

$$\frac{M2}{M1} = 1 - e^{-\lambda t} + R^* e^{-\lambda t} \quad (2)$$

$$210Pb_{ex} = 210Pb - 226Ra \quad (3)$$

where y is the water depth and Z is the ²²⁶Ra obtained in this study. For the error propagation of ²²⁶Ra, it was acquired from past literature (Eq. 2), where M2 and λ are the activity of ²¹⁰Pb and their decay constant, while M1 is the activity of ²²⁶Ra, respectively. The t is time (day) and R* is the initial ²¹⁰Pb/²²⁶Ra activity ratio [10,11]. Eq. (3) was used to calculate excess ²¹⁰Pb (²¹⁰Pb_{ex}), where ²¹⁰Pb is the total activity of ²¹⁰Pb obtained through the experiment and ²²⁶Ra is total ²²⁶Ra from the previous equations.

Results and discussion

Different input sources of ²¹⁰Pb and the roles of insitu parameter in water column

The ²¹⁰Pb radioactivity in the surface sediment of Peninsular Malaysia at the end of the Southwest monsoon is presented in **Tables 1** and **2**. The offshore sediment covered the South China Sea and the Strait of Malacca, whereas nearshore sediment involved the deltas that connect large rivers to this region known as the Kelantan and Pahang Deltas. The results show that ²¹⁰Pb in the offshore sediments of Peninsular Malaysia fall within a range of 14.71 - 109.16 Bq/kg with an average value of 46.69 ± 2.31 Bq/kg. ²¹⁰Pb recorded in the sediment of sSCS falls within a range of 14.71 - 65.52 Bq/kg while SM has a range of 26.86 - 109.16 Bq/kg. Overall, the sediment in the Strait of Malacca, located on the west coast of Peninsular has higher ²¹⁰Pb radioactivity with an average value of 58.25 ± 4.45 Bq/kg compared to sediment in the South China Sea that is located on the east coast, with a recorded value of only 40.91 ± 2.18 Bq/kg.

Table 1 Concentration of ^{210}Pb , ^{226}Ra , and $^{210}\text{Pb}_{\text{ex}}$ in the southern South China Sea.

Area	Station	Sampling Date	Water depth (m)	^{210}Pb (Bq/kg)	^{226}Ra Activity (Bq/kg)	$^{210}\text{Pb}_{\text{ex}}$ (Bq/kg)
Southern South China Sea (SSCS)	M1	18/09/2017	50	23.72 ± 16.5	29.17 ± 20.3	-5.45 ± -3.8
	M2	18/09/2017	53	24.25 ± 16.9	30.9 ± 21.5	-6.65 ± -4.7
	M3	18/09/2017	59.2	53.17 ± 17	34.48 ± 11.1	18.7 ± 6
	M4	18/09/2017	60.5	56.74 ± 17.7	35.22 ± 11	21.53 ± 6.8
	M5	18/09/2017	58.5	36.5 ± 17.4	34.07 ± 16.3	2.44 ± 1.2
	M6	20/09/2017	25	29.99 ± 18.6	14.75 ± 9.2	15.25 ± 9.5
	M7	20/09/2017	53.8	25.79 ± 16.9	31.36 ± 20.6	-5.57 ± -3.7
	M8	20/09/2017	61	45.67 ± 17.8	35.51 ± 13.9	10.17 ± 4
	M9	19/09/2017	74	18.55 ± 17.3	43.01 ± 39.9	-24.46 ± -22.7
	M10	19/09/2017	66	65.52 ± 18.9	38.4 ± 11.1	27.13 ± 7.9
	M11	19/09/2017	60	53.03 ± 18.3	34.94 ± 12.1	18.1 ± 6.3
	M12	20/09/2017	25	30.89 ± 21.2	14.75 ± 10.2	16.15 ± 11.1
	M13	21/09/2017	54.4	30.78 ± 16.1	31.71 ± 16.6	-0.93 ± -0.5
	M14	21/09/2017	74	42.5 ± 16.8	43.01 ± 17	-0.51 ± -0.2
	M15	21/09/2017	62.7	29.87 ± 17.6	36.49 ± 21.5	-6.62 ± -3.9
	M16	21/09/2017	63.5	62.3 ± 18.6	36.95 ± 11	25.36 ± 7.6
	M17	27/09/2017	66.2	65.21 ± 17.9	38.51 ± 10.6	26.71 ± 7.4
	M18	22/09/2017	58	43.4 ± 17.1	33.78 ± 13.3	9.63 ± 3.8
	M19	24/09/2017	62	25.97 ± 16.5	36.09 ± 22.9	-10.12 ± -6.4
	M20	21/09/2017	75	42.32 ± 19.7	43.59 ± 20.3	-1.27 ± -0.6
	M21	27/09/2017	71	43.56 ± 18.4	41.28 ± 17.5	2.29 ± 1
	M22	27/09/2017	80	52.62 ± 19.9	46.47 ± 17.6	6.16 ± 2.4
	M23	22/09/2017	37	41.36 ± 19.4	21.67 ± 10.2	19.7 ± 9.3
	M24	24/09/2017	67.5	23.01 ± 17.3	39.26 ± 29.5	-16.25 ± -12.3
	M25	24/09/2017	73	29.68 ± 19	42.43 ± 27.2	-12.75 ± -8.2
	M26	27/09/2017	76.1	20.27 ± 21.8	44.22 ± 47.5	-23.95 ± -25.8
	M27	22/09/2017	26.2	57.5 ± 19.8	15.44 ± 5.4	42.07 ± 14.5
	M28	24/09/2017	54	34.18 ± 18.1	31.48 ± 16.7	2.71 ± 1.5
	M29	24/09/2017	69	46.16 ± 22.6	40.13 ± 19.6	6.04 ± 3
	M30	22/09/2017	22.5	14.71 ± 22.6	13.31 ± 20.5	1.41 ± 2.2
	M31	23/09/2017	45	56.75 ± 17.8	26.29 ± 8.3	30.47 ± 9.6
	M32	27/09/2017	70.7	33.83 ± 19.1	41.11 ± 23.2	-7.28 ± -4.1
	M33	23/09/2017	16.5	39.13 ± 18.4	9.85 ± 4.7	29.29 ± 13.8
	M34	23/09/2017	41.5	45.98 ± 17.7	24.27 ± 9.4	21.72 ± 8.4
	M35	28/09/2017	66	43.54 ± 18.2	38.4 ± 16	5.15 ± 2.2
	M36	28/09/2017	31.3	54.63 ± 17.3	18.39 ± 5.9	36.25 ± 11.5
	M37	28/09/2017	60.5	48.89 ± 18.1	35.22 ± 13	13.68 ± 5.1
	M38	28/09/2017	14.2	63.64 ± 18.1	8.52 ± 2.5	55.13 ± 15.7
	M39	28/09/2017	45	35.85 ± 16	26.29 ± 11.7	9.57 ± 4.3
	M40	28/09/2017	28.5	45.01 ± 19.6	16.77 ± 7.3	28.25 ± 12.3

Table 2 Concentration of ^{210}Pb , ^{226}Ra , and $^{210}\text{Pb}_{\text{ex}}$ in the Malacca Strait, Pahang and Kelantan Delta.

Area	Station	Sampling Date	Water depth (m)	^{210}Pb (Bq/kg)	^{226}Ra Activity (Bq/kg)	$^{210}\text{Pb}_{\text{ex}}$ (Bq/kg)
Malacca Strait	M41	2/10/2021	63.5	57.91 ± 20	36.95 ± 12.8	20.97 ± 7.3
	M42	2/10/2021	17.3	83.64 ± 31.6	10.31 ± 3.9	73.34 ± 27.7
	M43	2/10/2021	103	77.87 ± 18.6	59.73 ± 14.3	18.15 ± 4.4
	M44	2/10/2021	90	46.65 ± 25.6	52.24 ± 28.7	-5.59 ± -3.1
	M45	2/10/2021	60.8	66.46 ± 21.3	35.4 ± 11.4	31.07 ± 10
	M46	2/10/2021	59	54.86 ± 18.6	34.36 ± 11.7	20.51 ± 7

Area	Station	Sampling Date	Water depth (m)	^{210}Pb (Bq/kg)	^{226}Ra Activity (Bq/kg)	$^{210}\text{Pbex}$ (Bq/kg)
	M47	2/10/2021	25.4	54.35 ± 20.4	14.98 ± 5.7	39.38 ± 14.8
	M48	1/10/2021	90.8	109.16 ± 20.5	52.7 ± 9.9	56.47 ± 10.6
	M49	1/10/2021	75.5	50.5 ± 22	43.88 ± 19.1	6.63 ± 2.9
	M50	1/10/2021	67.5	66.2 ± 20.1	39.26 ± 11.9	26.95 ± 8.2
	M51	1/10/2021	14.8	39.53 ± 18.4	8.87 ± 4.2	30.67 ± 14.3
	M52	1/10/2021	81.5	40.8 ± 18.4	47.34 ± 21.4	-6.54 ± -3
	M53	1/10/2021	63.3	80.45 ± 18.6	36.84 ± 8.5	43.62 ± 10.1
	M54	1/10/2021	50.1	53.37 ± 17.6	29.23 ± 9.7	24.15 ± 8
	M55	30/09/2017	72	37.5 ± 26.4	41.86 ± 29.5	-4.36 ± -3.1
	M56	30/09/2017	63.5	60.92 ± 18.4	36.95 ± 11.2	23.98 ± 7.3
	M57	30/09/2017	12	63.5 ± 19.2	7.25 ± 2.2	56.26 ± 17
	M58	30/09/2017	57.3	28.6 ± 21.2	33.38 ± 24.8	-4.78 ± -3.6
	M59	30/09/2017	51.4	26.86 ± 16.3	29.98 ± 18.2	-3.12 ± -1.9
M60	30/09/2017	76	65.91 ± 18.3	44.16 ± 12.3	21.76 ± 6.1	
Kelantan Delta	K2	17/09/2017	15	84.47 ± 28.6	8.98 ± 3.1	75.5 ± 25.6
	K4	17/09/2017	31.4	73.61 ± 22.2	18.44 ± 5.6	55.18 ± 16.7
	K6	17/09/2017	34.8	43.17 ± 18.9	20.4 ± 9	22.78 ± 10
	K9	17/09/2017	22	89.18 ± 27.2	13.02 ± 4	76.17 ± 23.2
	K11	17/09/2017	24.5	17.8 ± 21.3	14.46 ± 17.3	3.35 ± 4
	K13	17/09/2017	28	35.74 ± 18.6	16.48 ± 8.6	19.27 ± 10
	K16	17/09/2017	9.3	68.34 ± 25.8	5.7 ± 2.2	62.65 ± 23.7
	K18	17/09/2017	16.3	95.75 ± 19.6	9.73 ± 2	86.03 ± 17.6
	K20	17/09/2017	25	40.48 ± 17.5	14.75 ± 6.4	25.74 ± 11.1
Pahang Delta	P1	23/09/2017	11.5	67.33 ± 17.6	6.97 ± 1.9	60.37 ± 15.8
	P5	23/09/2017	25.6	33.05 ± 18.1	15.1 ± 8.3	17.96 ± 9.9
	P9	23/09/2017	42	24.72 ± 13.5	24.56 ± 13.4	0.17 ± 0.1
	P10	23/09/2017	19.5	77.78 ± 18.5	11.58 ± 2.8	66.21 ± 15.7
	P16	23/09/2017	32	35.03 ± 17.3	18.79 ± 9.3	16.25 ± 8
	P18	23/09/2017	48	33.13 ± 17.2	28.02 ± 14.6	5.12 ± 2.7
	P19	23/09/2017	12	72.5 ± 17.2	7.25 ± 1.8	65.26 ± 15.5
	P25	23/09/2017	28.3	53.14 ± 17.5	16.65 ± 5.5	36.5 ± 12
	P30	23/09/2017	31.5	37.72 ± 17.6	18.5 ± 8.6	19.23 ± 9

The analysis of variance shown below (**Table 3** and **Figure 4**) that the means of ^{210}Pb activity in the surface sediments of Peninsular Malaysia waters are significantly different between the 6 main zones with a p -value of less than 0.05. The temperature, conductivity and salinity were taken because it able to provide a vital information regarding the properties of ^{210}Pb within the respective water column in term of behavioral suspended particles and their attachment towards ^{210}Po and generation of ^{210}Pb through absorption and desorption processes in respective water column. Meanwhile, the map generation was via Inverse Distance Weighting (IDW), which runs through 5 simulations. The ^{210}Pb activity in the offshore

sediment followed a decreasing trend from the maritime zone SM1 to sSCS2, while the nearshore sediment of the Kelantan Delta had higher levels than the Pahang Delta. The results from the ANOVA Post Hoc (Tukey's test) showed that the SM1 zone had a significantly higher ^{210}Pb level than the sSCS1 and sSCS2 zones, while the mean difference of ^{210}Pb between sSCS1 and sSCS2 was not significant. This suggests that the sSCS region is a main sink for ^{210}Pb . The Kelantan and Pahang Deltas were found to be the main anthropogenic sources of ^{210}Pb input in the surface sediments of the sSCS, with the Kelantan Delta having a higher average ^{210}Pb level than the Pahang Delta. According to [12,13], the high level of contaminant present in the both rivers was due to the continuous mining and land clearing which in turn elevating the level of contaminant present in the both riverine. The data showed that stations closest to the river mouth in the deltas had higher ^{210}Pb concentrations and that this trend decreases with increased distance from the river mouth. The spatial analysis showed that the upper part of SM1 had the highest ^{210}Pb levels, while the middle of the Malacca Strait had lower levels before increasing again towards the lower part of the Strait.

Table 3 Selected in situ parameters in the water column of the study area.

Sea Zonation	Station	Layer, water depth [m]	Temperature [°C]	Conductivity [S/m]	Salinity [PSU]
sSCS1	M5	Surface (0 - 20)	29.55	5.41	32.45
		Middle (21 - 39)	29.53	5.44	32.64
		Bottom (40 - 54)	29.53	5.46	32.80
	M13	Surface (0 - 18)	29.37	5.38	32.38
		Middle (19 - 36)	29.33	5.44	32.78
		Bottom (37 - 52)	28.47	5.41	33.16
sSCS2	M37	Surface (0 - 20)	29.33	5.36	32.25
		Middle (21 - 49)	29.00	5.40	32.72
		Bottom (50 - 60)	26.49	5.29	33.74
SM1	M41	Surface (0 - 20)	29.23	5.20	31.23
		Middle (21 - 40)	29.21	5.36	32.30
		Bottom (41 - 63)	28.83	5.45	33.21
SM2	M58	Surface (0 - 19)	29.81	5.20	30.83
		Middle (20 - 38)	29.77	5.38	32.05
		Bottom (39 - 57)	29.72	5.40	32.25

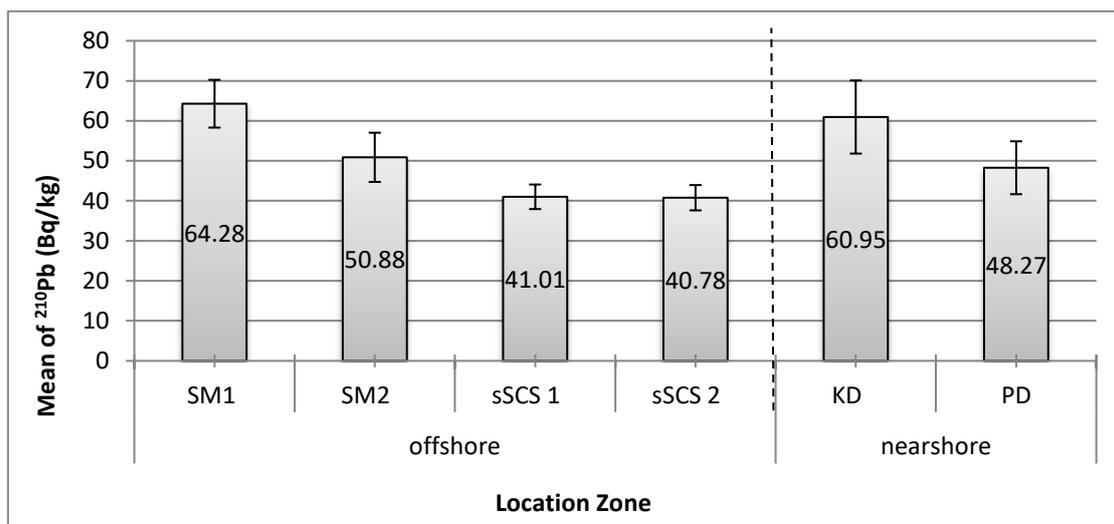


Figure 4 Mean values of ²¹⁰Pb in surface sediments of Peninsular Malaysian waters.

The radioactivity of ²¹⁰Pb in the water column of the Peninsular Malaysian Sea was studied using samples collected from different stations in different zones. The water column was divided into 3 layers: Surface, middle, and bottom. The ²¹⁰Pb activity was found to be higher in the surface layer of seawater in the sSCS1 zone, while it was higher in the bottom layer in the sSCS2 and Straits of Malacca zones. In-situ water parameters showed strong correlations with ²¹⁰Pb radioactivity levels in the surface and middle layers of seawater, with conductivity and salinity having the strongest correlation. However, there was no significant correlation detected between the variables in the sediment and bottom layer of the water column.

Table 4 Linear correlation between ²¹⁰Pb in sediment, ²¹⁰Pb in the water column and water parameter.

		Correlation								
Water column		Surface layer			Middle layer			Bottom layer		
Water parameter		Temp	Con	Sal	Temp	Con	Sal	Temp	Con	Sal
²¹⁰ Pb in surface seawater	Pearson correlation	-0.200	0.917*	0.901*	-0.117	0.889*	0.789	-0.014	0.247	0.226
	Sig.	0.747	0.029	0.037	0.851	0.044	0.113	0.982	0.689	0.714
²¹⁰ Pb in middle seawater	Pearson correlation	-0.863	-0.065	0.109	-0.639	-0.257	0.197	-0.212	0.285	0.573
	Sig.	0.060	0.917	0.862	0.246	0.676	0.751	0.732	0.642	0.312
²¹⁰ Pb in bottom seawater	Pearson correlation	-0.373	-0.464	-0.364	-0.435	-0.748	-0.327	-0.281	-0.138	0.339
	Sig.	0.536	0.431	0.547	0.464	0.146	0.591	0.647	0.825	0.577
²¹⁰ Pb in sediment	Pearson correlation	-0.766	-0.243	-0.077	-0.735	-0.547	0.025	-0.457	-0.101	0.651
	Sig.	0.131	0.694	0.902	0.157	0.340	0.968	0.439	0.872	0.234
Surface temp	Pearson correlation	1	-0.202	-0.389	0.902*	0.034	-0.545	0.605	0.113	-0.874
	Sig.		0.744	0.518	0.036	0.957	0.342	0.280	0.857	0.052
Surface con	Pearson correlation		1	0.981**	-0.271	0.922*	0.915*	-0.322	-0.143	0.398
	Sig.			0.003	0.659	0.026	0.029	0.597	0.819	0.507

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Temp = temperature Con = conductivity Sal = salinity

The eastern maritime region of sSCS (sSCS1) which shows a different ^{210}Pb pattern from the other zones by having a higher ^{210}Pb activity on the surface of the seawater compared to its bottom layer strongly shows that the region mainly receives ^{210}Pb input from the atmosphere and therefore proves that seawater in this region is more influenced by wind-borne sources from airborne ^{210}Pb or gaseous ^{222}Rn in the atmosphere. Depleting activity when going down through the water column indicates that scavenging may occur between the water-sediment medium.

Furthermore, the higher ^{210}Pb at the bottom layer of the water column at the southern maritime regions of sSCS (sSCS2) and the Strait of Malacca is due to the resuspension on surface sediment or the occurrence of lead dissolution from the bottom seafloor [14]. These increasing trends of vertical ^{210}Pb towards the bottom layer of the water column strongly support the discussion of previous sections where the influence of in situ seafloor sediment processes in the distribution of ^{210}Pb is attributed to the dynamic deposition environment, involving hydrodynamics that might increase sediment resuspension rates or complicated geologic compositions of the sediment because of complex origin sources. These complex origins include adjacent rivers that provide input from bordering land masses in both Sumatra and Peninsular Malaysia. The result that shows the highest ^{210}Pb values in the bottom layer of the water column compared to its surface at the sSCS2 stations might also support upwelling transport of radionuclides in this region during the southwest monsoon. This indicates seabed mobilization which lead to the higher rate of sediment resuspension.

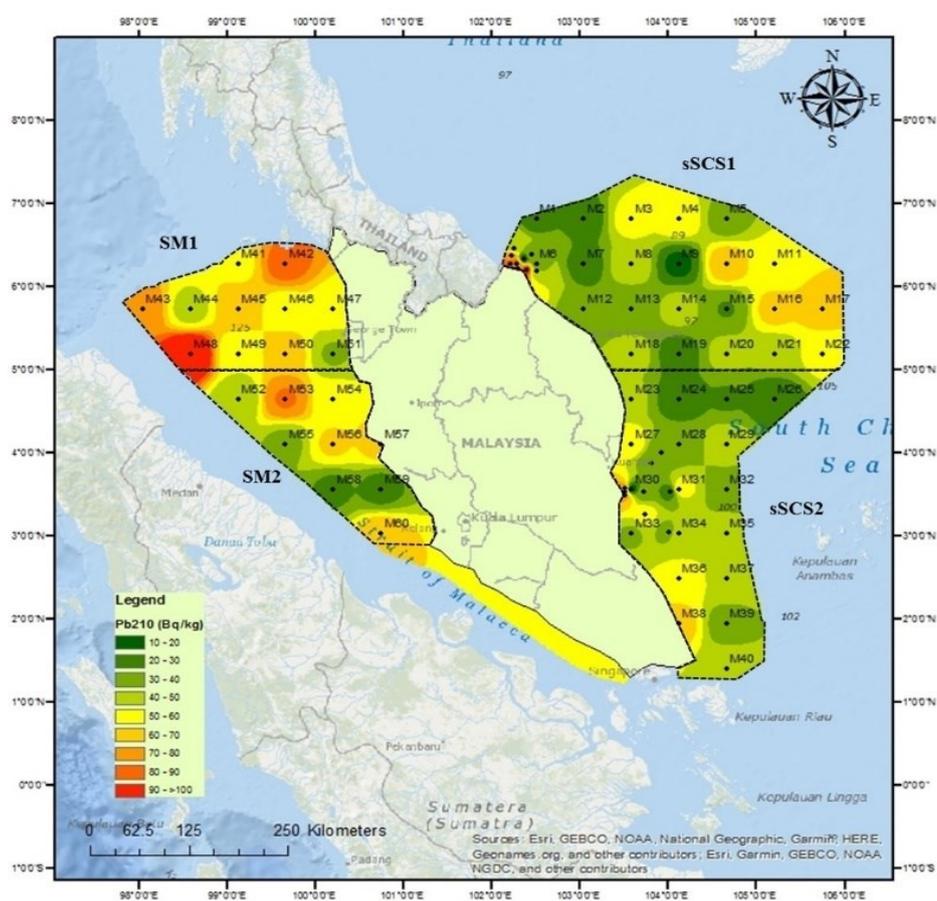


Figure 3 Interpolation map of ^{210}Pb radioactivity in surface marine sediments of the Malacca Strait and the sSCS, Peninsular Malaysia at the end of the Southwest Monsoon.

The result from this study further demonstrates the great potential of the SCS especially in the area of the eastern maritime zone of sSCS to be selected as a better station for sedimentology research focusing on the impact of monsoonal changes as it is proven to be dominated by wind-driven radionuclides compared to the Malacca Strait. The unique geological characteristic of Malacca Strait that has a very high ^{210}Pb radioactivity level influenced by various input sources will possibly complicate the process of source identification. Based on Keller and Richards [15], wind-driven sediments actually exist in the Malacca

Strait in the form of volcanic ash and pumice stone, but in very small amount and does not appear significant when compared to the quantity of river-borne materials deposited on the seafloor. Consequently, most of the ash found in the Malacca Strait is considered detrital rather than wind-borne. Therefore, although the Malacca Strait is part of the geographical area where the monsoon affects climatic and oceanology conditions, the direct impact of the seasonal wind is very difficult to see in this region because it is protected by archipelago land masses that overshadow the monsoonal effect with their massive terrestrial processes. Results from **Table 3** prove that the variation in surface sea conductivity and salinity can significantly affect the behaviour and distribution of ^{210}Pb radioactivity on the surface layer of the ocean. It is widely recognized that salinity and conductivity are interconnected. Often, conductivity will increase with increasing salinity due to an increase in soluble ions in the seawater. Further evidence can be seen in papers by Wang *et al.* [16], where variation of absorption efficiency increased in trend while salinity ranged from 3.5 to 7 and remained constant over a higher range of salinity (> 28 psu). Moreover, the increase in soluble ions in seawater also contributed to the conductivity, and in turn, there was an inverse relation to the radionuclide being present in the marine environments [17,18]. Furthermore, absorption and desorption behaviour of radionuclide in the sediment-water interface was affected by the oxyhydroxide processes which in turn influence the pH parameter in aquatic environments. According to Carvalho [19], it has been shown that the increased concentration of both ^{210}Pb and ^{210}Po in particulate matter in the studied area is possibly because of this mechanism of unselective co-precipitation. Thus, the increase in conductivity and salinity will potentially contribute to high ^{210}Pb radioactivity levels at the surface of the seawater especially in shallow water regions such as the waters of Peninsular Malaysia.

The present of excess ^{210}Pb in coastal waters surrounding Peninsular Malaysia

The distribution of excess ^{210}Pb was shown in **Tables 1** and **2** where the ^{226}Ra ranged from 8.52 to 46.47 Bq/kg with an average of 31.43 ± 16.04 Bq/kg while in the Malacca Strait, the ^{226}Ra ranged from 7.24 to 59.72 Bq/kg with an average of 34.77 ± 13.51 Bq/kg respectively. For delta regions, the ^{226}Ra in Kelantan Delta ranged from 5.69 to 20.39 Bq/kg with an average of 13.54 ± 6.41 Bq/kg, while in Pahang Delta, the ^{226}Ra ranged from 6.96 to 28.01 Bq/kg with an average of 16.37 ± 7.30 Bq/kg. Overall, the activity level of ^{226}Ra will affect the content of either ^{210}Pb from their parents (i.e., ^{226}Ra) or through the natural ecosystem, causing the gap between ^{210}Pb and ^{226}Ra output. For instance, there was a difference of about 13.1 % between ^{210}Pb and ^{226}Ra in sSCS stations. Meanwhile, in the Malacca Strait, a 25.2 % difference in concentrations was present between ^{210}Pb and ^{226}Ra . In the deltaic region, the Kelantan Delta and Pahang Delta showed a difference of 63.6 and 49.3 %, respectively. This early conclusion would result in the domination of ^{210}Pb over ^{226}Ra within both regions as the higher output presents in both coastal areas.

Low concentration of ^{226}Ra present in the deltaic region would suggest the presence of the mobilization and dilution of suspended particulate phase. Basically, the runoff present in both Kelantan and Pahang Rivers originated from multiple terrestrial sources, thus releasing a large amount of suspended particulate matter (SPM) towards the deltaic region. On top of that, the effect of desorption and absorption co-existed with oxyhydroxides such as Fe, Al, and Mn under the co-precipitation reaction in the sediment-water interface [20]. As mobilization occurred, the ^{226}Ra which has a high affinity towards the SPM was decaying to ^{210}Pb , thus leading to the freshly-deposited ^{210}Pb within the sSCS region. Furthermore, Zakaria [21], stated that the high discharge rates on both the Kelantan and Pahang Rivers contributed to the excess radium, as the mobilization of radium was being carried out as active dilution, thus leading to a higher volume of radium towards the sSCS.

On the other hand, a similar occurrence of sSCS occurred where a higher value of ^{226}Ra was present within the Malacca Strait. This may suggest the geologic existence of the surrounding island and archipelago which contributed to the higher ^{226}Ra concentration. Similarly, the presence of natural ^{238}U was found by Khandaker *et al.* [22], where the presence of black sands along Langkawi Island contributed to the ^{238}U increment towards the strait. The known content of several black sands such as ilmenite, zircon, monazite, magnetite, garnet, rutile and allanite, leads to the elevated ^{238}U and its daughters. Furthermore, the presence of granitic rocks also contributed to the increase in ^{226}Ra in the Malacca Strait. This can be obtained through Langkawi Island and its surrounding cluster of islands where the granitic rock becomes a viable source for the Malacca Strait [23]. The main composition of granite consists of SiO_2 , as this displays a uranium affinity within the igneous rocks and exhaling radon onto the surface horizon from weathered sources [24]. Furthermore, the oversaturation of the ^{226}Ra within the straits suggesting the boundary scavenging process contributed to the elevated concentration of ^{226}Ra . Mobilization of weathered product occurred within the Irrawaddy River, leading to longshore transport along the Martaban Bay towards southern Thailand, originated from Andaman Sea [25]. This eventually leads to an excess amount of ^{226}Ra

through lateral transport via wave current and Ekman transport which carry high loads of nuclides from other source towards the Malacca Straits [26].

Conclusions

In conclusion, the co-existence of the deltaic region and coastal waters along the Peninsular Malaysia leads to fluctuating level of ^{210}Pb , along with the excess ^{226}Ra as the deltaic region becomes a source for the sSCS, while the neighboring region becomes a dominant factor for supplying excess ^{226}Ra and ^{210}Pb towards the Malacca Strait. Continuous input of ^{210}Pb and ^{222}Rn via transboundary mobilization through variation of hydrological and atmospheric factors results in an increase in ^{210}Pb in the sSCS. On the other hand, *in-situ* processes within seabed sediment in the Malacca Strait are known for highly dynamic and complex deposition processes, leading to the difference in ^{210}Pb concentration in both water masses surrounding Peninsular Malaysia. This study might provide baseline data for long-term monitoring of radiation sources and further investigation associated with the dynamic biogeochemical processes in the waters of Peninsular Malaysia and other similar maritime regions that have almost similar climatological and oceanography characteristics

Acknowledgements

This study is funded jointly by the First Institute of Oceanography (FIO), China under grant ST-2017-001 through Universiti Kebangsaan Malaysia and grant DPK-2017-010. The authors wish to convey their gratitude to the leader of the Chemical Oceanography Laboratory, Faculty of Science and Technology, Universiti Kebangsaan Malaysia and the crews of RV Discovery from Universiti Malaysia Terengganu for providing facilities and constructive guidance during the cruise and laboratory work.

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