Use of Statistics in Nuclear Counting of Cesium-137

(Special case of Chernobyl and Fukushima)

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22/06/2022

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Outline

- Introduction
- Particular Case:
  - Chernobyl and Fukushima incidents
- Motivation and how to
- Statistical tool used: Linear regression
- Data analysis and discussions
  - Effect of time
  - Effect of water content of the marine sediments
  - Effect of other factors
- Results and conclusions

Chernobyl disaster (1986)

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- Result of a flawed reactor design that was operated with inadequately trained personnel
- Total activity of Cs-137 released estimated to 4.7 PBq (at least 5% of the radioactive reactor core)
- Caused death of 30 people within 3 months and further more.
- The effect extends to marine life especially in the Baltic sea and thus needs to be monitored on this aspect too.

The reference “Baltic sea” will be used very often in relation to Chernobyl NPP

Fukushima Daiichi (2011)

- Following a major earthquake, a 15-metre tsunami disabled the power supply and cooling of three Fukushima Daiichi reactors
- Total activity of Cs-137 released to the near sea estimated to 12-15 PBq
- 53% of the fish caught offshore this site in the following months exceeded the lower level of Cesium in food supply.

The reference “sea near FDNPP” will be used very often in relation to Fukushima Daiichi NPP

How and why?

- These radionuclides can be detected from marine environments (sea water, marine sediments,etc.) and marine organisms
- Slowly decaying radionuclides may have undesirable influences on marine eco-system for a considerable period
- For simplicity, we may evaluate the contamination level by measuring one representative radionuclide such as Cs-137

(provided that the environment reached a quasi-homogeneously contaminated condition) https://doi.org/10.1016/j.net.2019.07.017

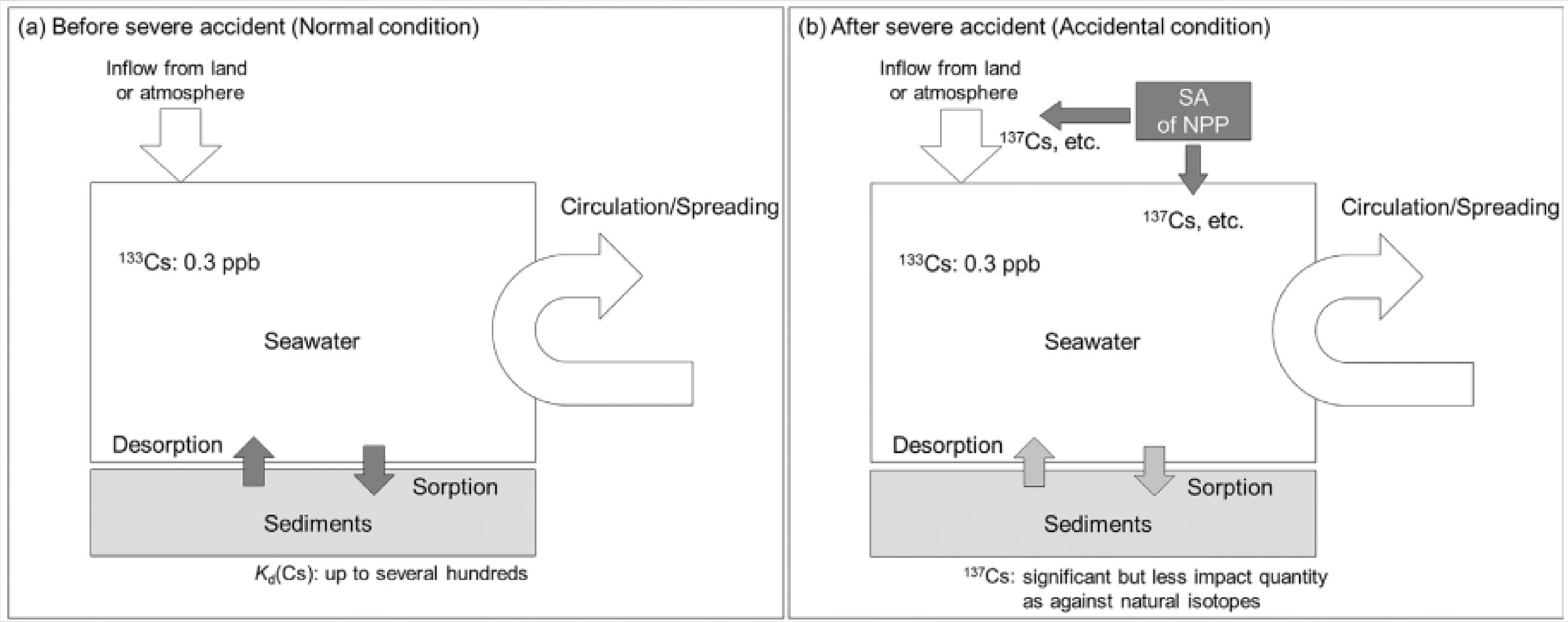


Figure 1

Several factors leading to radioactivity decrease

- Radioactive decay (half-life of 30.17 years for Cs-137)
- Precipitation
- High current
- Marine life

The surface concentrations of Cs radioisotopes in marine sediments would take approximately 0.4-26 years to decrease by 50% at several locations near Fukushima if only the mixing rates are considered.

https://doi.org/10.5194/bg-11-5123-2014

Linear regression

- Parametrized linear model $y = \alpha + \beta x + \varepsilon$
- Best estimator of $\hat{\beta} = \frac{\overline{xy} - \bar{x}\bar{y}}{\overline{x^2} - \bar{x}^2}$
- Standard error of $SE(\hat{\beta})^2 = \frac{\sigma^2}{n\left(\overline{x^2} - \bar{x}^2\right)}$
- T-value $t \equiv \frac{\hat{\beta}}{SE(\hat{\beta})}$ (eventually used to find the p-value; accepted if $p<0.05$)

Linear regression

- Goodness of fit can be expressed with $R^2 = 1 - \frac{\text{sum squared regression (SSR)}}{\text{total sum of squares (SST)}}$

$$= 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}.$$

Note: High R^2 value doesn't necessarily mean statistically significant and vice-versa. A residual plot can give more insights of the fit.

Sampling sites

https://doi.org/10.1016/j.net.2019.07.017

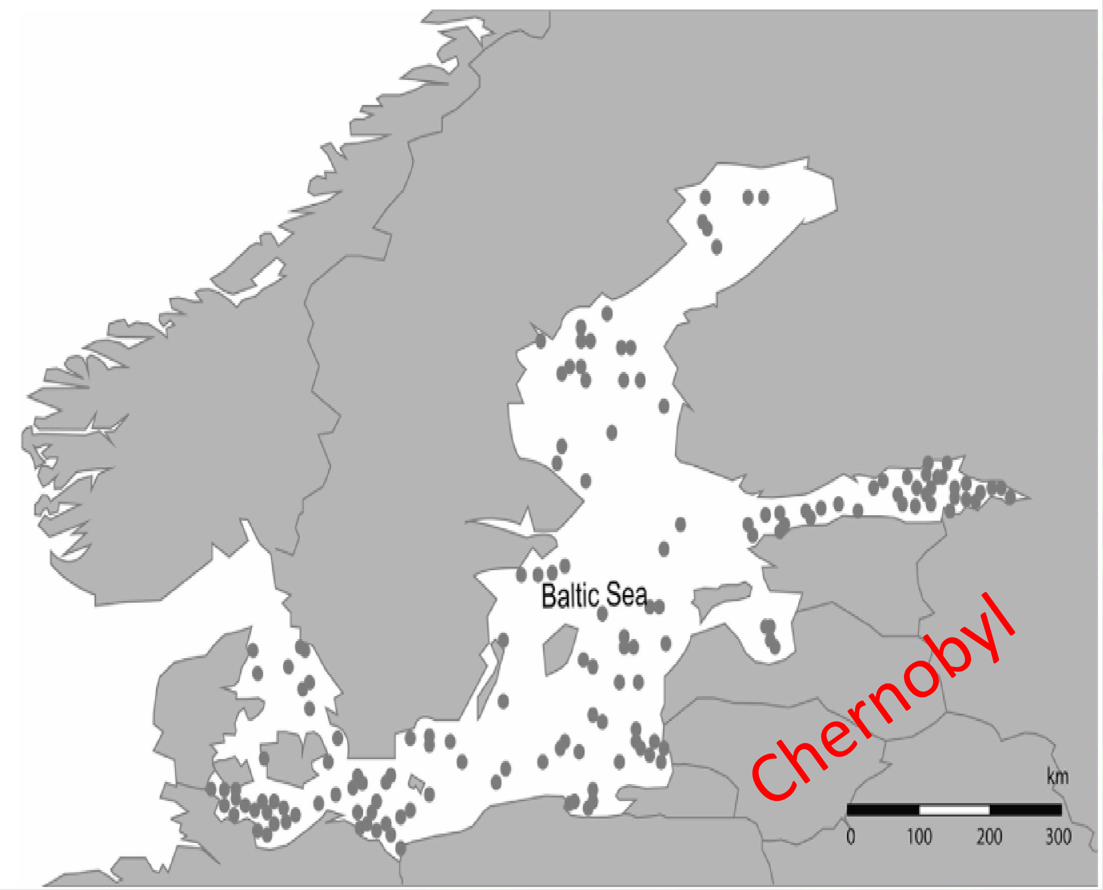
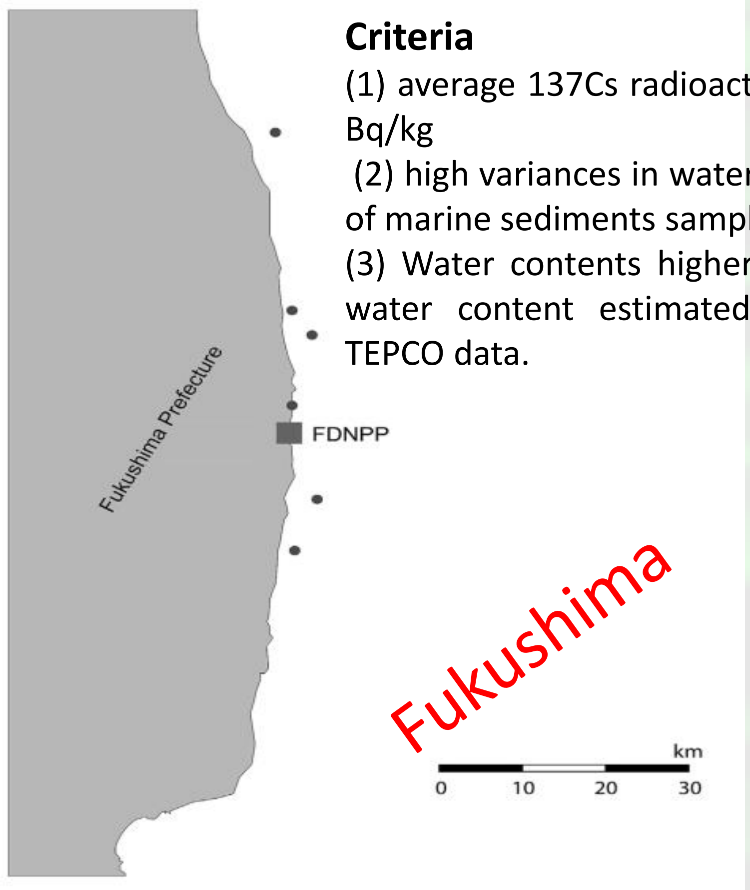


Figure 2



Criteria

(1) average 137Cs radioactivity more than 80 Bq/kg

(2) high variances in water content over time of marine sediments samples

(3) Water contents higher than the average water content estimated from the entire TEPCO data.

Figure 3

Decrease of Cs-137 radioactivity in marine sediments over time

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https://doi.org/10.1016/j.net.2019.07.017

Sediment type	P-value
Mud	1.84E-5
Clay and silt	0.2014
Sand	0.0301

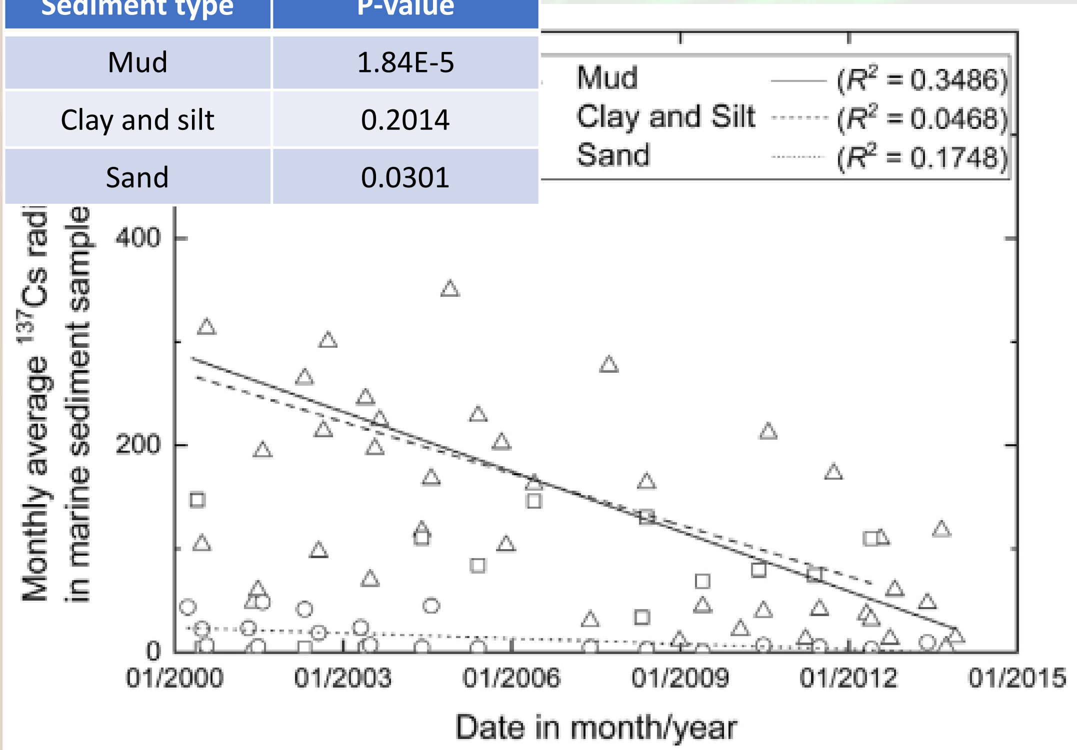

Figure 4
Monthly average Cs-137 radioactivity in marine sediment samples obtained from the Baltic Sea sites from 2000 to 2013.

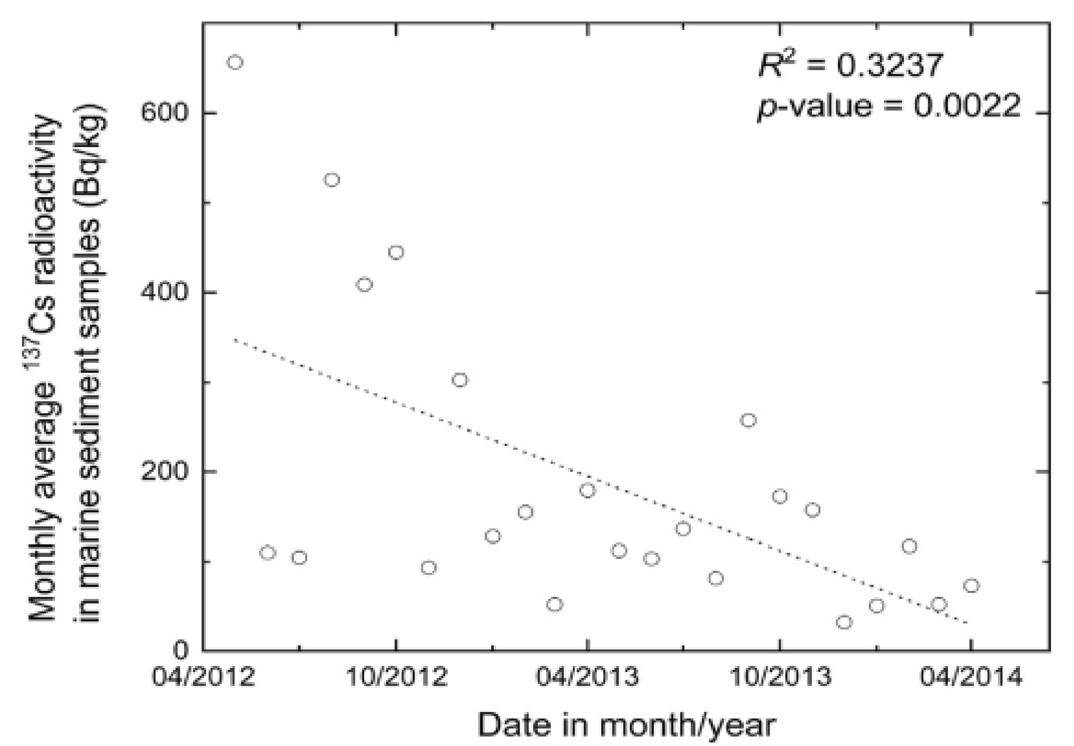

Figure 5
Monthly average Cs-137 radioactivity in marine sediment samples obtained from 6 sampling sites near the FDNPP from May 2012 to April 2014

Decrease of Cs-137 radioactivity in marine sediments over time

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Mud and clay and silt sample had high radioactivities compared to that of the sand samples; suggesting that smaller grain sizes adsorbed more Cs-137 because of their larger specific surface areas

The decrease rate of the marine sediment near the FDNPP was quite high compared to those in the Baltic seas; could be accounted by the fact the ocean near FDNPP is deeper and more open and rapid current.

Among the three trend lines, the line for Clay and Silt samples showed the smallest R^2 and statistically insignificant correlation.

Simplified sediment types for the Baltic Sea data	Original sediment types used in the IAEA database
Mud	Soft Mud, Pure Mud, Mud, Mud and Clay
Clay and Silt	Clay, Pure Clay, Pure Silt, Silt and Clay, Soft Clay, Clay and Silt
Sand	Pure Fine Sand, Pure Sand, Sand, Fine Sand

Correlation between Cs-137 radioactivity and water content of marine sediments

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- The data collected from the sampling sites in the Baltic sea did not contain information about the water content of the sediments.

- However, in the case of the sampling sites from the sea near FDNPP, this information was available and so a correlation between the radioactivity and the water content of the sediments was studied.

✓ Water content = 1 – (Dryness) = 1 - (Dry weight) / (Wet weight)

Correlation between Cs-137 radioactivity and water content of marine sediments

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https://doi.org/10.1016/j.net.2019.07.017

- Range of relative water content from 0.3 to 2.4

- Range of Cs-137 radioactivity from almost 0 to 2000Bq/kg.

- The R^2 and the p-value suggests a strong positive linear correlation between the two variables.

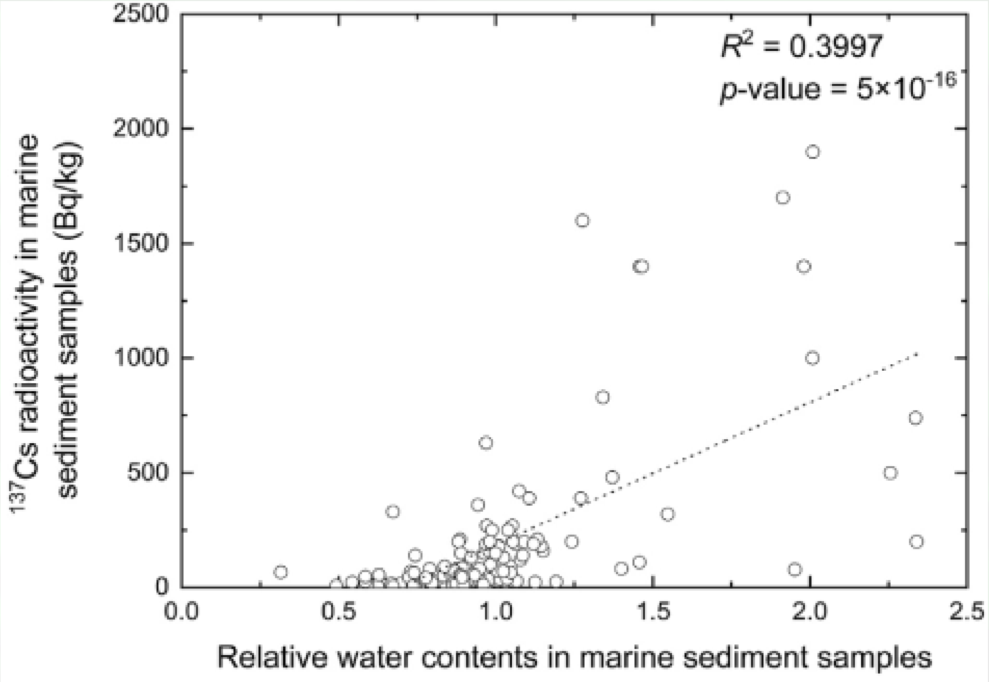

Figure 6

From six sampling sites near the FDNPP from May 2012 to April 2014 (average water content: 25.7% at a relative water content of 1.0)

Contribution of considerable factors to the Cs-137 radioactivity decrease

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https://doi.org/10.1016/j.net.2019.07.017

- The water content decrease over time seemed to be an unusual phenomenon that could have resulted from the sudden rearrangement of the ocean floor structures due to a severe Tsunami.
- The total Cs-137 radioactivity change due to the RMAWC change was calculated by the product of the slope of Fig. 6 and the total RMAWC change.
- The contribution was 51.2% of the total radioactive decrease.

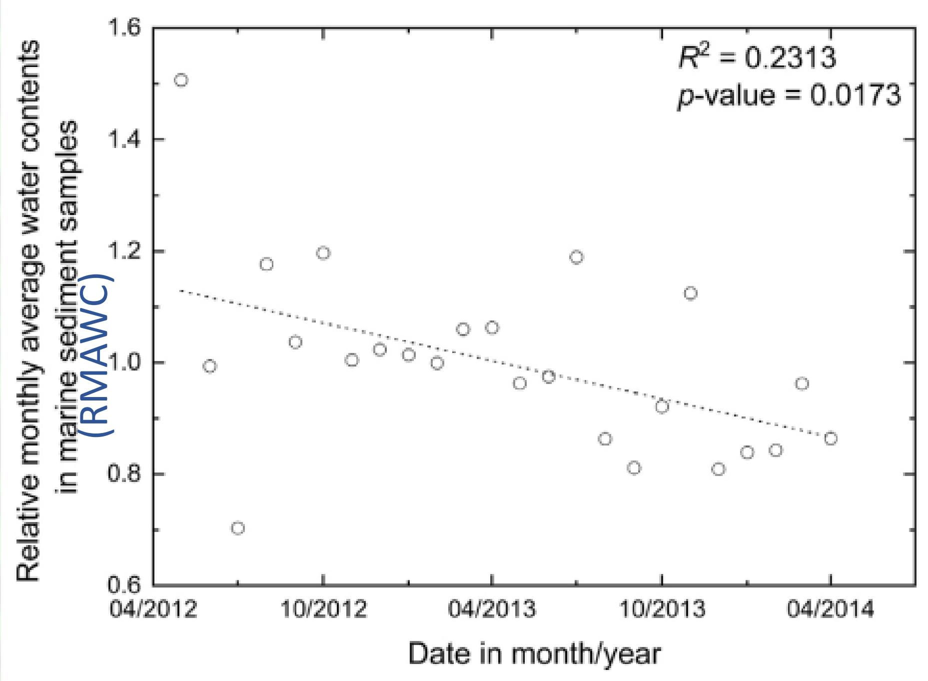

Figure 7

From six sampling sites near the FDNPP from May 2012 to April 2014

✓ (RMAWC) = (Monthly average water content) / (Average water content for total sampling period)

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Data analysis results of ^{137}Cs radioactivity in marine sediment samples from two oceans.

https://doi.org/10.1016/j.net.2019.07.017

	Sediment samples from the Baltic Sea			Sediment samples from the ocean near FDNPP
	Mud	Clay and Silt	Sand	
Initial ^{137}Cs radioactivity (Bq/kg) in Fig. 4 or 5	2.84×10^2	2.66×10^2	2.35×10^1	3.47×10^2
Final ^{137}Cs radioactivity (Bq/kg) in Fig. 4 or 5	2.26×10^1	6.67×10^1	3.4×10^{-1}	2.96×10^1
Average rate (Bq/(kg·d)) of ^{137}Cs radioactivity decrease	5.29×10^{-2}	4.54×10^{-2}	4.8×10^{-3}	4.53×10^{-1}
Total ^{137}Cs radioactivity decrease	92.1%	74.9%	98.6%	91.5%
Average rate (Bq/(kg·d)) of ^{137}Cs radioactivity decrease due to radioactive decay[a]	1.53×10^{-2}	1.46×10^{-2}	1.3×10^{-3}	2.13×10^{-2}
Total ^{137}Cs radioactivity decrease divided by total sampling period* (-/d)	1.86×10^{-4}	1.71×10^{-4}	2.05×10^{-4}	1.25×10^{-3}
Total RMAWC change in Fig. 7	–	–	–	2.62×10^{-1}
Total ^{137}Cs radioactivity change (Bq/kg) due to RMAWC change	–	–	–	1.62×10^{2}[b]
Average rate (Bq/(kg·d)) of ^{137}Cs radioactivity decrease due to RMAWC change	–	–	–	2.32×10^{-1}
Contribution of RMAWC change to average rate of ^{137}Cs radioactivity decrease	–	–	–	51.2%

Results and conclusions

- Radionuclides can be sorbed by the sediments, while those dissolved in the water spread quickly and widely with the water flow. The average rates of Cs-137 radioactivity decrease for the marine sediment near the FDNPP were higher than that for the Baltic Sea sediments .
- The sediments with smaller grain sizes, such as mud and clay types, sorbed more radionuclides because of the larger specific surface areas.
- It was also found for the sediment near the FDNPP that the RMAWC change contributed 51.2% of the average rate of the 137Cs radioactivity decrease
- For the analysis of radioactivity change of marine sediments, it is important to consider the change of water content values for the precise evaluation.

Thank you