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Deposition chronologies in a peat bog from Spitsbergen (High Arctic) using the ^{210}Pb dating method

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Abstract: This study reports on the accumulation rates and ^{210}Pb fluxes in Spitsbergen, Svalbard archipelago, wetlands. Six peat cores were collected in the Hornsund region, SW Spitsbergen (77°N) in 2007. The ages of peat layers were obtained with the Constant Flux/Constant Sedimentation and Constant Rate of Supply models based on the ^{210}Pb-dating technique. The obtained ^{210}Pb flux values ranged from 28 to 50 Bq m^{-2} y^{-1}, which was consistent with the level of ^{222}Rn emanation estimated for northern latitudes. The values of vertical and mass accumulation rates were slightly lower than reference data for peatlands of 50°–70°N. Furthermore, the vertical variations of peat accumulation rates exhibited the highest values in the upper part of the examined cores. The increasing tendency may be due in part to low compaction and low decomposition in the youngest peat layers. The analysis of the peat accumulation rate as a function of organic matter content and bulk density revealed positive and negative correlations, respectively, rather strong in both cases. The air temperature and precipitation gradients in the last few decades may have affected peat growth rates, which should be thoroughly investigated in future projects. Undoubtedly, the reported findings have provided a valuable addition to the relatively sparse dataset on recent peat deposits in Spitsbergen.

Keywords: Arctic, Svalbard, Hornsund, peat accumulation rate, radiometric dating, ^{210}Pb flux.

Introduction

The Arctic ecosystem is extremely sensitive to modern climate variations and reflects the changes in air temperature, precipitation, snow cover, permafrost, tundra vegetation, and active geomorphic processes (Owczarek *et al*. 2020). It is enough to mention that large-scale warming in the Arctic has accelerated during recent decades and is now occurring at a rate twice that of the global trend (Meredith *et al*. 2019). Faster-progressing transformation of northern areas, compared to temperate or tropical zones, is drawing the attention of scientists from around the world to the Far North regions. The researched topics include both assessing the state of the environment before a rapid acceleration of climate change and tracking its impact on various elements of Arctic nature (ACIA 2005; AMAP 2011, 2016; Meredith *et al*. 2019).

The terrestrial environment of the Arctic is composed, to a notable extent, of peatlands, *i.e.*, organic deposits being an important world's carbon store, acting as an effective sink for pollutants suspended in the atmosphere and comprising stratigraphic records (Appleby *et al.* 1997; Dowdall *et al.* 2005b; Loisel *et al.* 2021). As an archive, peats store physical, chemical, and biological signals or correlates of environmental conditions in the past decades or even millennia. One of the main interests of the scientific community investigating peat deposits is the level and variation of accumulation rates as a peculiar 'fingerprint' of peatland (Appleby *et al*. 1997; Sanchez-Cabeza and Ruiz-Fernández 2012; Olid *et al*. 2013, 2016; Mróz *et al*. 2017; Cwanek *et al*. 2021b; Yakovlev *et al*. 2021).

Two basic compartments can be distinguished within the peat column: the acrotelm corresponding to the relatively young, well-aired surface layer composed of living and poorly decomposed primitive plants, and the catotelm, *i.e.*, the deeper and permanently waterlogged anaerobic layer made up of decomposed and compacted dead remains (Clymo and Hayward 1982; Olid *et al*. 2016). Conditions favourable for vertical and/or lateral accretion of peat material occur in wetlands, where anaerobic or very cold deposits inhibit soil respiration. Peat accumulates when the rate of organic matter production at the surface exceeds the rate of organic matter decaying throughout the column, and the entire process is thought to be controlled more by slow decomposition than fast primary net productivity (Turetsky *et al*. 2004). The alternations occurring within the peat body are governed by many factors – from vegetation composition, through geographical location, to climatic conditions and changes. Therefore, a study on the accumulation rates provides not only baseline information on a given peatland but also enables the detection and tracking of any ongoing transformation in the entire ecosystem.

The farthest point in time and time resolution, attainable in both the organic and mineral deposit studies, are determined by the capability of the chosen dating method. Among many dating techniques, those using the radioactivity of certain common isotopes are of particular importance. The half-life, $T_{1/2}$, of these

radioisotopes plays a key role in how far into the past we can reach. A frequently used approach to calculating chronologies of young peat sequences, typically deposited during the last 150 years, is the ^{210}Pb ($T_{1/2}$ = 22 y) dating technique (Krishnaswamy *et al*. 1971; Appleby and Oldfield 1978). The timeframe seems to be sufficient when the main focus of the research is to explore the Anthropocene – a postulated new geological epoch in which human actions became predominant drivers of changes to the stratigraphic archive (Zalasiewicz *et al*. 2021).

The assessment of ^{210}Pb-derived ages allows determining the accumulation rates of deposits as well as ^{210}Pb flux in the ground-level air. The magnitude of the latter parameter is directly associated with the ^{222}Rn exhalation range, as both radionuclides are members of the uranium series (^{238}U). ^{222}Rn is the main contributor to environmental radiation exposure and its progenies, ^{210}Pb and ^{210}Po, represent approximately 8% of the average total internal radiation dose (UNSCEAR 1988). Furthermore, the distribution of ^{222}Rn together with ^{210}Pb has provided a wealth of data on several atmospheric, ocean, and terrestrial system processes (Feely and Seitz 1970; Paatero *et al*. 2003; Appleby 2008; Church and Sarin 2008; Zhang *et al*. 2015). Hence, the radiological monitoring of the aforementioned radioisotopes was and still is of great importance.

The research aimed to assess the recent age series, accumulation rates and ^{210}Pb fluxes of peat cores collected from Spitsbergen, Svalbard archipelago. The applied method incorporated the ^{210}Pb-based dating technique. Our main motivation was the fact that the above-mentioned topics have been extremely rarely investigated in wetlands of Spitsbergen and Svalbard as a whole. Undeniably, this fastest-warming place on Earth constitutes a unique area for environmental research.

Study area

The explored area is located in the Hornsund region (77°03’N, 15°11’E), SW Spitsbergen, Svalbard archipelago, along the coast of the Greenland Sea (Fig. 1). The area is home to patches of High Arctic wetlands. Permafrost is considered an important factor in their development, leading to the formation of the frequently water-logged active peat layer lying above the mineral substrate. The studied wetlands stretch in the vicinity of the proglacial zone of the Werenskiold glacier.

Compared to other parts of the Arctic, air temperature in Svalbard is the highest at this latitude and the observed warming dynamic is among the largest on Earth (Wawrzyniak and Osuch 2020). The meteorological observations carried out at the Stanisław Siedlecki Polish Polar Station in Hornsund (77°00’N, 15°33’E), SW Spitsbergen, since 1978, made it possible to monitor several weather parameters (Fig. 1). The annual variation of average air temperature (TA), and sum of precipitation (PA) over the 1979–2008 period are presented in

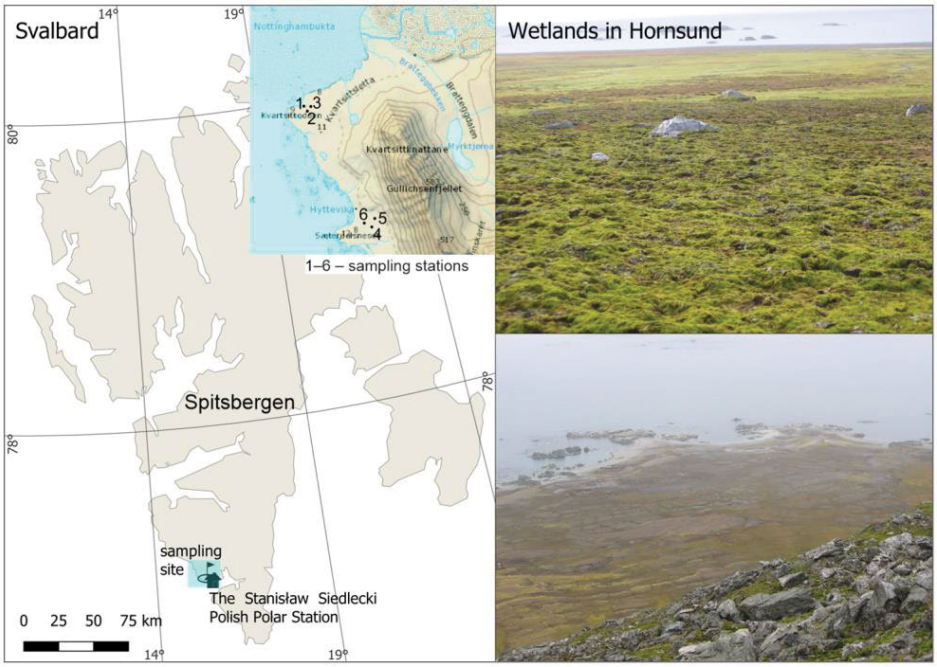

Fig. 1. The map of the Svalbard archipelago with marked sampling site and localization of the Stanisław Siedlecki Polish Polar Station in the Hornsund region (Spitsbergen) as well as pictures of explored wetlands.

Fig. 2. The estimated slopes of linear trends amount to 0.10(2)°C y^{-1} and 2(1) mm y^{-1} for TA and PA (uncertainties in the last digits, 1σ – in parentheses), respectively, revealing the warming processes of the Hornsund climate even on a short time scale. The growing tendency of TA and PA, however, show noticeable departures from a straight line, hence the coefficient of determination is 0.40 for TA and 0.15 for PA.

Methods

The research work described in this paper was part of the project involving a wide variety of measurements and analyses in the field of radioecology. They were discussed in more detail by Łokas *et al*. (2013). The topics of the project that had not been reported so far were addressed herein.

Field methods. — Six peat cores were collected during a July–August 2007 field campaign from an area that was 10 km long and up to 800 m wide (Fig. 1), by pushing the stainless steel cylinder, with an internal diameter of 10 cm, into the deposit (Łokas *et al*. 2013). The near-shore wetland was chosen to obtain profiles 1, 2, and 3 (18, 17.5, and 25 cm deep) from the edge of the wetland, below the storm bank (profile 1), and towards the centre (profiles 2 and 3).

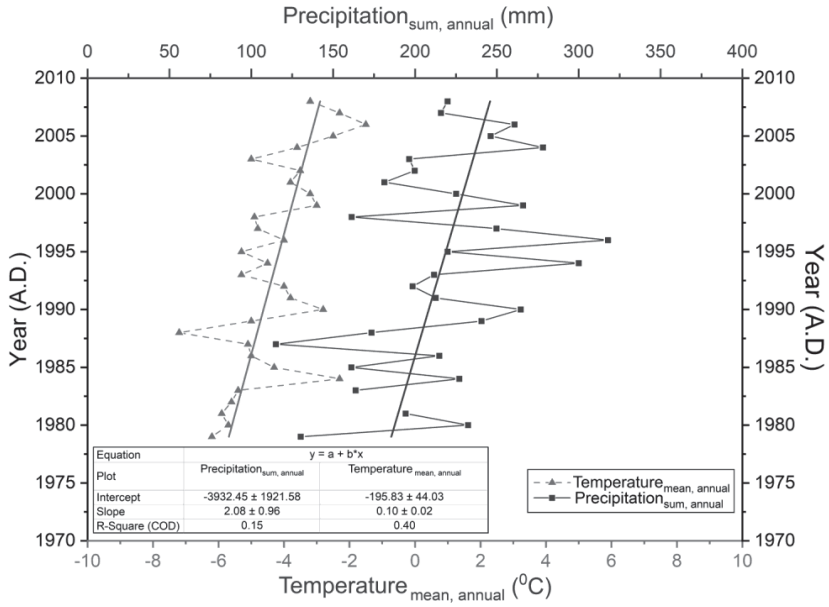

Fig. 2. The plot of air temperature and precipitation *vs.* year measured at the Polish Polar Station in Hornsund (Spitsbergen) with linear regression fitting coefficients (based on data from Wawrzyniak and Osuch 2020).

Profiles 4, 5, and 6 (16.5, 20, and 17 cm deep) were taken from another wetland, formed on a plain between the steep slopes of the Gullichsenfjellet massif (a coring site of profiles 4 and 5 located at its foot) and the sea (a coring site of profile 6 located 50 m from the shoreline). All profiles were sectioned into 1.0–1.5 cm thick segments and packed in plastic bags.

The examined peats correspond to blanket moss bogs common in the Hornsund region. Profiles 1, 4, and 6 were partially waterlogged, the water table occurred therein at depths of 5–7 cm, whereas the water table was not reached in profiles 2, 3, and 5.

Laboratory work. — The radiometric analysis concerned, among others, the radionuclides required by the ^{210}Pb-dating method. The activity of ^{210}Pb was estimated indirectly, *i.e.*, through its progeny radioisotope ^{210}Po ($T_{1/2}$ = 138 d). This method provides better detection sensitivity and precision with low-level ^{210}Pb activity in the samples, which was our case. For environmental samples, ^{210}Po is in radioactive equilibrium with ^{210}Pb. For freshly deposited ^{210}Pb, such an equilibrium is achieved after approximately 2 y, thus time elapsed between sampling and ^{210}Po analysis in top layers was approximately 2 y. For validation purposes, we also analysed $^{239+240}$Pu.

Both Po and Pu isotopes had to be separated from the sample matrix before measurements. The details of the Pu radiochemical procedures were presented elsewhere (Łokas *et al*. 2013). Hereafter, we summarised the key stages of Po treatment.

In the laboratory, sub-samples were dried at 70°C overnight, milled, homogenized, and prepared for radionuclide analysis. For the chemical recovery assessment of applied treatment, an internal yield tracer of ^{208}Po ($T_{1/2}$ = 3 y) was required. The activity of ^{208}Po added per sample depended on the depth of a peat section and amounted to (max, min): 0.17 Bq (top segments) and 0.02 Bq (bottom segments). Approximately 1–6 g of the spiked dry sample was mineralized using hot concentrated HNO_3 and H_2O_2, in adequate amounts and sequence. When the sample matrix was completely digested (no macroscopic objects), the solution was converted to 0.5M HCl. Next, we adjusted the proper oxidation state of elements such as Fe, Cr, and others, with the use of NH_2NH_2 2HCl. Finally, a thin alpha-spectrometric Po source was prepared by spontaneous electrodeposition onto a silver plate (Fernández *et al*. 2012; Lee *et al*. 2014). The chemical recovery averaged 73(3)% (SD, 1σ). The remaining solution was used for the separation of Pu isotopes.

The main concept of activity measurements was based on the fact that the target radioisotopes are alpha emitters. Measurements of alpha particles were conducted by alpha-ray spectrometers (Silena Alphaquattro, Silena S.p.A; AlphaDuo, Ortec) equipped with semiconductor, passivated planar silicon detectors (PIPS, Canberra).

Quality assurance was through the preparation and analysis of IAEA Reference Materials (IAEA-375 and IAEA-447; IAEA 2022) as well as blank samples processed per procedures applied to the studied material. The results for reference standards agreed well with certified values (Table 1). The blank samples were not affected by any external- and/or cross-contaminations.

Calculations. — In this work, the preferred assumptions on transfer and accumulation patterns of ^{210}Pb in a natural deposit were those formulated upon Constant Rate of Supply (CRS, known also as Constant Flux or CF) and Constant Flux/Constant Sedimentation (CF/CS) models. Considering the published mathematical procedures for dealing with raw data in ^{210}Pb-based chronology,

Table 1.

The accuracy of the method, radiometric analyses, tested with standard reference materials for the peat profiles from Spitsbergen. Uncertainties (SE) of measured values were reported at a 1σ confidence level.

Reference material (the reference date)	^{210}Pb (Bq kg^{-1})		$^{239+240}$Pu (Bq kg^{-1})	
	measured	certified	measured	certified
IAEA 385 (1996-01-01)	na[1]		2.70(23)	2.94(09)
IAEA 447 (2009-11-15)	419(25)	420(20)	5.38(33)	5.30(16)

[1] not analysed

we strictly followed the calculation approach recommended by Sanchez-Cabeza and Ruiz-Fernández (2012) and Sanchez-Cabeza *et al*. (2014) .

The main principle is that the total ^{210}Pb deposited in young sediments consists of two fractions, the so-called unsupported ^{210}Pb (airborne) and supported ^{210}Pb (lithogenic), as follows:

$$^{210}Pb_{tot} = {}^{210}Pb_{uns} + {}^{210}Pb_{sup} \quad (1)$$

The atmospheric part, ^{210}Pb$_{uns}$ declines downwards the core so that the ^{210}Pb$_{tot}$ at older (deeper) layers is composed of a constant lithogenic part, ^{210}Pb$_{sup}$ only. The ^{210}Pb$_{sup}$ activity concentration was calculated as the ^{210}Pb$_{tot}$ mean value from those sections, where the ^{210}Pb$_{tot}$ level had become a steady state. When such an approach could not be applied, we examined the possibility of ^{210}Pb$_{sup}$ estimation by fitting the curve for the lowermost layers with an equation:

$$y = y_0 + Be^{-bz} \quad (2)$$

where: y – ^{210}Pb$_{tot}$ activity concentration, z – depth, and y_0, B, b – parameters obtained by the fitting; ^{210}Pb$_{sup}$ activity concentration was expressed by y_0.

Finally, by subtracting ^{210}Pb$_{sup}$ from ^{210}Pb$_{tot}$ on a level-by-level basis, the unsupported fraction (^{210}Pb$_{uns}$) was calculated. For the next key steps of dating, only ^{210}Pb$_{uns}$ values were included. Obtained age-depth series enabled the assessment of vertical, s, and mass, r, accumulation rates as well as ^{210}Pb flux for each profile and dating model, using formulas described by Sanchez-Cabeza and Ruiz-Fernández (2012).

A common issue in ^{210}Pb dating, highlighted by scientists, is the difficulties in estimating age-depth relationships for natural deposits reliably, because the real environment is usually far more complex than mathematical modelling (Appleby 2001; Turetsky *et al*. 2004). For this reason, it is important to validate calculated dates using an independent time marker. To provide a reference horizon for our study, we examined the vertical variation of $^{239+240}$Pu activity with the depth of investigated peat cores (for details see Łokas *et al*. 2013). These anthropogenic radionuclides showed a maximum in radioactive fallout history correlated with the Partial Test Ban Treaty signed in 1963 (UNSCEAR 2000).

The examined parameters, such as the ages as well as accumulation rates, were calculated for the middle of the section thickness. The decay correction was adjusted to the date of sampling. We followed a guide by ISO/IEC (2008) in uncertainty estimations, which were reported as 1σ. Pairwise correlations between accumulation rates (r and s), loss on ignition (LOI), and bulk density (d) parameters were computed as the Pearson correlation coefficient values.

Results

^{210}Pb distribution and level. — The total ^{210}Pb activity concentration ($^{210}Pb_{tot}$) *vs.* profile depth for peat deposits 1−6 is presented in Fig. 3 and Table 2. We noted the trend shape of $^{210}Pb_{tot}$, which was overall characteristic for peat (Appleby *et al*. 1997; Benavides *et al*. 2013; Olid *et al.* 2013, 2016; Cwanek *et al*. 2021b). Specifically, the highest activity did not occur in the topmost layer, but within intermediate depths. Besides, there were significant deviations from the simple monotonic decrease of atmospheric component, which often fluctuated downward, presumably reflecting episodic variations in recent peat growth or decomposition rates. Considering profiles 3−6, the stable threshold of $^{210}Pb_{sup}$ was reached below 5−15 cm of depth, depending on the profile. In contrast, cores 1 and 2 were more challenging as there were no clear tendencies towards a steady state at the bottom of the cores. However, due to showing the downtrend, $^{210}Pb_{sup}$ could be estimated by fitting for profile 2. A similar procedure proved to be impossible for profile 1, where $^{210}Pb_{tot}$ activity concentration varied with depth without any consequent decline. As mentioned before, profile 1 was taken at the edge of the wetland, near the seashore, which may have resulted in a disturbance of the original distribution of accreted material. Therefore, this core was excluded from further analysis. The obtained $^{210}Pb_{sup}$ activity concentrations did not exceed a dozen Bq kg^{-1}, reaching maximum of 14.4(4) Bq kg^{-1} for profile 3 (Table 3).

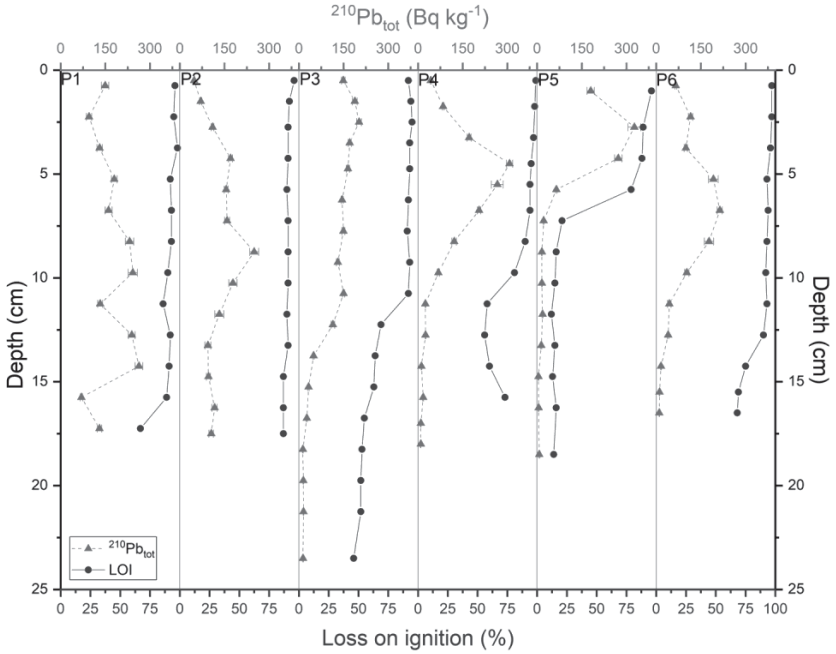

Fig. 3. The plots of $^{210}Pb_{tot}$ activity concentrations and loss on ignition (LOI) *vs.* depth for peat profiles 1–6 from Spitsbergen.

Table 2.

The values of the depth, $^{210}Pb_{tot}$ activity concentration, and bulk density obtained in the examined peat layers (for the middle of the section thickness) from Spitsbergen; estimated uncertainties in parentheses.

	Depth (cm)	$^{210}Pb_{tot}$ (Bq kg^{-1})	Bulk density (g cm^{-3})
Profile 1	0.75	149(13)	0.03
	2.25	95(9)	0.03
	3.75	131(9)	0.02
	5.25	180(9)	0.02
	6.75	161(12)	0.03
	8.25	231(14)	0.03
	9.75	242(15)	0.04
	11.25	133(8)	0.12
	12.75	239(11)	0.06
	14.25	263(13)	0.08
	15.75	70(4)	0.09
	17.25	130(7)	0.14
Profile 2	0.5	48(2)	0.02
	1.5	70(4)	0.03
	2.75	110(5)	0.03
	4.25	171(7)	0.02
	5.75	156(6)	0.04
	7.25	159(9)	0.04
	8.75	250(15)	0.06
	10.25	178(14)	0.06
	11.75	133(15)	0.06
	13.25	94(10)	0.07
	14.75	96(7)	0.09
	16.25	117(9)	0.06
	17.5	106(8)	0.06
Profile 3	0.5	149(6)	0.02
	1.5	188(8)	0.02
	2.5	202(8)	0.02
	3.5	171(5)	0.04
	4.75	165(5)	0.03
	6.25	145(4)	0.02
	7.75	150(5)	0.03
	9.25	131(5)	0.03
	10.75	150(4)	0.05
	12.25	114(6)	0.13
	13.75	49(2)	0.17
	15.25	33(2)	0.19
	16.75	27(2)	0.20

Table 2 - *continued.*

	Depth (cm)	$^{210}Pb_{tot}$ (Bq kg^{-1})	Bulk density (g cm^{-3})
	18.25	14(1)	0.21
	19.75	15(1)	0.19
	21.25	15(1)	0.22
	23.5	14(1)	0.21
Profile 4	0.5	43(2)	0.04
	1.75	84(3)	0.03
	3.25	172(6)	0.04
	4.5	308(10)	0.08
	5.5	267(20)	0.12
	6.75	205(6)	0.11
	8.25	121(7)	0.12
	9.75	68(4)	0.12
	11.25	25(1)	0.16
	12.75	25(1)	0.13
	14.25	12(1)	0.11
	15.75	17(1)	0.09
	17	10(1)	0.09
	18	10(1)	0.09
Profile 5	1	180(12)	0.06
	2.75	327(21)	0.11
	4.25	273(12)	0.14
	5.75	65(2)	0.16
	7.25	22(2)	0.59
	8.75	16(1)	0.87
	10.25	16(1)	0.54
	11.75	19(2)	0.84
	13.25	14(2)	0.86
	14.75	5(1)	1.12
	16.25	5(1)	0.73
	18.5	7(2)	0.36
Profile 6	0.75	66(3)	0.03
	2.25	115(7)	0.04
	3.75	100(5)	0.04
	5.25	192(16)	0.06
	6.75	214(9)	0.07
	8.25	177(16)	0.07
	9.75	103(7)	0.08
	11.25	44(6)	0.10
	12.75	40(2)	0.11
	14.25	16(1)	0.11
	15.5	11(1)	0.13
	16.5	10(1)	0.16

Table 3.

The values of target parameters for peat profiles 2–6 from Spitsbergen. Abbreviations: CF/CS – Constant Flux/Constant Sedimentation model, CRS – Constant Rate of Supply model. Estimated uncertainties in parentheses.

Profile no.	$^{210}Pb_{sup}$ (Bq kg^{-1})	^{210}Pb flux (Bq m^{-2} y^{-1})		Vertical accumulation rate, s (cm y^{-1})	Mass accumulation rate, r (g cm^{-2} y^{-1})
		CF/CS	CRS	CF/CS	CF/CS
2	4(26)	50(20)	43(4)	0.3(1)	0.017(6)
3	14.4(4)	28(2)	28(1)	0.20(4)	0.013(1)
4	12(2)	48(7)	42(1)	0.09(2)	0.010(2)
5	12(2)	40(10)	47(2)	0.07(3)	0.010(3)
6	13(2)	30(10)	29(1)	0.17(7)	0.012(4)

Age series. — The results of the dating are illustrated in Fig. 4. In each case, two age series were generated following CF/CS and CRS models. Furthermore, obtained dates were combined with reference horizon by $^{239+240}$Pu peak in 1963 A.D. The latter action allowed for critical assessment and verification of the chronologies.

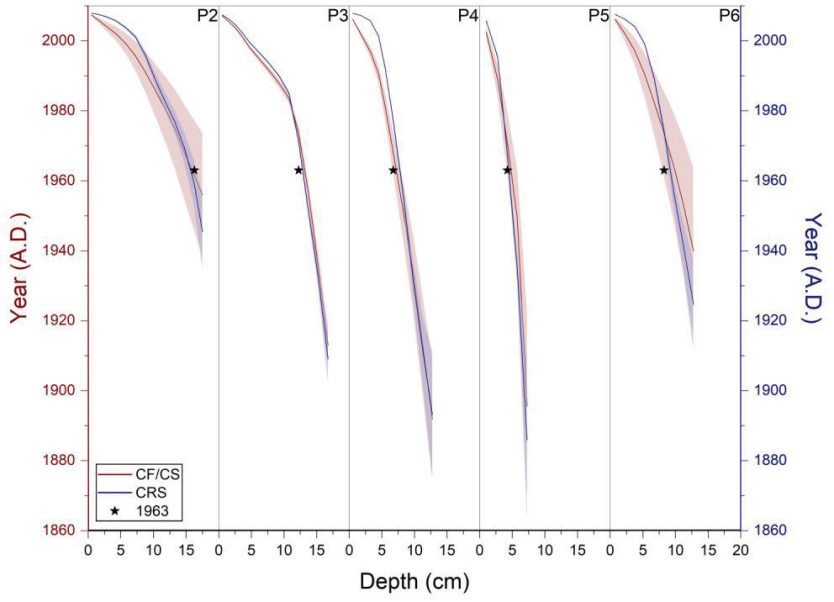

Fig. 4. The plots of results from dating procedure applied to young peat sequences (profiles 2–6) from Spitsbergen, using both, the Constant Flux/Constant Sedimentation (CF/CS) and Constant Rate of Supply (CRS) models.

In the CF/CS model, simple regression fitting to the plot of natural logarithm of $^{210}Pb_{uns}$ *vs.* mass depth was applied. Since none of the profiles showed a decrease of ^{210}Pb activity with depth in the uppermost layers (Fig. 3), we removed 1–3 top points (depending on the profile) from the analysis. This was necessary to obtain a relatively linear trend and good consistency with the Pu reference horizon. To apply the CRS model, we calculated the total deposition above and below a given layer. Next, the latter values were corrected based on the mean accumulation rate by the CF/CS model to eliminate encountered problem of systematic deviation of CRS dates toward erroneously old ages, *i.e.*, the so-called 'old-date error' (Binford 1990; Sanchez-Cabeza and Ruiz-Fernández 2012). This step resulted in a far better agreement between the age series and Pu time marker.

Summing up, the dating procedure applied to young peat sequences from Spitsbergen was rather successful and allowed for the subsequent assessments of accumulation rates and ^{210}Pb fluxes. However, some issues were noted, which are addressed below.

Accumulation rates and ^{210}Pb fluxes. — The application of the CF/CS model allows for the determination of accumulation rates *s* and *r* that are constant over time (depth), whereas the CRS model enables the tracking of changes in the accumulation rates over time (depth). This is a direct consequence of different base assumptions of these methods.

The values of *s* and *r* from CF/CS are presented in Table 3. The maximum value of 0.3(1) cm y^{-1} for *s* and of 0.017(6) g cm^{-2} y^{-1} for *r* were observed in profile 2. Overall, the studied accumulation rates (CF/CS model) were rather homogenous for investigated peatlands in Spitsbergen.

The plots of *s* and *r* from CRS model *vs.* age are presented in Fig. 5. Temporal variations of both *s* and *r* showed the same pattern of the increasing trend upward the core. The highest differentiation, extending from 0.04(1) cm y^{-1} (bottom) to 3.7(4) cm y^{-1} (top), and from 0.008(1) g cm^{-2} y^{-1} (bottom) to 0.14(1) g cm^{-2} y^{-1} (top), was noted for profile 4.

Considering the quantitative and qualitative assessment of the possible relationship between *s* and *r* against the LOI and *d*, respectively, calculated as the Pearson correlation coefficients, we obtained the following results. The strongest positive correlations of *s*, *r vs*. LOI were noted for profile 6, whereas the only negative correlation of *r vs.* LOI appeared for profile 5. The correlations of *s*, *r vs. d* were negative (with one exception for profile 5) and even stronger than for LOI, especially in the case of profiles 2 and 6. Details are presented in Table 4.

Both dating models (CF/CS and CRS) assume a constant rate of airborne ^{210}Pb supply to the deposits. The results of ^{210}Pb flux assessment for peat cores from Spitsbergen are provided in Table 3. The values exhibited the same order of magnitude, *i.e.*, a few tens of Bq m^{-2} y^{-1}. Furthermore, the obtained range of 28–50 Bq m^{-2} y^{-1} was not affected by the sampling site, especially the fact that profiles 2–3 were collected near shore, whereas profiles 4–6 came from wetland below mountain slopes.

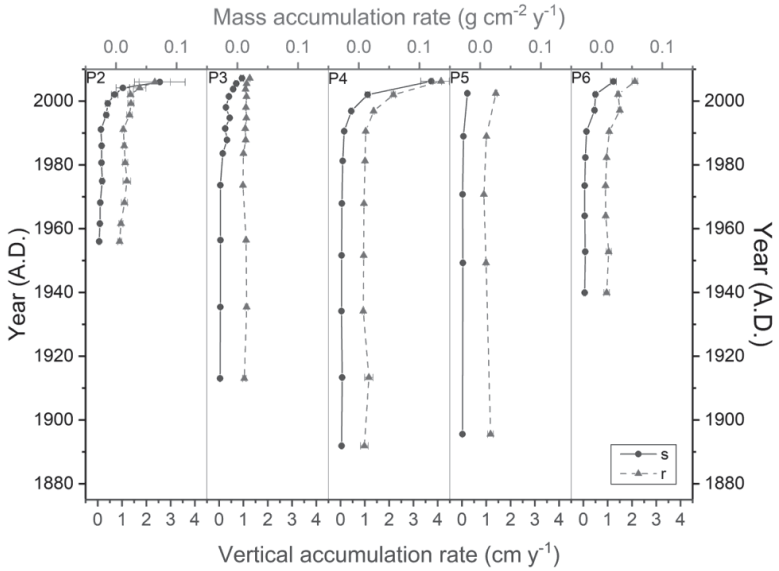

Fig. 5. The variation of vertical, *s*, and mass, *r*, accumulation rates *vs.* date determined for peat profiles 2–6 from Spitsbergen. Presented parameters were estimated by the Constant Rate of Supply, CRS, model.

Table 4.

The Pearson correlation coefficient values for chosen pairs of parameters from peat profiles 2–6 from Spitsbergen. Vertical accumulation rate (*s*) and mass accumulation rate (*r*), were estimated by the Constant Rate of Supply model.

	Profile 2		Profile 3		Profile 4		Profile 5		Profile 6	
	s	*r*	*s*	*r*	*s*	*r*	*s*	*r*	*s*	*r*
Loss on ignition	0.5152	0.6018	0.6906	0.3073	0.3837	0.3675	0.5046	–0.0888	0.7782	0.8040
Bulk density	–0.7325	–0.7107	–0.8159	–0.3007	–0.6962	–0.6389	–0.4847	0.0705	–0.7819	–0.7847

Discussion

^{210}Pb-based chronology: problems and solutions. — The age uncertainties were significant, especially for CF/CS model. As the main reasons, we considered the relatively low time resolution achieved for the cores or the fact that the basic assumptions of a given dating model were most likely not met for every layer of the examined profiles.

The time resolution of young sediment dating is determined by the thickness of sectioned intervals. Usually, *c.* 1 cm thick sections are good enough for an accurate ^{210}Pb dating procedure. However, the biological turnover at the northerly latitudes, with their low precipitation and low temperatures, is reduced

manyfold, resulting in slower accumulation rates than, *e.g.*, those in temperate zones. Organic soil and peat can be found in the High Arctic as thin horizons, typically between 5 and 20 cm deep, although thicker deposits have been also found on Spitsbergen (Dowdall *et al*. 2005a). We are therefore convinced that sections thinner than 1 cm could provide better precision and accuracy for the ^{210}Pb chronology when analysing sediments from the Far North region.

The other issue might be related to the decreasing tendency of ^{210}Pb activity towards the topmost layers for each examined profile (Fig. 3). This is a rather common observation for peat deposits, and it has been associated by Olid *et al*. (2016) with the possibility of Pb vertical transport within the peat column. Such mobility could lead to the deviation of the ^{210}Pb activity profile from the monotonic exponential decay, with peaks well below the surface. The assumption of Pb immobility in ^{210}Pb-based dating models has been repeatedly questioned by the scientific community (*e.g.*, Damman 1978; Urban *et al*. 1990). However, the experiments carried out in *Sphagnum*-dominated peats by Vile *et al*. (1999) showed the binding of Pb^{2+} with organic matter at the peat surface and the absence of Pb mobility. Due to the lack of results for other airborne isotopes supplied continuously to examined peatlands (*e.g.*, ^{7}Be; Hansson *et al*. 2014), we cannot unambiguously demonstrate or deny the migration of Pb throughout peat layers. Nevertheless, the exclusion of the topmost ^{210}Pb activity values as well as slight correction of ^{210}Pb total inventory toward higher value during CF/CS or CRS modelling, respectively, resulted in better consistency of age series and reference horizon in our study.

Comparative analysis. — The values obtained for $^{210}Pb_{sup}$ fractions (Table 3) were rather typical of peat deposits (Appleby *et al.* 1997; Lamentowicz *et al*. 2019; Fiałkiewicz-Kozieł *et al*. 2020; Cwanek *et al*. 2021b), but significantly lower than those typical of lake sediments (usually tens of Bq kg^{-1}; Cwanek *et al*. 2021a). This indicates the scarcity of mineral components in the wetlands of Spitsbergen. By analysing the LOI parameter versus depth (Fig. 3), it is clear that considered peat deposits have consisted mostly of organic matter. However, the LOI values declined with profile depth to a different extent. The fastest decrease was revealed for profile 5, while the slowest for profiles 1 and 2.

The level of ^{210}Pb fluxes for peats in Spitsbergen (77°N) was significantly lower, even by one order of magnitude, than that for areas of 50°–70°N (Fiałkiewicz-Kozieł *et al*. 2014; Mróz *et al*. 2017; Cwanek *et al*. 2021b; Yakovlev *et al*. 2021). The noted latitudinal downward trend of ^{210}Pb flux with increasing latitude corresponded well with the findings by Baskaran (2011) regarding the distribution of an airborne ^{210}Pb. The latter is produced by exhaled ^{222}Rn decay. According to Conen and Robertson (2002), ^{222}Rn emanation level decreased with increasing latitude, from 1 atom cm^{-2} s^{-1} at 30°N to 0.2 atom cm^{-2} s^{-1} at 70°N, which was attributed to the increased water saturation in the soils with increasing latitude.

The literature data on average peat accumulation rates for lower latitudes were slightly higher than values from our observations, but usually represented the same order of magnitude. For example, *s* and *r* values by Cwanek *et al*. (2021b) amounted to 0.38(7) cm y^{-1} and 0.025(4) g cm^{-2} y^{-1}, respectively, for peat from Northern Ural, Russian Federation (60°N), whereas the range of *r* for peat bog records was 0.02–0.04 g cm^{-2} y^{-1} in the Jura Mountains, Switzerland (47°N) (Appleby *et al*. 1997).

Accumulation rates – vertical changes tendency. — Our most challenging finding was the peculiar growth of accumulation rates in the youngest layers of examined peat profiles (Fig. 5). While referring to Appleby *et al*. (1997), Fiałkiewicz-Kozieł *et al*. (2014), Mróz *et al*., (2017), Cwanek *et al*. (2021b), and Yakovlev *et al*. (2021) we learned that the noted tendency in the recent accretion rates represents rather a common feature for peatlands; a question arises as to the main reason for such behaviour.

The issue of climate change is a rather imposing argument when analysing the dynamics of changes in parameters related to the natural environment over time. Therefore, we were tempted to consider whether and how the progressing warming in the Hornsund region could have influenced the recent development of the wetlands, particularly, whether it is a determinant of the peat accretion rates. When combining the temperature and precipitation growth pattern (Fig. 2) with an increase in accumulation rates (Fig. 5) for the Spitsbergen region, a similar tendency can be noted for the recent period. Furthermore, Benavides *et al*. (2013) revealed, studying *Distichia*-dominated peatlands located in the northern Andes, the highest rates of peat accretion in recent decades. The raised air temperatures and water excess from nearby glacier melt were pointed out as important contributors to their findings. Ovenden (1990) suggested that the effect of climate on peat accumulation is indirect and probably varies from one site to another and also indicated the problem of limited knowledge on how peatlands had responded to previous periods of warming. In our view, the complexity of occurring processes makes it difficult to show clear connections, hence any attempt to demonstrate the impact of global warming on the development of investigated wetlands appears to be speculative so far.

Comparing the changes in the accumulation rates with LOI and *d* values at a given depth (Figs. 2 and 5; Table 2), we detected usually higher accumulation rates for layers with higher organic matter content and lower compactness, *i.e.*, for the topmost layers of Spitsbergen peats. Indeed, the analysis of the basic Pearson correlation indicated that *d* and LOI parameters constituted significant factors that affected the peat accretion patterns in Spitsbergen (Table 4).

Olid *et al*. (2016) proposed interesting explanations for the highest accumulation rates in the upper layers of Swedish peatland. The authors hypothesized that the extent of the downwash of ^{210}Pb could have changed strongly in response to variations in physical peat characteristics (*e.g.*, degree of decomposition, bulk density, compaction), being presumably higher in low

compacted and low decomposed peatlands characterized by a high porous acrotelm, such as those located at high latitudes. The idea of ^{210}Pb mobility within peat cores from Sweden was supported by the observed deeper penetration of the atmospherically deposited isotope of ^{7}Be (Hansson *et al.* 2014). The ^{210}Pb outflow from the top layers to the bottom ones was stated as the main cause of the accretion rates behaviour in the uppermost peat segments.

The aforementioned explanation of specific peat accumulation rate variation seems to be a probable reason for what we observed in the uppermost sections of examined peat deposits, as the low compaction and high porosity appeared in the acrotelm. If so, this would point to some downward transport of ^{210}Pb causing loss of ^{210}Pb activity in the topmost layers, which resulted in overestimated peat accumulation rates for these sections. We believe, however, that more pieces of evidence and analyses are needed to provide a complete view of the processes occurring in Spitsbergen wetlands.

Conclusions

Our research was focused on exploring the peat accumulation rates and ^{210}Pb fluxes in the High Arctic wetlands, which are seldom analysed in this respect. The study was based on six peat deposits collected from SW Spitsbergen. Of special concern was to obtain well-estimated ages of peats layers. This goal was achieved for five out of six examined profiles, using the CF/CS and CRS models based on the ^{210}Pb-dating technique, and $^{239+240}$Pu peak in 1963 as a time marker.

Considering ^{210}Pb fluxes, their values reached merely a few tens of Bq m^{-2} y^{-1}, which was consistent with the distribution of ^{222}Rn emanation. The vertical and mass accumulation rates proved to be slightly lower than those expected for peatlands of 50°–70°N. The low compaction and low decomposition in the youngest peat layers may be, at least in part, responsible for the especially high vertical variations of peat accumulation rates detected within the upper part of the studied cores. The analysis of the Pearson correlations between the peat accumulation rates and organic matter content as well as bulk density revealed positive or negative, respectively, and rather strong correlations. In recent decades, peat growth rates may have been, admittedly, affected by the air temperature and precipitation gradients, and such a potential impact requires more in-depth analyses.

This research provided baseline information for the peatland system in the Spitsbergen as of the early 21st century. Future research projects inspired by the results presented in this article would likely provide further insight into the specifics of changes and the identification of processes taking place in the Arctic environment.

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