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Natural gamma radiation at the sea level around the Antarctic continent recorded south of the 62° parallel

Naturalne promieniowanie gamma na poziomie morza wokół kontynentu antarktycznego zarejestrowane na południe od równoleżnika 62°

Abstract This study presents the results of dosimetry radiation measurement performed in the Antarctic region at the surface of the sea which was conducted between January and March 2018. Over 2 200 records were collected using a portable Gamma Scout Online radiometer during a 72-day voyage circumnavigating the continent of Antarctica. The mean average of the measured radiation dose rate was 0.091 µSvh^{-1} and varied from 0.052 to 0.193 µSvh^{-1}. These result are above global average dose rate of radiation at sea level (0.031 µSvh^{-1}) and often higher than those recorded on the Antarctic continent. Yet generally our records fall within well recognized latitudinal trend of radiation being higher toward poles. This is results of troposphere begins at lower altitude in Antarctic in comparison to lower latitudes. The origin of this radiation is natural and results from the presence of higher cosmic rays and secondary radiation induced in the atmosphere. The presence of terrestrial radionuclides in the Antarctic environment has a local, secondary influence on the measured values of radiation. The theoretical calculated annual dose equivalent for humans present in Antarctica could often exceed the limit of 1 mSv as recorded for other Antarctic locations yet our results (0.772 mSv per year) do not confirm that.

Keywords Antarctic continent, sea level, dose rate monitoring, cosmic radiation, hazards of ionizing radiation.

Zarys treści W pracy przedstawiono wyniki dozymetrycznych pomiarów promieniowania, przeprowadzonych przez załogę jachtu Katharsis II, w trakcie 72-dniowego rejsu wokół Antarktydy. Podczas rejsu trwającego od stycznia do marca 2018 roku, za pomocą przenośnego radiometru Gamma Scout Online rejestrowano dawki promieniowania na poziomie morza w odstępach 10-minutowych. Po wstępnej analizie statystycznej uzyskano dane w postaci 2 200 rekordów, które wykorzystano do wnioskowania o rozkładzie promieniowania w rejonie Antarktyki. Średnia zmierzona moc dawki promieniowania wyniosła 0,091 µSvh^{-1} i wahała się od 0,052 do 0,193 µSvh^{-1}. Wyniki te są powyżej średniej globalnej mocy dawki promieniowania na poziomie morza (0,031 µSvh^{-1}) i często wyższe niż te zarejestrowane bezpośrednio na Antarktydzie. Jednak, generalnie zarejestrowane przez nas dawki promieniowania mieszczą się w dobrze rozpoznanym równoleżnikowym trendzie, w którym promieniowanie jest wyższe w kierunku biegunów. Związane jest to z cieńszą warstwą troposfery w rejonach biegunowych w porównaniu z niższymi, równikowymi szerokościami geograficznymi. Ogólnie pochodzenie tego promieniowania jest naturalne i związane z silniejszą penetracją troposfery przez promieniowanie kosmiczne oraz obecnością promieniowania wtórnego indukowanego w atmosferze. Obecność radionuklidów naziemnych w środowisku Antarktyki ma lokalny, wtórny wpływ na mierzone wartości promieniowania. Teoretycznie obliczony roczny ekwiwalent dawki dla ludzi, w różnych miejscach Antarktydy, może przekraczać limit 1 mSv, natomiast nasze wyniki (0,772 mSv rocznie) tego nie potwierdzają.

Słowa kluczowe Kontynent antarktyczny, poziom morza, monitorowanie mocy dawki, promieniowanie kosmiczne, zagrożenia promieniowaniem jonizującym.

1. Introduction

The cosmic radiation is defined as mixed protons (85.5% contribution) and alpha particles (12%) together with other heavier nuclei (including uranium). The energy of the cosmic particles ranges from 10^8 to 10^{20} eV. As a result of interactions of primary cosmic rays in the upper layers of the earth's atmosphere, secondary components can be produced, which include particles of muons, neutrons, electrons, positrons, and photons (UNSCEAR 2000).

The origin of cosmic radiation can be divided into galactic radiation, solar radiation, and radiation from the earth's radiation, so called Van Allen belts. Dose rate values vary drastically with the route (latitude, longitude, altitude) and the phasing of the solar event. High-energy protons and electrons are captured by magnetic fields and create mentioned Van Allen belts over the Earth (Métrailler *et al.* 2019). The daily equivalent dose to human skin in the internal belt is equal to several tens of Sieverts for protons and thousands of Sieverts for electrons (UNSCEAR 2000).

In general, the presence of a magnetic field dramatically reduces the cosmic radiation dose close to the earth's surface. Minimal dose rates can be observed on the equator and maximal values can be observed near to the geomagnetic poles. With increasing altitude the effective dose of cosmic radiation can be raised even fourth fold (Cai *et al*. 1995; Nakajima *et al*. 1995; UNSCEAR 2000; Kruetzmann 2006; Bakshi *et al*. 2017).

Cosmic radiation interacts with nuclei present in the atmosphere; the resulting interaction produces charged and uncharged nuclei, neutrons, pions, and radionuclides e.g. ^{3}H, ^{7}Be, ^{14}C, ^{22}Na, and others. After cascade reactions in the atmosphere, most energy reaches the Earth's surface as secondary particles and photons. As a result of pions decaying, charged muons are effectively generated. High-energy muons (with energies from 1 to 20 GeV) make a significant contribution to equivalent doses at ground level (UNSCEAR 2000).

A global average dose rate of radiation at sea level was estimated to be 0.031 μSvh^{-1}. The annual effective dose from the ionizing component of cosmic rays is believed to be 270 μSv. This is 10% of the total dose from natural radiation (UNSCEAR 2000).

This study focus on the Antarctic region where the natural dose rate of radiation is believed to be higher than at the equator. Several factors are responsible for this including (1) proximity to the geomagnetic pole, (2) overall significant high altitude of the Antarctic continent, (3) thin layer of the atmosphere and (4) significant local contribution of natural radionuclides in soil, rocks, and sediment (Cai *et al*. 1995; Nakajima *et al*. 1995; UNSCEAR 2000; Kruetzmann 2006; Bakshi *et al*. 2017).

The Antarctica magnetic and geomagnetic poles differ from the 90˚S geographic South Pole due to their constantly shifting locations. In 2015, the magnetic South Pole was located at 64°28'S and 136°59'E (UNSCEAR 2000). The height of the troposphere depends on the latitude and altitude. In the South Pole region, the troposphere begins at an altitude of 8 km, while at the equator, this lies at approximately 17 km. High energy particles from space (e.g. protons) collide with the atoms in the upper layers of the atmosphere and are effectively transported through the troposphere to the Earth's surface. As a result, UV radiation in Antarctica has an elevated value. The thinner layer of atmosphere in the Antarctic region has significant potential to reduce the protection effect of the biosphere (Bakshi *et al*. 2013, 2017).

An almost two-kilometer thick ice sheet covers 98% of Antarctica. Antarctica is the continent with the highest average elevation – 2500 meters with its highest peak Mount Vinson (4897 m a.s.l.). Such geomorphological characteristic of the continent reduces distance to the troposphere resulting in higher dose of cosmic radiation than for example at the equator (UNSCEAR 2000).

Radioanalytical research in Antarctica polar regions are not common. Cai *et al*. (1995) noticed that the distribution of natural, terrestrial radiation in the Antarctic region is very irregular. At Bharati, the Indian Antarctic research station (69°24'S, 76°11'E) in the Larsmann Hills, the gamma radiation was recorded at average level of 0.203 ± 0.010 μSvh^{-1}, which is a few times higher than in other locations on this continent. In some regions of Antarctica, the concentration of natural radionuclides ^{232}Th and ^{40}K, which contribute to local level of radiation, is significantly higher than in other locations. In soil samples collected close to Bharati Station, the activity concentrations of ^{232}Th and ^{40}K were 228 ± 51 and 1006 ± 50 $Bqkg^{-1}$ respectively. In Terra Nova Bay (Scuba Lake, 74°20'S and 165°07'E), ^{40}K activity concentrations measured in lake sediments and soil were 1150 ± 16 and 1334 ± 10 $Bqkg^{-1}$ respectively (ICRP 1990; Bakshi *et al*. 2017). There is evidence that at higher altitudes and closer to the magnetic South Pole the equivalent dose could increase above the limit of 1 mSv per year, which is recommended amount of radiation for public exposure (ICRP 1990). The presence of higher concentrations of terrestrial radionuclides in some regions can increase the local dose rate.

During the 60s and 70s at McMurdo Station (US Antarctic base), located 1360 km from the South Pole, a portable nuclear reactor provided a power supply. The small nuclear reactor called Nukey Poo was planned to be the first of many installed in Antarctica. The reactor was powered by highly radioactive ^{90}Sr pellets. High costs and the environmental impact resulted in the closure of the facility in October 1972. The presence of radioactive pollution in the local environment caused political tensions. The reactor vessel and reactor components, primary building, and thousands of tons of crushed contaminated rocks and other waste were removed and sent back to the USA (Report 2013).

This study takes unique opportunity to measure radiation in off shore waters around Antarctica during one summer season which was provided by voyage of a sailing vessel south of the 62° parallel. No such trip in human history was ever conducted what Guinness record achievement by the crew is confirming. This study aims to estimate for the first time ever the equivalent dose rate around Antarctica at the sea level. We hypothesize that the radiation in off shore waters of Antarctica will be lower than that on the continent as effect of altitude, yet it will fall within the latitudinal trend. There has been no similar study that had attempted to provide such information, therefore it was also necessary to investigate the contribution of secondary cosmic rays in the dose rate due to magnetic South Pole displacement and secondary radiation distribution in the Antarctic environment. This study is providing baseline information which exhibit the current radiation state of the area.

2. Materials and methods

The non-stop sailing on the yacht Katharsis II from Cape Town, South Africa to Hobart, Australia around the Antarctic continent took place between 23 December 2017 (06:56:20 UTC) and 5th April 2018 (05:55:25 UTC) (Fig. 1, 2). The whole expedition lasted 103 days, while circumnavigation of Antarctica bellow 62° parallel lasted 72 days.

The radiation dose rate was measured with use of a Geiger-Müller Gamma-Scoutevery 10 minutes during the whole voyage. The yacht position was recorded simultaneously with measurements (Fig. 1).

Fig 1. The radiation dose rate analysis by Geiger-Müller Gamma-Scout on Katharsis II yacht

Ryc. 1. Radiometr Geiger-Müller Gamma-Scout w ręku kapitana Michała Barasińskiego na jachcie Katharsis II, w porcie Cape Town, RPA, dzień przed startem

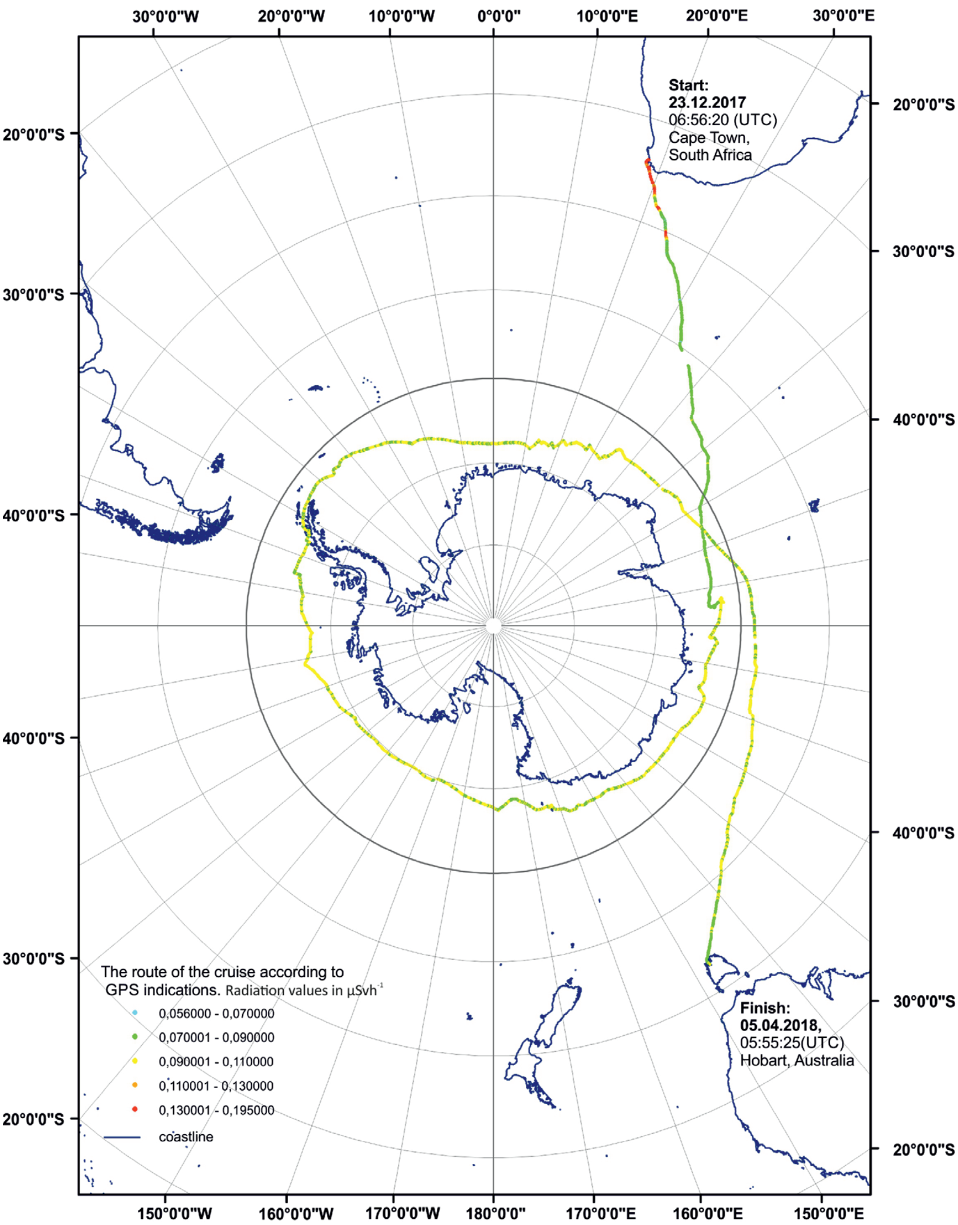

Fig 2. The gamma dose rates [μSvh^{-1}] measured during the voyage around the continent of Antarctica

Ryc. 2. Mapa przedstawiająca trasę rejsu oraz zarejestrowane dookoła Antarktydy moce dawki promieniowania gamma [μSvh^{-1}]

3. Results

The dose rate at sea level in Antarctica and partly outside Southern Ocean measured during circum Antarctic sailing expedition is presented in Fig. 1–4. The average dose rate recorded from the beginning to the very end of the expedition (103 days) was 0.091 ± 0.010 μSvh^{-1} ranging from 0.076 to 0.139 μSvh^{-1} (Fig. 1–3). Similar average dose rate which equals 0.091 ± 0.008 μSvh^{-1} was measured during 72 days of the circumnavigation of Antarctica which took place only south of the 62° parallel. The elevated values in comparison to the overall results have been noticed close to Cape Town (South Africa) starting from 23rd to 27th of December 2017. Taking into account our values from whole expedition such pattern of radiation does not follow the latitudinal trend of higher radiation values at high latitudes and this is most likely the result of proximity of land (South Africa) which cause the presence of elevated concentrations of terrestrial radionuclides in soil and rocks. After this zone with highest values of radiation we recorded reduced, the lowest during period of measurement values of radiation which were obtained between 27th December 2017 and 10th January 2018 (Fig. 3, 4). Interestingly we have not recorded elevated values in the vicinity of magnetic pole which was reached by the expedition on the 31st of January.

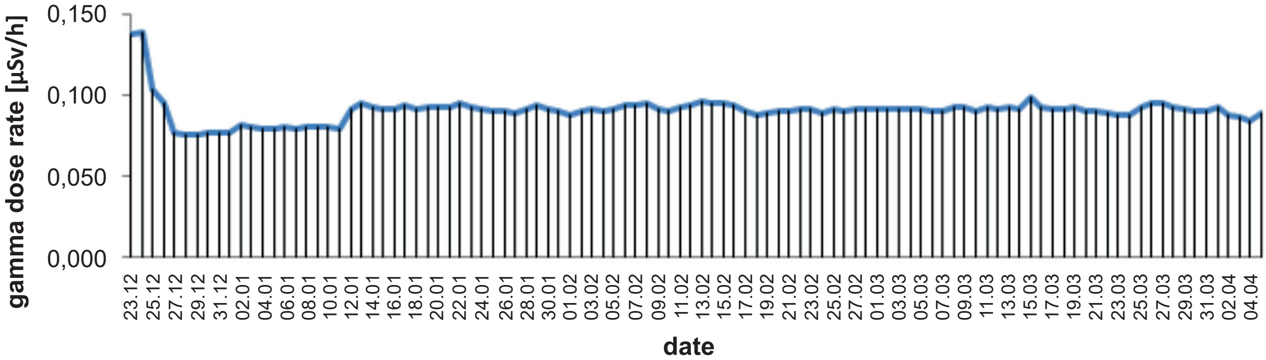

Fig. 3. Results of the average daily doses of gamma radiation recorded during the entire 103 days of the cruise

Ryc. 3. Wyniki średnich dobowych dawek promieniowania gamma zarejestrowanych w ciągu 103 dni rejsu

All measured values of radiations during this investigation are above a global average dose rate at sea level which is estimated to be 0.031 μSvh^{-1} (UNSCEAR 2000). And such pattern is not a surprise as our result overall follows the known latitudinal pattern of radiation being higher towards higher latitudes therefore our predictions are confirmed. For comparison, at the Papeete-Tahiti_987_Agg_Cp location on the Pacific Ocean island, the gamma dose rate was measured as 0.059 μSv/h; on the Atlantic Ocean island location Fratel-Sara the monitored dose rate was 0.023 μSvh^{-1}; and on the Indian Ocean island Location St-Louis-La-Reunion_974_Agg_Cp, the dose rate was 0.067 μSv/h (JRC map), and in Poland 0.090 μSv/h (Długosz-Lisiecka 2019; Długosz-Lisiecka, Nowak 2021). Such pattern is the result of already mentioned in the introduction height of the troposphere which at high latitude starts lower and could be at 8 km altitude in comparison to tropical areas where it is located at 17 km. From a radiological perspective, average value of the gamma dose rate equal 0.091 μSvh^{-1} in the Antarctic region could be the result of the elevated radiation, on the one hand, and on the other hand, the presence of elevated concentration of terrestrial radionuclides in soil and rocks. Additionally in Antarctica, over 100 volcanoes have been discovered; most of them are still beneath the ice sheet, which can contribute to overall radiation elevation (Riley *et al*. 2020; Smellie 2020).

Low natural radon ground level activity and low artificial radionuclide content at sea level around Antarctica indicate indeed relatively low gamma radiation content in this region (Szufa *et al*. 2018; Mietelski *et al*. 2000; Szufa *et al*. 2021). The maximum ^{238}U and ^{234}U activity measured in mosses and lichens was equal 7 Bq/kg, respectively, while observed ^{137}Cs activities show large variations: from 4.1 ± 0.4 to 74 ± 3 Bq/kg.

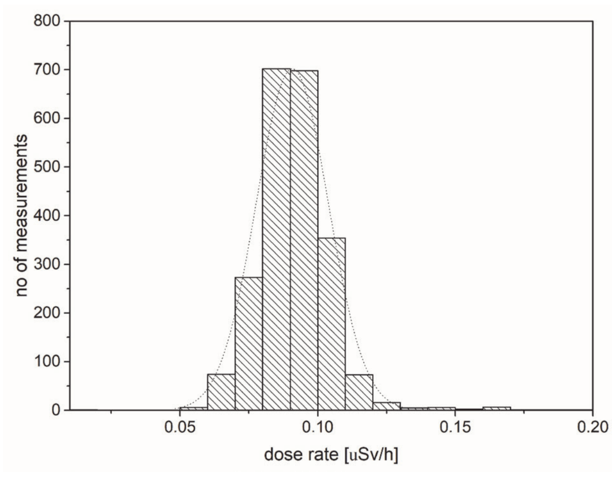

Fig. 4. Equivalent distribution of gamma radiation dose [μSv/year] in the Antarctic region over 103 travel days

Ryc. 4. Równoważny rozkład dawki promieniowania gamma [μSv/rok] w rejonie Antarktydy w ciągu 103 dni podróży

Yet when it comes to comparison of our result with other locations in Antarctica situation is getting complicated and dose rate values vary drastically (Fig. 4). The dose rate or equivalent dose rates measured in previous years at various Antarctic locations are summarized in Table 1. Some results exhibited values of radiation even at sea level yet in the proximity to land or at higher altitudes lower than the ones recorded offshore by this study. For example, the atmospheric radiation level at the Marambio Antarctica Base (64°13'S – 6°43'W; 196 m above sea level) measured in 2015 by a LIULIN 3 dosimeter was 0.080 ± 0.001 µSvh^{-1} (Zanini *et al*. 2017). Measurements in vicinity to the sea however within the ice (93 cm) at Showa Station (69°00'15"S, 39°34'48"E) have shown radiation at the level of 0.043 µSvh^{-1} (Nakajima *et al*. 1995). As Nakajima *et al*. (1995) stated these values are result of dependence on altitude above sea level of the exposure rate increases by almost three-fold with each increase of 2000 m of altitude (Fig. 5). On the other hand, we have examples of measurements which had values much higher to the once recorded by us. Bakshi *et al*. (2013) recorded values of radiation ranging between 0.350 and 0.700 µSvh^{-1}. Such high values were ascribed to variation in the fast neutron dose rate measured from the surrounding materials of the detector sets and to peak solar activity during 2011–12 periods.

Table 1. Dose rate and equivalent dose rate at different Stations in Antarctica

Tabela 1. Moc dawki i równoważna moc dawki na różnych stacjach na Antarktydzie

Location/Coordinates	Dose rate/equivalent dose rate	Reference	Measurement method
69°24'50"S, 76°11'24"E	0.290 ± 0.035 µSvh^{-1}	(Guillaume and Sébastien 2017)	Passive/TLD
69°24'56"S, 76°12'12"E	0.371 ± 0.024 µSvh^{-1}	(Guillaume and Sébastien 2017)	Passive/TLD
69°22'23"S, 76°22'17"E	0.200–0.600 µSvh^{-1} range	(Bakshi *et al*. 2013)	Active survey
69°22'23"S, 76°22'17"E	0.290–0.380 µSvh^{-1}	(Bakshi *et al*. 2013)	Passive/TLD
Showa Station 69°00'15"S, 39°34'48"E	0.043 µSvh^{-1}	(Nakajima *et al*. 1995)	Passive/TLD 93 cm deep in ice
Bharati Station 69°24'50"S, 76°11'24"E	0.350–0.700 µSvh^{-1} range	(Bakshi *et al*. 2013)	Active/RadEye G
Argentine Antarctic Marambio 64°14'27"S, 56°37'38"W	0.042 ± 0.003 µSvh^{-1}	(Nakajima *et al*. 1995)	Active Atomtex BDKG-04 detector
McMurdo Station 150 m a.s.l. 77°50'53"S, 166°40'06"E	0.076 ± 0.024 µSvh^{-1}	(Kruetzmann 2006)	Passive/TLD
South of the 62° parallel, around Antarctica	**0.091 ± 0.010 µSvh^{-1}**	**this study**	**Active/Gamma-Scout**

In the Antarctic region, due to the high altitude and the very low magnetic field. On the basis of equation (1) cosmic ray dose rate appears to double for every two-kilometer rise in altitude (UNSCEAR 2000). For the region with the highest elevation on the continent, with an altitude of over 4 kilometers, an annual dose can be 3–4 mSv per year (Fig. 5); similar results have been calculated by Bakshi *et al*. (2013).

4. Conclusions

During the 103 days of the journey, members of the crew were exposed to an average dose of 0.218 mSv (0.772 mSv per year). Sea level dose rate results measured in this study are comparable with the values obtained for the most European countries, over a similar time period. The average dose rate during the circumnavigation of Antarctica south of the 62th parallel was 0.091 ± 0.010 µSvh^{-1}. A similar value, 0.090 µSvh^{-1}, was measured in central Poland. The global average dose rate of cosmic radiation

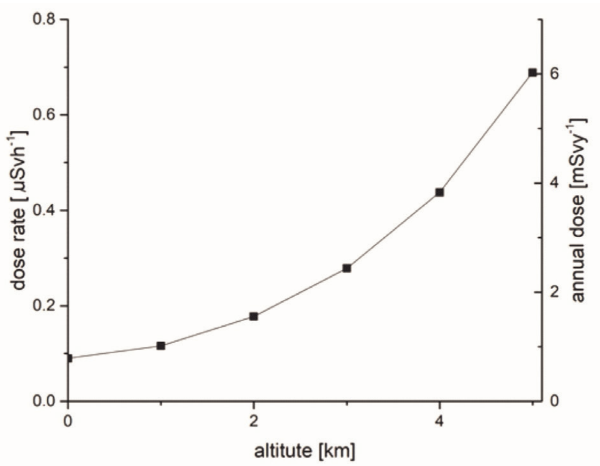

Fig. 5. Graph of the variation, calculated theoretically from Equation 1, of the gamma equivalent dose distribution [µSv/year] and dose rate with increasing altitude in kilometers in the Antarctic region

Ryc. 5. Wykres zmienności, obliczony teoretycznie, na podstawie równania 1, równoważnego rozkładu dawki gamma [µSv/rok] i mocy dawki wraz ze wzrostem wysokości w kilometrach w rejonie Antarktydy for humans measured at sea level has been estimated at 0.36 mSv per year and the public radiation limit which is not harmful to humans should not exceed 1 mSv per year. Therefore, estimated radiation, which is result of atmospheric ionizing radiation induced by cosmic rays in the region is rather no problematic to humans staying at sea in Antarctic. Yet continental measurements in Antarctic often exhibited an equivalent dose higher than those allowed for humans of 1 mSv per year. At Bharati Stationduring 3 months period 1.68 mSv was recorded (Bakshi *et al*. 2017). At Vostok Station located at the 3,5 km altitude radiation was at the level of 0.84 mSv within the same time framework (Guillaume and Sébastien 2017). Such level of radiation can be harmful to humans, however, there is no evidence of an increased incidence of cancer for people staying for a limited period.

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