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Radioactivity soundings of the upper atmosphere in Finland 1962-2022

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Abstract

Radioactivity soundings have been performed in Finland since the early 1960s to measure radiation and radioactivity levels in the atmosphere up to the altitude of almost 40 km. A sonde package based on a Geiger-Müller (GM) tube is carried up to the stratosphere by a balloon filled with hydrogen or helium. En route the GM tube count rate values are sent to the ground station with a radio transmitter. These radioactivity soundings revealed the presence of abnormal radioactivity in the stratosphere over Finland due to Soviet atmospheric nuclear tests in 1962. Between 1964 and 1980 artificial radioactivity in the stratosphere originating from the Chinese nuclear tests were observed too.

The radioactivity soundings have brought information on cosmic radiation even if the main motivation has been the surveillance of artificial radioactivity in the upper atmosphere. The effects of the solar cycle, geomagnetic latitude and solar proton events on the radiation environment of the upper atmosphere have been measured. The produced vertical ionization profiles may also be useful in studies concerning ion-induced or ion-mediated new particle formation events in the atmosphere.

Keywords: Atmosphere; Cosmic radiation; Nuclear tests; Balloons; Ionization rate

1. Introduction

Professor Victor Hess [1912] discovered the cosmic radiation during his famous balloon flights in Vienna in 1912. Ever since balloons, both manned and unmanned, have been used to carry radiation detectors into the upper atmosphere. In Germany Georg Pfotzer [1936] used a triple Geiger-Müller (GM) tube coincidence counter attached to an unmanned balloon to measure the vertical profile of the cosmic radiation in the atmosphere. He found out that the radiation intensity increases upwards and reaches a maximum at about 8 cmHg pressure level (≈107 hPa ≈16 km altitude) before starting to decrease again. This maximum was often called "Pfotzer maximum" and more recently "Regener-Pfotzer maximum" to acknowledge the contribution by Professor Erich Regener, Pfotzer's supervisor. Traditionally such upper air soundings have been called radioactivity soundings even though more precisely speaking they should be called count rate or dose rate soundings. However, the traditional phrase radioactivity sounding is used in the following.

Data on cosmic radiation has several uses in addition to cosmic ray research itself. Bursts of high-energy Solar particles may trigger magnetic storms in the Earth's magnetic field which, in turn, can induce geomagnetic currents in electric grids and in long pipelines carrying e.g., natural gas. On the other hand, cosmic radiation can vary significantly in relation to the activity of the Sun. Cosmic radiation affects the air chemistry in the upper atmosphere, for example, in the ozone forming and destruction chemistry [Denton et al., 2018]. Cosmic radiation can be a significant source of radiation dose to flight crews, and to a lesser extent to passengers, onboard aircraft.

Artificial radioactive substances can end up into the upper atmosphere from military or terrorist nuclear detonations or so-called dirty bombs, from severe nuclear reactor accidents, from accidents of nuclear-powered vessels or from re-entries of satellites carrying nuclear or radioisotope power sources. The monitoring of the radioactivity and radiation in the upper atmosphere with aircraft and unmanned aerial vehicles is expensive and suitable platforms are not necessarily always available. In addition, sending an aircraft crew into a radioactive plume is questionable from the radiation protection point of view. The radiation monitoring of the upper atmosphere is important as the airborne radionuclides can be scavenged down to the Earth by precipitation and become incorporated in various food webs. Also, their transfer to the surface air would expose the population to inhalation of radionuclides. Information obtained with radioactivity soundings concerning the altitude and movement of contaminated air layers can provide an early warning to military CBRN (Chemical, Biological, Radiological and Nuclear) protection and civil defense authorities. Radioactivity soundings also provide input data for atmospheric transport and dispersion models and, on the other hand, they can be used for the verification of modeled atmospheric dispersion and deposition of airborne radioactivity.

During the intense nuclear testing in the late 1950s and early 1960s there were cases at least in Japan, USA, Sweden, Norway, Germany, and Soviet Union, when artificial radioactivity from the tests were observed with radioactivity soundings [Ishii, 1956; Mantis and Winckler, 1960; Kepler et al., 1964; Riedler, 1965; Stozhkov et al., 2009). During the last two decades radioactivity soundings have been made at least in United Kingdom [Harrisson et al., 2014; Aplin et al., 2017; Dyer et al., 2018], Israel [Yaniv et al., 2016], India [Sarkar et al., 2017], USA [McIntosh et al., 2021] and South Africa [Mosotho et al., 2021].

In Finland three organizations have performed radioactivity soundings, Vaisala Corporation, the Finnish Meteorological Institute (FMI), and the University of Oulu. Vaisala Corporation producing meteorological and special sounding systems has made radioactivity soundings as a part of the company's research and development projects and quality control actions. The FMI's main motivation has been the radioactivity surveillance of the upper atmosphere but during recent years also space weather applications. A review of these past activities and a summary of the ongoing sounding programme is reported in the following.

In addition to the operational radioactivity sounding activities balloon soundings dedicated to cosmic radiation research were made by the University of Oulu. These sounding activities were coordinated by SPARMO organization (Solar Particles and Radiation Monitoring Organization), later with the name SBARMO (Scientific Ballooning and Radiation Monitoring Organization). Contrary to the operational radioactivity soundings the SPARMO sondes were lifted to a pressure level of 5-10 hPa (altitude of ~30-40 km) where the sondes were drifting with the wind for up to several days. The main aim of these soundings was to obtain data on the particle flux and x-ray intensity and energy in the stratosphere in the auroral zone. The sondes were equipped with triple GM counter coincidence systems and NaI scintillation detectors. Altogether 114 soundings were performed from 1965 to 1979. In addition to scientific results these activities helped the then new university to network with the international scientific community [Kangas, 1966; Kangas, 1968; Nygrén et al., 1973; Kangas & Tanskanen, 2010; Bösinger, 2021].

2. Radioactivity soundings 1962-1980

2.1 Instrumentation and operations

Vaisala Corporation developed a radioactivity sounding system in the early 1960s. The first published test flights were conducted in 1961 [Lindqvist, 1961]. The commercial version of the radioactivity sonde was given the type name NS11 and the ground equipment the type name NR11. The NS11 sonde was equipped with a GM tube. The size of the sonde's polystyrene foam enclosure was 10 cm × 15 cm × 22 cm. The weight of the flight set (a sonde, a parachute and a suspension string) was about 900 g of which over a half was due to the sonde battery. The count rate signal of the GM tube was frequency modulated and transmitted with an output power of 500 mW and a transmission frequency of 151-154 MHz to the ground station. The measurement range of the sonde was 0-200 $\mathrm{mRh^{-1}}$ corresponding to an absorbed dose rate of approximately 0-2000 $\mathrm{\mu Gyh^{-1}}$. The sondes were factory calibrated individually with a ^{226}Ra source [Jägermalm et al., 1963].

The ground equipment NR11 had measures of 55 cm × 57 cm × 38 cm and a weight of 60 kg. It received the sonde telemetry, processed it, and produced the radioactivity sounding output with a strip chart recorder and two counters working alternately for one minute.

An interesting detail is that the Vaisala Corporation designed a version of the sounding system for a ground-based radiation detection network where several sondes transmitted the count rate observations to the central monitoring station using the sonde telemetry, a very sophisticated areal wireless radiation monitoring concept at that time [Jägermalm, 1963].

The radioactivity sounding system was used at two locations in Finland. Radioactivity soundings were performed at the aerological test station of Vaisala Corporation (60°18'N, 24°54'E, h = 35 m a.s.l) in Helsinki metropolitan area as a part of the company’s research, development, and quality assurance programmes.

The Finnish Defence Forces (FDF) acquired the Vaisala’s radioactivity sounding system in 1963. This system was placed at the FMI’s meteorological observatory of Jokioinen (60°49'N, 23°30'E, h = 104 m a.s.l). The staff of the observatory operated the system. Initially radioactivity soundings were performed once a week but later less and less frequently so that in 1980 only one sounding, in November, after the so far last atmospheric nuclear test, was performed. After 1980 no more radioactivity soundings were performed at Jokioinen with the system. The 1986 Chernobyl plume would have been easily detected with the system, especially because the air mass that was over the Chernobyl area during the initial explosion was moving above Jokioinen region a couple of days later [Valkama et al., 1995; Paatero et al., 2006]. Based on the annual reports of the Jokioinen observatory the number of radioactivity soundings was 323 from 1963 to 1971 and 35 from 1972 to 1980, altogether 358. There are only a few publications based on these soundings, all related to the atmospheric nuclear tests made in China [Rossi, 1966; Rossi, 1967; Huovila and Kulmala, 1968]. One reason was that the FDF kept the operational radiation surveillance data secret. The FMI obviously had access to the gathered sounding data but perhaps there was simply a lack of scientific interest and/or human resources to analyze the data further. According to Jägermalm [1966] the plumes from all the first four Chinese nuclear tests were detected in Finland.

2.2 Soviet nuclear tests in 1962

Vaisala Corporation made a radioactivity sounding at the company’s aerological test station in Helsinki area on 15 October 1962 [Jägermalm et al., 1963]. Compared to an average radioactivity sounding profile this sounding indicated excess radiation above the pressure level of 150 hPa (≈13.5 km altitude, Fig. 1). NOAA HYSPLIT air mass back trajectories [Stein et al., 2015] indicate that the air masses over Helsinki area were coming from the central Arctic Ocean. The Soviet Union performed several atmospheric nuclear tests at the Novaya Zemlya test site during the preceding weeks, eight megaton range tests in September and two kiloton range tests in October [Khalturin et al., 2005].

2.3 Nuclear test in October 1964

The first nuclear test by the People’s Republic of China was conducted on 16 October 1964 [UNSCEAR, 2000]. The 20 kiloton of TNT equivalent test was made on land surface. According to the radioactivity sounding data from Jokioinen the main plume from the test crossed southern Finland on 26 October, in other words 10 days after the test (Fig. 2). The bottom of the plume was on a pressure level of 350 hPa which corresponds to an altitude of about 8 km. The absorbed dose rate was still on a clearly higher level during the balloon burst on the pressure level of 26 hPa (≈25 km altitude). The absorbed dose rate maximum, 8.2 μGyh^{-1}, was reached on the 34 hPa pressure level (≈23 km altitude). The increase from the usual level was about 50%. Taking into consideration the rather modest yield of the test [UNSCEAR, 2000] the explosion plume rose to a surprisingly high altitude.

These radioactivity sounding data, originally in exposure rate units (mRh^{-1}), were found in a then secret report by the chief of the CBRN Protection Office, Defence Command of the FDF. Nowadays the declassified document is freely available at the National Archives of Finland (File “PE Slutsto D1 sal, Omat toimitteet, Lähteneet asiakirjat 1960-1967”, archive unit code T-25979/2).

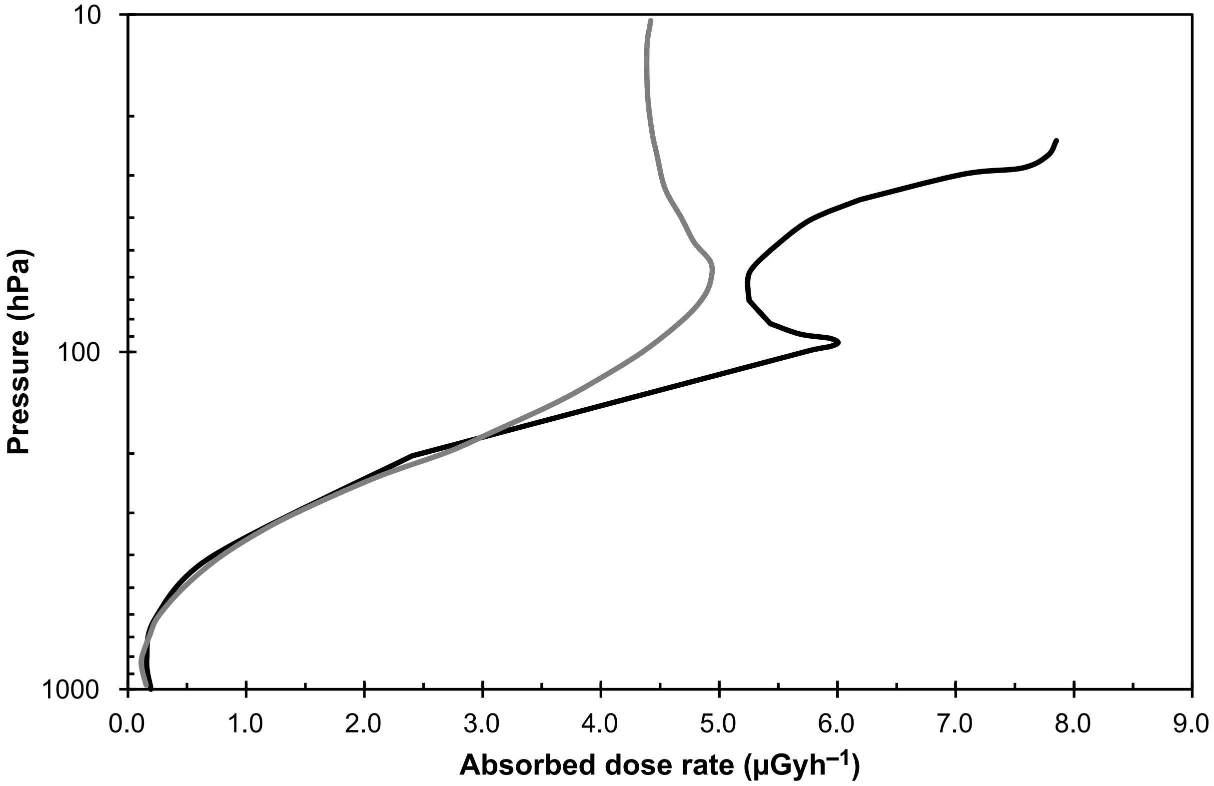

Figure 1. Radioactivity sounding launched at Vaisala aerological station in Helsinki metropolitan area 15 October 1962 (black curve). The grey curve depicts the average radiation level. The data was compiled from the report of Jägermalm et al. [1963]. The original exposure rate values (mRh^{-1}) have been converted to absorbed dose rate values (µGyh^{-1}).

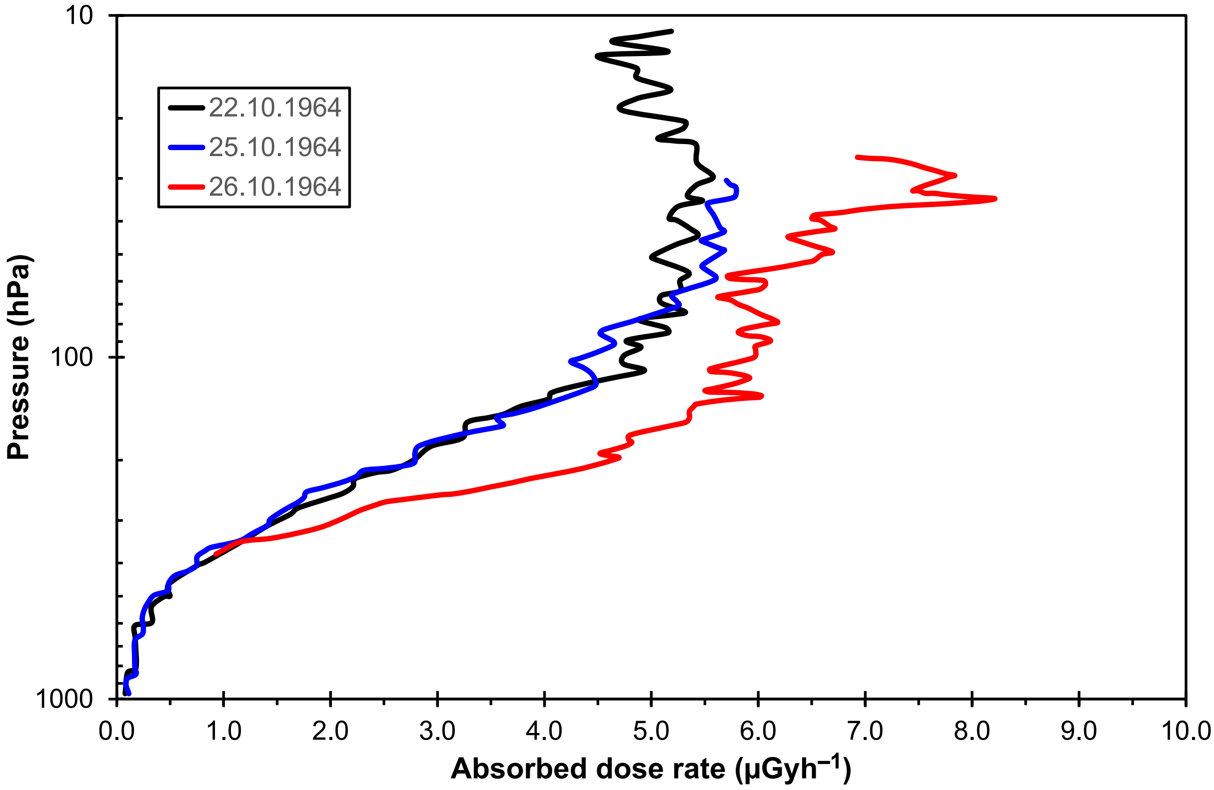

Figure 2. Radioactivity soundings made at Jokioinen in October 1964 following the atmospheric nuclear test in Lop Nor, Xinjiang, China 16 October 1964. The original exposure rate values (mRh^{-1}) have been converted to absorbed dose rate values (µGyh^{-1}). Data: National Archives of Finland.

3. Radioactivity soundings since 1991

3.1 Instrumentation

The sounding system used in the on-going sounding programme consists of the radioactivity sonde, the weather sonde (so-called PTU sonde), and the ground equipment. The system is manufactured by Vaisala Corporation. The radioactivity sonde consists of two GM tubes and an integrated interface to the PTU sonde that measures pressure, temperature, humidity and wind speed and direction. It is therefore possible to measure the vertical distribution of atmospheric radiation together with these meteorological parameters from ground-level up to a pressure level of a few hPa. One of the GM tubes measures only gamma radiation while the other measures both beta (>0.25MeV) and gamma radiation. The wall thickness of the GM tubes is 250 $\mathrm{mgcm^{-2}}$ and 32-40 $\mathrm{mgcm^{-2}}$ for the gamma only tube and gamma and beta tube, respectively. The GM tubes are specially designed for a low-temperature environment down to –70 °C. The accuracy of the tubes is ±10%. The sensitivity of the GM tube depends on the type and the energy of the incident radiation. The energy spectrum of a mixture of artificial radionuclides is typically unknown. In addition, the natural radiation environment in the stratosphere differs significantly from the radiation emitted by single nuclear disintegrations. This prevents an accurate conversion from measured pulse rates (cps) to absorbed dose rate in the air D ($\mathrm{\mu Gyh^{-1}}$). In this work we used the conversion equations based on the radiation emitted by ^{137}Cs and provided by the GM tube manufacturer. The conversion equations are for the gamma tube:

$$D(\mathrm{\mu Gyh^{-1}}) = 0.23 \cdot R^{1.15}, \tag{1}$$

and for the beta and gamma tube:

$$D(\mathrm{\mu Gyh^{-1}}) = 1.1 \cdot R^{1.02}, \tag{2}$$

where R is the measured count rate ($\mathrm{s^{-1}}$).

The measuring range of the radioactivity sonde is wide, up to 100,000 $\mathrm{\mu Gyh^{-1}}$ for the gamma only tube and 200,000 $\mathrm{\mu Gyh^{-1}}$ for the gamma and beta tube. As there is no means to measure radiation produced by artificial radioactivity alone, the natural background determines the minimum detectable artificial radioactivity level. The GM counters are sensitive to electrons, photons, muons and other high-energy charged particles but not to neutrons.

3.2 Radioactivity sounding climatology

The 11 years long activity cycle of the Sun modulates the intensity of the cosmic radiation [Lantos, 1993]. Sunspots have been traditionally used as a proxy for the Solar activity. When the activity of the Sun increases the amount of plasma emitted by the Sun increases within the solar system. This makes the interplanetary magnetic field stronger resulting to a reduction of galactic cosmic ray (GCR) particles reaching the Earth’s vicinity. On the other hand, when the activity of the Sun decreases also the interplanetary magnetic field becomes weaker resulting to an increase of galactic cosmic ray particle flux reaching the Earth’s surroundings. This variation might have an effect on the climate [Svensmark and Friis-Christensen, 1997].

Results of radioactivity soundings in southern Finland from 1991 to 2022 is presented in Figure 3. The soundings in the autumn of 1991 were performed at Vaisala Corporation in Helsinki area and the rest at Jokioinen. The dataset consists of 39 radioactivity soundings. The sunspot data were obtained from the World Data Center SILSO, Royal Observatory of Belgium, Brussels [https://www.sidc.be/SILSO].

On the pressure levels of 50 and 100 hPa a twofold increase of the absorbed dose rate from the solar activity maximum to minimum has been found. An earlier observed about one year lag between the number of sunspots and the radiation intensity cannot be confirmed due to the sparsity of the observations. This lag has been attributed to interactions of outward moving solar wind and inward propagating GCRs and variations in the solar magnetic

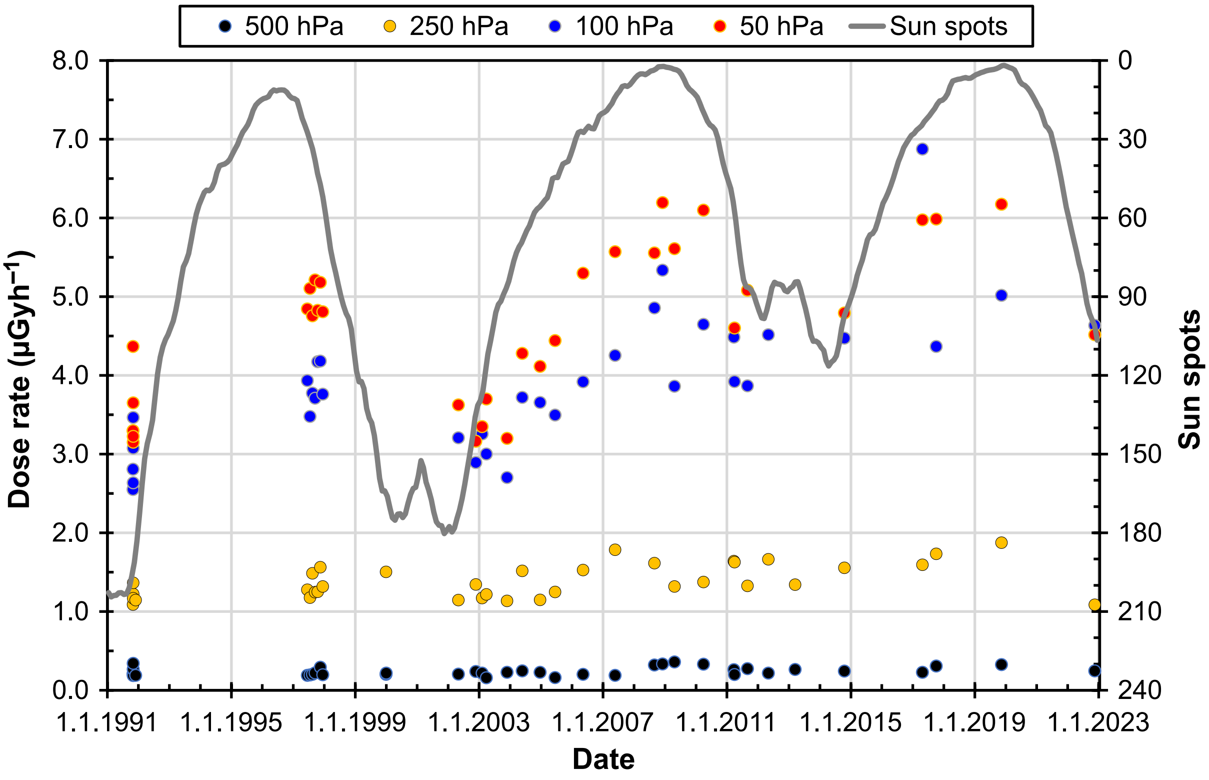

Figure 3. Absorbed dose rate (μGyh^{-1}) in the atmosphere on four pressure levels over southern Finland 1991-2022 and the 13-month smoothed number of sunspots [World Data Center SILSO, Royal Observatory of Belgium, Brussels]. Note the inverted vertical scale in the sunspot numbers.

field [Wang et al., 2022). The variation of the cosmic ray intensity decreases downwards in the atmosphere and on the ground-level the neutron flux variation between the solar minima and maxima has usually been of the order of ±10-15% [https://cosmicrays.oulu.fi].

Similar radioactivity soundings have been performed also at the FMI's Tikkakoski sounding station in central Finland (62°24'N, 25°40'E, 19 soundings from 1999 to 2016) and at the FMI's Arctic Research Centre at Sodankylä, northern Finland (67°22'N, 26°39'E, 30 soundings from 1995 to 2019). The data is not presented here but it is available from the FMI.

3.3 Influence of the geomagnetic latitude on cosmic radiation

The Arctic Summer Cloud Ocean Study, ASCOS, was an Arctic field experiment project based on a Swedish icebreaker expedition during the summer of 2008 [Tjernström et al., 2014; Paatero et al., 2009]. The expedition reached the latitude 87.5°N. The project contributed to the International Polar Year 2007/2008 (IPY) coordinated by the World Meteorological Organization (WMO). On-board the icebreaker Oden six radioactivity soundings were made, from which three were selected to the subsequent analysis (Fig. 4). They represented three different geomagnetic latitudes. For comparison two radioactivity soundings were performed in Finland, one at Jokioinen, southern Finland and the other at Sodankylä, northern Finland. Additional radioactivity sounding data made with similar instrumentation was obtained from Hong Kong Observatory close to the geomagnetic equator [Lui and Lee, 2009; Li et al., 2007].

It has been known over a half a century that the intensity of cosmic radiation increases from the magnetic equator towards the magnetic poles but that the intensity levels off above 50th latitude [Neher and Stern, 1955]. There the shielding effect of the atmosphere becomes stronger than the cosmic radiation cutoff. This is reflected in the plot of radioactivity soundings in Figure 4. There is no clear difference in the soundings made in Finland and Arctic Ocean, neither in the intensity of radiation nor in the altitude of the Regener-Pfotzer maximum. In the case of 80.5°N sounding over the altitude of 25 km the intensity is only marginally higher than compared with the other soundings. Neher and Anderson [1962] found out that over Thule, Greenland, with a geomagnetic latitude of 88°N the altitude of the Regener-Pfotzer maximum varied between 21-24 km but under different Solar forcing compared with this study. On the contrary there is a marked difference between the northern soundings and the sounding of Hong Kong where the Regener-Pfotzer maximum lies between 16 km and 18 km. The intensity is clearly lower, too. The intensity at the Regener-Pfotzer maximum is 20 times higher compared with the lowest atmosphere. But at the latitude 80.5°N the intensity increases from the sea level to the altitude of 23-24 km by a factor of 127. The geometry of the Earth's magnetic field plays a decisive role in the penetration of cosmic rays in the atmosphere because charged particles prefer moving along geomagnetic field lines in the magnetosphere and ionosphere. At high latitudes, the geomagnetic field lines are quasi-vertical and even the numerous low-energy charged particles can quite easily penetrate into the stratosphere by spiraling along geomagnetic field lines. But these particles are quickly stopped and thus the maximum intensity of their secondary particles occurs at a relatively high altitude. On the other hand, at low latitudes, where the geomagnetic field lines are almost horizontal, only few very energetic particles can penetrate the atmosphere traveling through different geomagnetic field lines, and, consequently, depositing their energy and forming secondary particles at lower altitudes.

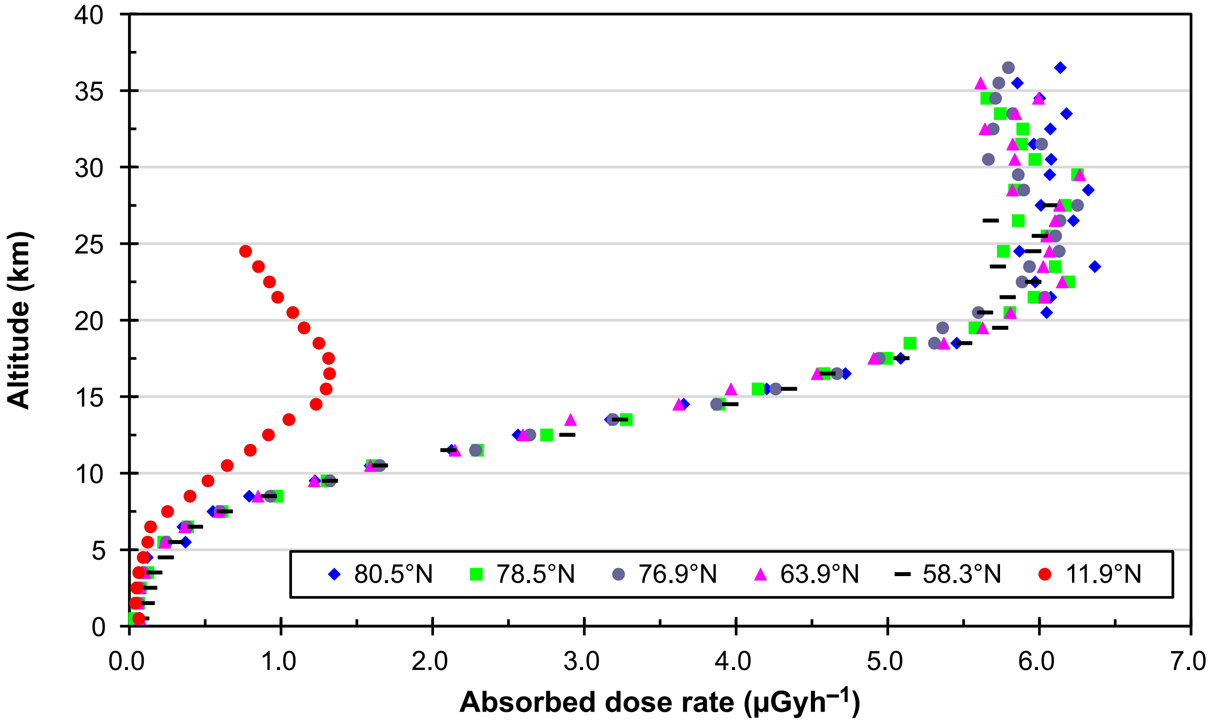

Figure 4. Radioactivity soundings (gamma tubes) made at different geomagnetic latitudes, 80.5°N, 78.5°N, 76.9°N, 63.9°N, 58.3°N, and 11.9°N. The data for the 11.9°N sounding is from the report of Lui and Lee [2009].

3.4 Solar proton event in January 2005

A massive solar flare occurred on 20 January 2005 just before 07 UTC ejecting a billion-ton cloud of plasma (CME, coronal mass ejection) into space which triggered the strongest radiation storm and geomagnetic activity since October 1989. Solar protons accelerated to nearly the speed of light entered the Earth's orbit minutes after the flare. The GOES-11 satellite observed an increase of four orders of magnitude in the proton flux with an energy above 100 MeV [Wu et al., 2009].

In Finland, the ground-level neutron flux has been monitored by the University of Oulu (65°03'N, 25°28'E) with the 9-NM-64 neutron monitor since 1964 [Niemi, 1966]. Over three-fold increase in the neutron flux occured at 07 UTC which is the highest increase ever recorded with the instrument [https://cosmicrays.oulu.fi]. The CME caused a magnetic storm in the Earth's magnetic field one and a half days later resulting in e.g., aurora borealis that were visible even in central Europe [Pajunpää and Nevanlinna, 2006].

Just by chance, Vaisala Corporation launched a radioactivity sonde in the Helsinki metropolitan region (60°17'N, 24°53'E) on 20 January 2005 06:47 UTC. The balloon reached an altitude of 17832 metres in 3014 seconds (Fig. 5). The radiation intensity was reasonably normal from the ground-level to the altitude of 5 km, but above that altitude the GM tube count rates were increasing exponentially as a function of the altitude rising to a level which was more than an order of magnitude higher than usually. When the intensity and the altitude dependence of the radiation was observed, the conclusion was that the radiation was coming from the space and the Earth's atmosphere was absorbing the radiation [Paatero et al., 2006]. Similar results were obtained in Kola peninsula, north-western Russia [Bazilevskaya et al., 2008]. A sonde flying between 07:32 and 08:38 UTC recorded at an altitude of 18 km a 15-fold increase in the GM tube count rate.

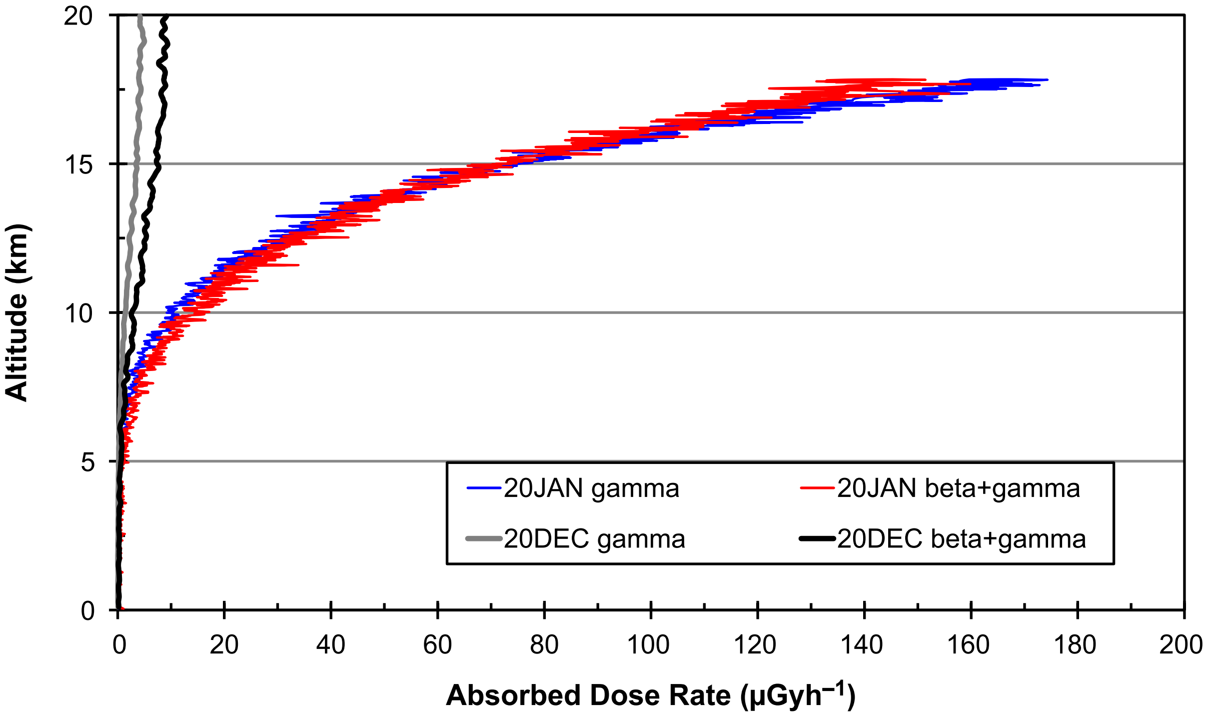

Figure 5. Radioactivity sounding launched at Vaisala aerological station in Helsinki metropolitan area 20 January 2005 06:47 UTC (the blue and the red curve). For comparison, results from a normal situation a month earlier, 20 December 2004, are shown with the grey and the black curve [Paatero et al. 2006].

In Finland the ground-level absorbed dose rate caused by the external radiation varies between 0.03 and 0.30 μGyh^{-1} depending mainly on the natural radionuclide content of the surface soil and the water content of the snow cover attenuating gamma radiation from the ground [Hatakka et al., 1998]. Assuming an average ground-level absorbed dose rate of 0.15 μGyh^{-1} it can be calculated that passengers and crew members onboard an aircraft at an altitude of 10 km over southern Finland would have received in one hour an extra absorbed dose of 10 μGy corresponding to an external radiation dose of three days in normal ground-level background conditions. In other words, in this case the additional radiation exposure due to this space weather event was insignificant. Larger potential doses would have been received over the circumpolar areas [Lantos, 2006].

Earlier it has been observed that the increased ionization created by solar eruptions can cause an increase of the NO_x concentration in the stratosphere, which, in turn, can destroy the stratospheric ozone protecting the biosphere from the adverse effects of the solar ultraviolet radiation [Seppälä et al., 2004]. In this case too, a significant loss of ozone was observed by the GOMOS satellite instrument. However, the ozone loss was most severe in the mesosphere (altitude of 70-80 km), in other words well above the range of balloons used in this work [Seppälä et al., 2006].

3.5 Ion production profile over the Arctic Ocean

One of the challenging uncertainties in climate change scenarios has been the role of atmospheric aerosol particles. For over three decades ago a phenomenon called “new particle formation event” was discovered. One theory for the mechanism producing these new particles in the atmosphere has been atmospheric ions, either by working as “seeds” for aerosol particles or by mediating the physicochemical reactions leading to particle formation. For these studies information on the atmospheric ion production rate has become important [Yu and Turco, 2000; Jokinen et al., 2018].

Due to the thick ocean water layer the gamma radiation from the Earth’s crust doesn’t reach the atmosphere over the central Arctic Ocean. The low content of natural radionuclides in the ocean water creates only a weak gamma radiation field over the ocean. About 99 percent of the airborne radon-222 (^{222}Rn) originates from continents and less than one percent originates from oceans [Baskaran, 2011]. Therefore, the activity concentration of ^{222}Rn and its progeny in the air over the central Arctic Ocean is low [Bigg, 1996]. The same applies to other natural and artificial radionuclides except krypton-85 (^{85}Kr). Being a noble gas with a long half-life (10.76 years) ^{85}Kr is distributed relatively homogeneously around the atmosphere with a concentration level of about 1 Bqm^{-3} [Smith et al., 2005] producing thus 0.005 ion pairs cm^{-3}s^{-1}. Other factors, e.g. splashing ocean water, are negligible ion sources [Hirsikko et al., 2011]. Thus, over the central Arctic Ocean the great majority of atmospheric ions are produced by cosmic radiation.

Based on a radioactivity sounding made on the geographical latitude 87°N during the 2008 ASCOS expedition, a profile of ion production rate was calculated from the absorbed dose rate values using an energy of 34 eV to produce one ion pair. As the absorbed dose rate unit expresses the radiation energy absorbed to a unit mass (J kg^{-1}) the ion production rates were converted to volumetric units using the ideal gas law. The conversion was made to two conditions: ambient conditions measured with the radiosonde and standard conditions (temperature 0°C and pressure 1013 hPa, STP, Fig. 6).

In ambient conditions the average ion production rate is about 3 ion pairs cm^{-3}s^{-1} in the atmospheric layer from sea level to one kilometer. It increases then up to the altitude of 13-14 km reaching a tenfold value after which it gradually decreases to a value of about 2 ion pairs cm^{-3}s^{-1} at an altitude of 36 km. It should be noted that the maximum ion production rates are found several kilometers below the Regener-Pfotzer maximum.

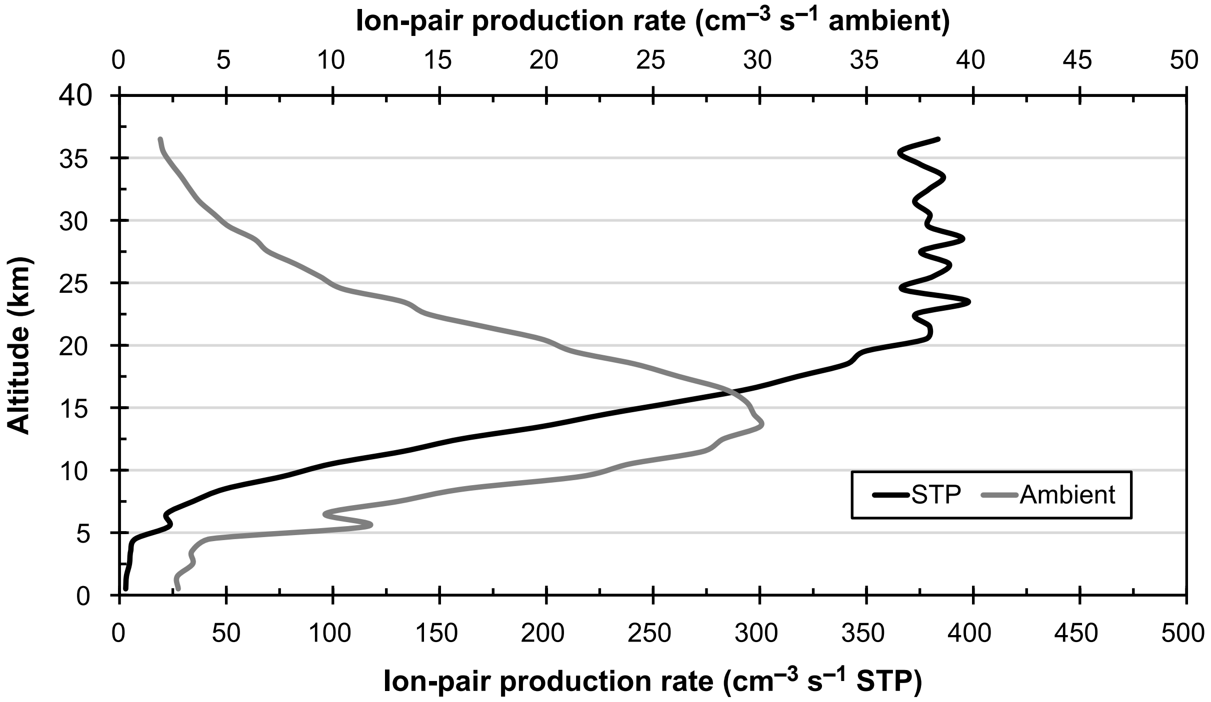

Figure 6. Ion production rate (ion pairs cm^{-3}s^{-1}) over the Arctic Ocean, 28 August 2008. The black curve depicts the ion production rate in NTP conditions (temperature 0°C and pressure 1013 hPa) while the grey curve represents the ion production rate in ambient conditions.

The ion production rate in standard conditions describes the ability of incident cosmic ray particles to release their energy to atmospheric atoms. This ability, in turn, depends on the energy of the particles. In standard conditions the ion production rate increases from 3 ion pairs $cm^{-3} s^{-1}$ to a level of 375 ion pairs $cm^{-3} s^{-1}$ at an altitude of 20 km. Above that the ion production rate remains relatively constant in standard conditions indicating only minor changes in the energy spectrum of the incoming cosmic ray particles.

4. Conclusions

Balloon-borne radiation sondes have been shown to be a flexible and a cost-efficient method to measure radiation and radioactivity in the upper atmosphere. The sondes are usually disposable and thus in a severe fallout situation contamination of the sonde is not an issue. However, it is possible to equip the sondes with a parachute recovery system.

Information about the vertical distribution of a radioactive plume provided by soundings is essential for a reliable atmospheric dispersion estimation. This, in turn, helps to plan and execute protective measures, e.g., stable iodine prophylaxis. For example, in the case of the Chernobyl accident the radioactivity released reached unexpectedly high altitudes because of the extra heat caused by the burning graphite [Valkama et al., 1995]. The Chernobyl plume would have been clearly distinguishable from the normal background radiation giving important input data for dispersion and deposition calculations [Paatero et al., 2006]. On the other hand, the altitude information about observed airborne radioactivity of unknown origin benefits the inverse modeling to find out the possible source areas of the release. This can be useful, for example, in detecting clandestine nuclear activities or undeclared nuclear incidents, such as the European-wide ruthenium-106 case in the autumn of 2017 [Masson et al., 2019].

An equally significant application of radioactivity soundings is the monitoring of cosmic radiation and related space weather phenomena. The importance of this subject area is constantly increasing because we rely more and more on satellite communication and global satellite navigation systems not to mention air traffic and manned space missions.

A future development area is to incorporate the radioactivity sondes to drones and tethered balloon systems. These could deliver important data, for example, in the case of an ongoing accident in a nuclear facility.

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