Chapter 8

Cosmic radiation and cosmogenic radionuclides

This chapter addresses the effects of cosmic radiation. Cosmic rays are atomic nuclei accelerated to high energy levels, thus creating electrons, gamma rays, neutrons and mesons when interacting with atmospheric nuclei.

Cosmic-radiation flux depends highly on altitude above sea level.

The intensity of cosmic radiation also depends on solar activity and variations in the geomagnetic field; together with other factors, this triggers a 50% variation in production rates of cosmogenic radionuclides on the Earth. Cosmogenic radionuclides are created when cosmic rays interact with gases and particulate matters in the Earth’s atmosphere.

The first section describes the rationale of the Annual Cosmic-Ray Dose Map, which has been developed by the Joint Research Centre of the European Commission. This map has a resolution of 1 km × 1 km and shows that the cosmic-ray dose mean value in Europe is about 390 microsievert (µSv). It also shows a strong correlation between dose and altitude, with the highest dose levels occurring in the Alps, the Pyrenees and in eastern Turkey, all mountain regions.

The dose map section illustrates annual effective dose per capita per country; it shows that Turkey has the highest value (399 µSv/a) and Iceland the lowest (298 µSv/a), with an average of 334 µSv/a for the countries studied.

The next section addresses cosmogenic radionuclides. Concentration of cosmogenic radionuclides depends on the interaction between cosmic radionuclide production, decay, transport and deposit at the Earth’s surface. Examples of different cosmogenic radionuclides are listed, along with illustrative applications showing how measurements of cosmogenic radionuclides can be used. For example, specific radionuclides may be used to date soil sediments and ground water in aquifers. Radionuclides are also useful for studying global climate change and air quality, thus making measurements important regionally and globally.

Monitoring beryllium-7 (7Be) activity concentration is of special interest. This radiisotope is created in the stratosphere and in the upper troposphere, attaches to aerosols and is transported horizontally and vertically by wind and gravity. Then it is removed from the atmosphere through the mechanism that also governs aerosols. Therefore, monitoring 7Be can greatly help in research on mass exchange between the stratosphere and troposphere as well as on local meteorological conditions.
Cosmic radiation and cosmogenic radionuclides

The Earth is constantly bombarded by high-energy cosmic-ray particles which, upon entering the Earth's atmosphere, interact with its gaseous and particulate constituents to produce a variety of cosmogenic radioisotopes. This chapter presents and describes the European Annual Cosmic-Ray Dose Map. It displays the annual effective dose that a person may receive from cosmic rays at ground level. Moreover, the cosmogenic radionuclides will be described, focusing on their application as tracers in environmental studies.

The cosmic radiation is composed of penetrating ionising radiation (both particulate and electromagnetic). By observing them, it has been established that cosmic rays are ordinary atomic nuclei accelerated to very high energy levels (e.g., Drury, 2012) which move through space at almost light speed.

Depending on their origin, the cosmic rays vary greatly in their composition. Almost 90% of cosmic rays are galactic in origin and are composed of high-energy particles (0.1–10 GeV) in the form of protons (87%), helium nuclei (alpha particles, about 12%) and heavy nuclei (about 1%) (Masarik & Breer, 1999). On the contrary, solar cosmic rays, with lower energies (<100 MeV), have a much higher proton content (98%) and lower alpha particle contribution (2%), but do not have any heavier nuclei or energetic electrons. For the physical background and details, we refer to Wissmann et al. (2005) and to Gaisser et al. (2016).

The intensity of cosmic rays presents a wide variety of timescales as well as spatial modulation in the Earth's atmosphere. Many field studies have been designed to assess the understanding of spatial and temporal variations in cosmic rays in the heliosphere, and their relation to effects of the Sun (e.g., Heber et al., 2013). The worldwide neutron monitor network (http://w3.nmdb.eu), which is considered as a reliable network of ground-based detectors of cosmic rays, records many cosmic-ray variations.

Variations in elevation and atmospheric conditions influence the amount of cosmic radiation received. The intensity of the cosmic-ray flux increases greatly as a function of altitude. At 6–9 km above the Earth's surface, it is 30 times greater than at ground level (e.g., Morem, 2012). In addition, cosmic radiation is partly screened and modulated by the Earth's magnetic field and the atmosphere (Turner & Graustein, 2003). The heliospheric environment considerably modulates the intensity of the cosmic radiation reaching the Earth. On short timescales, Forbes decreases (also known as Forbes effects) (Forbush, 1954) are sudden decreases in the intensity of cosmic radiation and in the amplitude of a few percent for several days. They occur after an increase in solar activity, such as coronal mass ejections. On a longer timescale and with stronger influence, the intensity of cosmic rays is influenced by the degree of solar activity and to variations in the geomagnetic field. Many studies have investigated and demonstrated the rigidity dependence of the galactic cosmic-ray and solar activity (e.g. Dorman et al., 2001), reporting that high-sunspot activities are highly correlated with low-cosmic-ray intensity, and vice versa. In particular, the number of sunspots, which can be considered an indicator of disturbances in the Sun’s magnetic field, varies from year to year and exhibits a nearly 11-year cycle. In this line, some works (e.g. Sloan & Wolfendale, 2013, Stashkov et al., 2017) cite solar activity, either directly or through its effect on cosmic rays, as an underestimated contributor to global warming.

All these factors may trigger variations of 50% in production rates of cosmogenic radionuclides on the Earth, which are radioactive isotopes produced and distributed within the Earth's system. Cosmogenic activation strongly depends on the nuclues flux, neutron-to-proton ratio and energies available. For instance, at sea level, radionuclide production is mainly dominated by neutrons at low energies because of charged particles being absorbed in the atmosphere, whereas if materials are flown at high altitude, cosmic flux is much greater, energies at play are larger and activation by protons cannot be neglected (Lal & Peters, 1967).

Production of this kind of radionuclides can be described in three main stages: the production of (i) primary cosmic rays, (ii) secondary cosmic rays (see Figure 8-1) and (iii) nuclues via nucleonic reactions (spallation, neutron capture, or muon capture) in the atmosphere or at Earth's surface (Gosse & Phillips, 2001).

The radionuclides with the highest activity concentrations in the environment are: 8Be, 14C, 10Be and 3He (see Table 8-1).

Primary cosmic rays (mainly protons) are stable, charged particles that have been accelerated to enormous energy levels by astrophysical sources located somewhere in our universe. Secondary cosmic radiation is generated when primary rays penetrate into the Earth's magnetic field and interact with atmospheric gas nuclei. This radiation is composed of high-energy neutrons (e.g. protons and neutrons) and mesons (e.g. muons). In its displacement to the Earth's surface, secondary-ray particles collide with atoms in the atmosphere. The interaction with nuclei causes a ‘spallation’ reaction, i.e. a nuclear reaction where a highly energetic nucleon collides with a target nucleus. Spallation reactions cause the formation of multiple particles (protons, neutrons and clusters). These accelerated particles cause a wave of secondary interactions and, again, spallation reactions as they strike more atmospheric nuclei. The result of this cascade of reactions is the creation of cosmogenic nuclues and high-energy radiation (neutrons), although, through successive interactions, energy is lost until the particles have insufficient energy to cause a spallation reaction upon collision with another particle.

By far, spallation is the most common mode of production of cosmogenic radionuclides in the atmosphere, but other reactions such as fragmentation, induced fission or capture can be very important for some nuclei (Lal & Peters, 1967). Indeed, processes such as neutron and slow muon capture commonly produce cosmogenic radioisotopes (also called terrestrial cosmogenic radionuclides) at the Earth's surface (e.g. Darvill et al., 2013). In this sense, most terrestrial cosmogenic radionuclides are hence formed within the top few centimetres of a rock, as the cosmic-ray intensity flux becomes attenuated with depth.

Notably, natural background radiation is the largest contributor to the average radiation dose received by individuals. Among the natural sources, cosmic rays represent about 13% of the total effective dose received by the population at ground level, with only a very small contribution (0.4%) due to cosmic ray neutrons (UNSCEAR, 2008). However, as altitude increases, there is less air to act as a shield, and hence exposure to cosmic radiation also increases.

### Table 8-1

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-life</th>
<th>Major radiations</th>
<th>Target nuclei</th>
<th>Typical concentrations (Bq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Be</td>
<td>160 a</td>
<td></td>
<td>N, O</td>
<td>2*10^5</td>
</tr>
<tr>
<td>14C</td>
<td>12.2 a</td>
<td></td>
<td>Ar</td>
<td>2 * 10^6</td>
</tr>
<tr>
<td>39Cl</td>
<td>5.7 a</td>
<td></td>
<td>N, O</td>
<td>5*10^3</td>
</tr>
<tr>
<td>10Be</td>
<td>2.7 a</td>
<td></td>
<td>Ar</td>
<td>4*10^3</td>
</tr>
<tr>
<td>14C</td>
<td>12 a</td>
<td></td>
<td>N, O</td>
<td>6*10^3</td>
</tr>
<tr>
<td>39Cl</td>
<td>260 a</td>
<td></td>
<td>Ar</td>
<td>7.6*10^3</td>
</tr>
<tr>
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<td>53.3 a</td>
<td></td>
<td>N, O</td>
<td>7.10*10^5</td>
</tr>
<tr>
<td>34M</td>
<td>35.9 a</td>
<td>K X ray</td>
<td>N, O</td>
<td>6.6*10^3</td>
</tr>
<tr>
<td>37Ar</td>
<td>53.3 a</td>
<td></td>
<td>Ar</td>
<td>3.5*10^3</td>
</tr>
<tr>
<td>39Cl</td>
<td>25.3 a</td>
<td></td>
<td>Ar</td>
<td>2.8*10^4</td>
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<td>Ar</td>
<td>2.5*10^4</td>
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<td>20.9 a</td>
<td></td>
<td>Ar</td>
<td>2.10*10^5</td>
</tr>
<tr>
<td>37Ar</td>
<td>15.0 a</td>
<td></td>
<td>Ar</td>
<td>3.0-5.9*10^5</td>
</tr>
<tr>
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<td>263 a</td>
<td></td>
<td>Ar</td>
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<td>Ar</td>
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<tr>
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<td>30.0 a</td>
<td></td>
<td>Ar</td>
<td>1.5-25*10^5</td>
</tr>
<tr>
<td>34M</td>
<td>32.0 a</td>
<td></td>
<td>Ar</td>
<td>1.5-25*10^5</td>
</tr>
</tbody>
</table>

### Table 8-2

Cosmogenic radionuclides, induced in the Earth’s atmosphere by cosmic rays, listed in order of decreasing half-life.
8.1 Cosmic-ray dose map

8.1.1 Introduction

As described above, interactions between primary particles and atmospheric nuclides produce electrons, gamma rays, neutrons, and mesons (Gnedin, 2001). At ground level the dominant component of the cosmic-ray field is muons with energies mostly between 1 and 20 GeV (UNSCEAR, 2008: Volume 1, Annex B, p. 231). Only 0.05% of primary protons penetrate to sea level (Eisenbud & Geiss, 1997: Chapter 6).

Cosmic radiation (photons, direct ionising and neutron components) represents about 13% of the total effective dose received by the population (UNSCEAR, 2008).

For radiation protection of aircrews and frequent flyers it is important to assess exposure to cosmic radiation on board aircraft (ICRP, 2016; European Communities, 1996a; European Union, 2004). According to the latest Basic Safety Standards (BSS) Directive (European Union, 2013), exposure of aircrew to cosmic radiation should be managed as a planned exposure situation (European Communities, 1996b; European Union, 2009; European Union, 2013: art. 35.5). It is worth noting that the BSS Directive explicitly excludes exposure of members of the public or workers other than air- or space crew to cosmic radiation in flight or in space from the scope of the Directive (see Section 1.2 for further details on legal aspects). However, assessing cosmic-ray exposure at ground level is indispensable to understanding population exposure to ionising radiation (Chen et al., 2009; Sato, 2016b; Poje et al., 2012). Several studies have been conducted to estimate and map outdoor gamma dose rate and their components (i.e. terrestrial, cosmic, radon etc.), using different geostatistical techniques (Yesilkiran et al., 2016; Bossew et al., 2017; Szabó et al., 2017).

The Joint Research Centre of the European Commission has developed the European Annual Cosmic-Ray Dose Map (at 1 km × 1 km resolution) (Cinelli et al., 2017). It displays the annual effective dose, on average over its temporal variability, that a person will receive from cosmic rays at ground level, if she/he spends all the reference time at that elevation. Our simple and easy approach to estimate the cosmic-ray dose, based only on elevation data, has been compared with more sophisticated models, such as EXPAKs (Sato, 2016a) and CAR-6 (O’Brien et al., 1996; O’Brien et al., 2005), which consider both latitude and longitude dependences of the cosmic-ray doses, the water density in the ground (EXPAKs) and the date (solar cycle variation).

Thanks to the availability of maps showing the geographical distribution of the European population (Batista e Silva et al., 2015a, 2013a, 2013b; Lavalle & Jacobs-Crisini, 2016), it is possible to extend the analysis by including population data. In Cinelli et al. (2017), the annual cosmic-ray collective dose, i.e. the total dose incurred by a population, has been evaluated using population data available at the European level. The collective dose is the sum of all individual doses to members of the population. Therefore the population-weighted average annual effective dose due to cosmic rays has been estimated for each European country considered in this study, as well as for all of them together. The coverage of the European Annual Cosmic-Ray Dose Map is conditioned by the availability of the population data (Batista e Silva et al., 2013a, 2013b; Lavalle & Jacobs-Crisini, 2016).

8.1.2 Materials and methods

Dose calculation

Several software programmes are available for calculating cosmic-ray dose rates at aviation altitudes. A detailed overview is given in the EURADOS 2012-2013 report (Bottollier-Depois et al., 2012), and a comparison of programmes assessing radiation exposure of aircrew can be found in the Radiation Protection 173 issue of the European Commission (European Union, 2012). In general, given geographical information (latitude, longitude and altitude) and time (date), these codes are used to calculate the cosmic-ray dose rate. These programmes are mainly used to assess radiation doses for aircrew members.

Here, cosmic-ray dose rate at ground level has been estimated for most European countries, using the same methods as those for UNSCEAR (UNSCEAR, 2008: Volume 1, Annex B, Chapter 2). The photons and direct ionising component of cosmic radiation are considered separately from the neutron ones. The dose rate value may be considered as averages over the 11-year solar cycle, with a range of variation of about 10% (UNSCEAR, 2000: Annex B, Chapter 1, Bouville & Lawder, 1988). The only spatial variable considered is the altitude effect, and not the latitude. The altitude data used in this study are described below.

Photons and direct ionising component of cosmic radiation

To estimate the dose rates from photons and direct ionising component of cosmic radiation at ground level (at different altitudes), the following formula (Bouville and Lowder, 1988) was used:

\[
\frac{1}{E_{1}(z)} = \frac{1}{E_{1}(0)} [0.21 e^{-1.649z} + 0.79 e^{0.4528z}] \]

where \(z\) is altitude in km and \(E_{1}(0)\) the annual effective dose rate at sea level, which is 240 μSv/yr. The latter quantity has been estimated by assuming a dose rate of 32 nGy/h at sea level (UNSCEAR, 2000: Annex A), a value deemed appropriate for the latitudes considered here (between 30° N and 70° N). This value agrees with that of 2.7 nGy/h cited by Wissmann et al. (Wissmann et al., 2005), measured at a latitude of 52° 17’ N and a longitude of 10° 28’ E. Only altitude has been considered, because ground level, doses from photons and the direct ionising component of cosmic radiation depend strongly on altitude, and weakly on latitude. The dose rate is about 10% lower at the geomagnetic equator than at high latitudes (UNSCEAR, 2008: Annex B). At sea level, variation in dose rate has been estimated to be around 10% over the 11-year solar cycle (Wissmann, 2006).

A mean shielding factor of 0.8, and an indoor occupancy factor of 0.8 have been assumed (UNSCEAR, 2000: Annex A).

Neutron component of cosmic radiation

To estimate the neutron component of cosmic radiation is much more complicated. Both altitude and latitude variation should be taken into account because both quantities strongly affect exposure rates. The approach described in UNSCEAR (2000: Annex A, Chapter 2) has been used. In this work a fixed latitude of 50° has been assumed as an average value for Europe, our area of interest.

A neutron fluence rate of 0.013 cm⁻² s⁻¹ at sea level has been assumed (UNSCEAR, 2000: Annex A, p. 28), and its attenuation with altitude is described using Equation 8-2, where \(p\) is the atmospheric depth in g/m². The following relation between height, \(h\), in km, above sea level and atmospheric depth, \(p\), is used:

\[
h = 44.54 - 11.86 \exp \left( \frac{p}{10} \right) \]

A neutron fluence energy distribution weighting factor of 200.5Gy/cm² (that is of 200.5 rad (s/0.71 g/cm²)) has been applied (UNSCEAR 2000: Annex A, p. 28).

As for photons and direct ionising component, a shielding factor of 0.8 and an occupancy factor of 0.8 were assumed for the neutron component (UNSCEAR, 2000: Annex A).

Geographical information: altitude

In order to obtain altitude data for this work, a global digital elevation model (DEM), called the GTG030 dataset (https://www.usgs.gov/media/images/gtopo30-elevation-source-data) was used. This dataset has been derived from several raster and vector sources of topographic information and is georeferenced with a horizontal grid spacing of 30 arc seconds (approximately 1 km).

With the aim of overlaying the altitude data grid and the population data grid, described in the next section, and hence for proceeding with the calculation, it was necessary to transform the original DEM to Lambert azimuthal equal-area (LAEA) projection (http://spatialreference.org/ref/epsg/etr98-etr-laea/). Then, to align the DEM grid with the population grid, the re-projected DEM was resampled using the resample tool in ArcGIS® (ESRI, 2011).

Population data

The European Population Map 2006 (Batista e Silva et al., 2013a, 2013b; Lavalle & Jacobs-Crisini, 2016), created by the Joint Research Centre of the European Commission and by the Centro de Estudos de Geografia e Ordenamento do Território of Portugal, was used as reference in this study. This database was chosen because it is the most recently updated and complete European population grid map.

The data are organised in a digital raster grid that lists the number of residents (night-time population) in 100 m × 100 m cells. It has been produced by downscaling census population data, at the finest resolution available, to the 100 m grid-cell level given pycnophylactic constraints (redistribution or ‘disaggregation’ of data given on input support such as administrative polygons into grid cells, preserving total ‘volume’, i.e. population numbers in this case). This downscaling is done by using data on land use (a refined version of the Corine Land Cover from 2006) and soil-sealing. In addition, the final outcome of this cartographic exercise was validated against reference data.

This level of resolution (100 m × 100 m cells) was then reduced to 1 km × 1 km to compare it with the information included in the European Annual Cosmic-Ray Dose Map (1 km × 1 km cells). This upscaling process was performed using the ‘aggregate’ tool in ArcGIS® (ESRI, 2011) so that each output cell contains the sum of the input cells (100 m × 100 m) enclosed by that cell.
Plate 8: The European Annual Cosmic-Ray Dose Map shows the annual effective dose, on average over its temporal variability, that a person should receive from cosmic rays at ground level, if she/he spends all the reference time at that elevation, considering a shielding factor of 0.8 and an indoor occupancy fraction of 0.8. The annual effective dose resulting from cosmic radiation (photons, direct ionising and neutron components) has been calculated following a simple methodology based only on elevation data. A global digital elevation model (DEM), called the GTOPO30 dataset (https://www.usgs.gov/media/images/gtopo30-elevation-source-data), was used as reference for elevation data, so that the grid used for rendering the map is the same as for the DEM, with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometre). Source: Cinelli et al. (2017).
Cosmic radiation and cosmogenic radionuclides

8.1.3 Discussion and conclusions

Cosmic-Ray Dose Rate Map

The effective dose due to cosmic radiation (photons, direct ionising and neutron components) at ground level has been calculated following the methodology and using the elevation data described above. In turn, the annual cosmic-ray dose at ground level has been calculated by summing the components. The map displays the European annual cosmic-ray dose at 1 km × 1 km resolution. Each value on the map shows the annual effective dose that a person may receive from cosmic rays at ground level if she/he stays there all the reference time with an occupancy factor of 0.8 at that altitude considering a shielding factor of 0.8 (UNSCEAR, 2008). Descriptive statistics of the Annual Cosmic-Ray Dose at 1 km × 1 km resolution are listed in Table 8-2.

The spatial distribution of the cosmic-ray dose rate over Europe clearly reflects elevation above sea level. The map shows that for half the territory considered, the annual cosmic-ray dose is below 360 µSv and for less than 1% above 1 000 µSv. The highest values are found in the highest-lying areas of Europe, such as the Alps, the Pyrenees and in eastern Turkey (with mountains above 3 000 m a.s.l.), reaching a maximum value of 3 955 µSv in the Alps. Intermediate values, ranging from 400 to 900 µSv, also reflect the natural elevation, for instance in Spain with a medium elevation of 600 m or in the European Plain, which stretches 2 000 km from the French Atlantic coast to the Ural Mountains. On the contrary, the minimum value of 301 µSv at sea level coincides mainly with coastal locations. Exceptions are cliffs and mountains diving into the sea, as for example in Norway.

Cinelli et al. (2017) compared this simple and easy approach to estimate the cosmic-ray dose, based only on elevation data, with more sophisticated models, such as EXPACS and CAR-6 (O’Brien et al., 1996; O’Brien et al., 2005), that consider the latitude and longitude dependence of the cosmic-ray doses, the water density in the ground (EXPACS) and the date (solar cycle variation). The results of comparative analysis are satisfactory: the difference (below 15%) between this simple (solar cycle variation) and the more sophisticated EXPACS and CAR-6 models is of the same magnitude as variation due to other parameters (such as solar modulation, building shielding effects, ground condition, indoor occupancy etc.). Thus, we consider that this simple method is adequate for the purpose of developing this European map.

Population exposure

The collective, annual cosmic-ray dose has been calculated for each cell (1 km × 1 km) by multiplying the annual cosmic-ray dose value with the number of residents in that cell.

First, we explored how many persons are exposed to a certain annual cosmic-ray dose (µSv) by dividing the dose rate by the annual reference time of 365 days, and then multiplying by the population density (inhabitants per 1 km × 1 km cell) to obtain the number of persons per 1 km × 1 km cell. The results of this analysis are shown in Figure 8-2a, and they reveal a high degree of correlation between the two variables.

Cinelli et al. (2017) compared the estimated population-weighted average annual effective dose due to cosmic ray for each European country considered here, with those reported by Sato (Sato, 2016a), based on different population data and methodology. The comparison is satisfying, considering that in the two studies different models and different population data are used. However, the differences are comparable with the variation due to solar cycle, measurements uncertainty and so on.
8.2 Cosmogenic radionuclides

8.2.1 Introduction

Since cosmic radionuclides were first discovered, there has been a wide interest in studying their production induced by galactic cosmic rays (e.g. Libby, 1946; Beer et al., 2012). In accordance with the variation in the intensity of cosmic rays, the cosmogenic radionuclide production:

- increases with latitude because the decreasing mass of the incident cosmic ray corresponds to a reduced attenuation of cosmic rays;
- increases with latitude because cosmic rays strike the Earth subparallel to geomagnetic field lines at high latitudes and are thus deflected less than at lower latitudes (Lal & Peters, 1967); and
- varies in relation to the intensity and orientation of the geomagnetic field that modulate the primary cosmic-ray flux (e.g. Pigati & Litten, 2004).

Therefore, the production rate of cosmic radionuclides primarily depends on the cosmic-ray particle flux at the top of the Earth's atmosphere, whereas the concentration of cosmogenic radionuclides is the result of an interplay between four processes, namely production, decay, transport, and deposition at the Earth's surface. Below, examples of different kinds of production of cosmogenic radionuclides are briefly given:

- **Beryllium-10** (10Be) (T½ = 1.6 × 10⁶ a) is produced in the lower stratosphere and upper troposphere by cosmic-ray-induced spallation reactions involving O and N. Peak-production rates occur at approximately 16–20 km at mid-latitudes. 10Be is also generated when spallation products reach crust (mostly constituted by O, Mg, Si, Fe).

- **Beryllium-7** (7Be) (T½ = 5.33 d) is a cosmogenic radionuclide produced primarily in the stratosphere and upper troposphere as a natural product of cosmic ray spallation of nitrogen and oxygen nuclei. Once produced, 7Be rapidly forms BeO or Be(OH)₃ through ionic reactions, then attaches to sub-micrometre atmospheric aerosol particles and diffuses throughout the atmosphere.

- **Carbon-14** (14C) (T½ = 5730 a) is produced in the atmosphere by a low-energy cosmic-ray neutron reaction with nitrogen. Its production rate is the highest of all cosmogenic radionuclides, because nitrogen is the most abundant element in the atmosphere and has a very large thermal neutron absorption cross-section.

- **Phosphorus-32** (32P) (T½ = 14.28 d) and phosphorus-33 (33P) (T½ = 25.3 d) are mainly produced by the spallation reactions induced by neutron on atmospheric argon. In the ocean, an additional source derives from spallation reactions with chlorine and sulphur and, to a lesser extent, with potassium and calcium.

- **Silicon-30** (30Si) (T½ = 160 a) is when neutrons from cosmic radiation bombard 28Ar atoms in the atmosphere. Its daughter product is the strong beta-emitter 30P. The cosmogenic 30Si activity increased about 4 times during the second half of the 1600s, as a result of bomb-produced 30Si.

- **Krypton-81** (81Kr) (T½ = 2.2 × 10⁶ a) and krypton-85 (85Kr) (T½ = 10.6 a) are produced in the upper atmosphere by cosmic-ray spallation involving protons and by reactions from the stable 80Kr and 85Kr isotopes, respectively. So far, there is neither significant subsurface production nor an appreciable anthropogenic source for 81Kr, while 85Kr is also produced by nuclear fusion.

- **Sodium-22** (22Na) (T½ = 2.6 a) is produced by cosmic rays which induce spallation of atmospheric Ar. 22Na is a suitable isotope for detecting solar cycle intensity variations in meteorites, because it is averaging sufficiently well over the 2.6-year period. 22Na is also produced by nuclear weapons tests.

8.2.2 Environmental applications

Froehlich (2010) justified using environmental radionuclides as ideal tracers of environmental processes indicating the following properties:

- A tracer must behave in the system exactly (physical and dynamic characteristics) as the traced material in the particular process to be studied.
- A tracer must have at least one property that distinguishes it from the tracer material (e.g. radioactive decay). This definition implies that an ideal tracer should have neither sources nor sinks in the system other than those to be studied.
- A tracer should move with the same velocity in the system (air, water, soil and sediment) as the material to be traced.
- A tracer should not be confused with trace elements, which have no corresponding major or minor components; thus, the behaviour of trace elements depends on their own concentration and properties.

Specifically, a wide range of cosmogenic radionuclides can be used as tracers since their source functions, together with the large range of different physical and chemical properties and half-lives, are fairly well known (Table 8-1); in particular, due to their different properties, the ultimate choice of the appropriate tracer depends on the physical, chemical, geological and biological process at hand.

Variation in half-lives (extending from seconds to millions of years) as well as their incorporation in the different Earth system reservoirs including the atmosphere, the hydrosphere, the biosphere, the cryosphere and the lithosphere allow the use of cosmogenic radionuclides as chronological markers and general tracers. Excellent summaries of the principles of cosmogenic radionuclide dating include Cerling & Craig (1994), Kurz & Brook (1994), Gosse & Phillips (2001) and Dunai (2010).

There is an extensive bibliography on the use of cosmogenic radionuclides in dating sediments (e.g. Granger & Musketa, 2001; Balco et al., 2005; Von Blankenburg, 2005), continental ice sheets (e.g. Lal & Jull, 1992; Balco et al., 2007), ground water (e.g. Fröhlich, 1990; IAEA, 2013; Kazemi et al., 2005), timing of geologic processes and rates of change in the Earth's surface (e.g. Fabel & Haroor, 1999; Gosse & Phillips, 2001) and atmospheric processes (e.g. Young et al., 2009; Lal & Basrakaru, 2012). More information is available in Davi (2013), who presents a complete summary of the range of applications for which cosmogenic radionuclide dating have been used (e.g. volcanic landforms, floods, desert pavements).

For example, the long half-life of 14K allows radiometric dating in the 50,000 – 1,500,000-year age range (Loesli & Oeschger, 1969). 14K has already been used to determine the residence time of ground water in old aquifers (e.g. Sturchio et al., 2004), while its trapping in bubbles in glacial ice allows it to be used to date polar ice (e.g. Buerzert et al., 2014). The use of this cosmogenic radionuclide allows accurate dating of up to 1.5 million-year-old ice. Other examples of dating the terrestrial glacial record is the use of 14C and 9Be ratios in quartz to determine the age of deeply buried palaeosols and underlying till layers (Balco et al., 2005), or to analyse millennial-scale glacial advances by insomnic cosmogenic, 10Be, 14C, and 9Be exposure ages, supported by the analysis of 14C ages (Kaplan et al., 2004).

Rihmalki & Libarking (2007) discuss the theory behind cosmogenic-nuclide palaeoaltimetry, sampling strategies, and practical limitations of the technique. Palaeoaltimetry is a method for estimating quantitatively past elevation of the land surface. The terrestrial cosmogenic nuclides are produced in rock when secondary cosmic rays interact with rock at the Earth’s surface. In particular, Rihmalki & Libarking (2007) present the terrestrial cosmogenic nuclei that are of interest to palaeoaltimetry (stable nuclides: 14N, 13Ar, 36Ar; radiocarbon 14C, 9Be, 10Be, 11B, 11C, 13C, 14C, 15N, Kr, Ar, and 81Kr). Summaries of other geological applications of cosmogenic isotopes are included in Gosse & Phillips (2001) and Bierman (1994). 10Be and 26Al cosmogenic radionuclides have been measured to investigate the erosion rates in selected rock samples from the Antarctic mountains (Nishizumi et al., 1991), and to measure middle Pleistocene erosion rates in buried alluvial sediments (e.g. Balco & Stare, 2005).

Distributions of both cosmogenic and anthropogenic 14C have also been used to study the interaction of the atmosphere with the surface water layer and the oceanic deep waters (e.g. Bard et al., 1994; Matsumoto & Yokoyama, 2013). 14C is also widely used in dating soil organic matter (SOM) (e.g. Persenda et al., 2001; Blyth et al., 2011) and in studies of the controversial subject, mainly due to the complexity of the soil formation. The main problem with 14C dating of the SOM is the difference in ages due to the invasion of roots, infiltration of organic compositions dissolved in water, influence of microorganisms, and of the soil fauna, resulting in the rejuvenation of the estimated ages (Nowaczyk & Pazdur, 1990). Lal et al. (1970) demonstrated that 32Si could be used in ground-water studies, where a comparison of 32Si and 14C ages would be extremely valuable for delineating ground-water characteristics.

Measurements of cosmogenic radionuclides at mountain peak stations out of the tropospheric boundary layer, i.e. the station lies freely exposed in the advection layer, can be used to draw conclusions about the atmospheric circulation and exchange processes between atmospheric layers. These kinds of location are exposed to air mass transport from far away and, hence, can also serve as good early warning monitoring stations for radioactivity. A good example using these strategic measurement sites to study chemical-physical characteristics and climatology of the free troposphere, as well as to carry out studies regarding stratosphere-to-troposphere exchange (STE), is the Italian climate observatory ‘O. Vittori’, which forms part of the Global Atmosphere Watch network of the World Meteorological Organization (WMO-GAW, 2004) global station ‘Monte Cimone’ (Cristianelli et al., 2018).

Concentrations of 14C at different latitude belts, have provided deeper insight into the time scales of interhemispheric exchange in the troposphere, rates of meridional transport within the two hemispheres, mixing time scales of air masses within Hadley and Polar cells (Lal, 2002). 10Be and 9Be (Lal & Peters, 1967) are considered as tracers of stratospheric-upper tropospheric influence and subsidence processes, as well as of air mass transport and can be used to test global circulation models (e.g. Liu et al., 2001). In turn, once their potential to correctly reproduce the radionuclides pattern is established, these can be used to analyse the impact of transport, convection and deposition on their seasonal and interannual variability (e.g. Brattich et al., 2017). Due to differences in tropospheric lifetimes, concentrations and isotopic ratios of different nuclides (e.g. 9Be/10Be, 11B/11C, 10Be/Na) may be used as tracers of mid-latitude wet deposition and storm type, air mass history, and season (Kriess, 1994). These studies also show the need for integrating the tracer-based information, i.e. their temporal and spatial variability, with meteorological information in order to fully understand the atmospheric dynamics. In this sense, and as an example, Heikila et al. (2008) studied production and climate-related changes of 10Be and 9Be transport and deposition in polar regions during the last millenium.
8.2.3 Databases

The previous section covered a wide spectrum of in-situ applications of cosmogenic isotopes, together with specific and generic examples of exposure dating and erosion. Since then, it has been recognised that cosmogenic radionuclides are useful in a global monitoring network for atmospheric composition to support global climate change and air-quality research, and therefore they are measured at many of the regional, global, and contributing partner stations in the WMO-GAW network. Because cosmogenic radionuclides are important as tracers and contributors to natural background radiation, measurements of these nuclides are incorporated into databases. In general, environmental radionuclide databases contribute to scientific knowledge of the processes affecting radionuclide distribution and the sources introducing radionuactivity into the environment. They provide critical inputs to the evaluation of environmental radionuclide levels at regional and global scales, deliver information on temporal trends of radionuclide levels and identify gaps in available information. This information is used as a basis to estimate radiation doses to local, regional and global human populations and biota. The purpose of this kind of repository is to provide a better understanding of the past, which is key to predicting the future.

1958 example of worldwide monitoring and repository in large databases of cosmogenic radionuclides (e.g. ²³⁰Th, ²¹⁰Po, ²³⁴U) is the International Monitoring System (IMS), set up by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO; www.ctbto.org/). CTBTO is an international organisation which aims to achieve the object and purpose of the Comprehensive Nuclear-Test-Ban Treaty (CTBT), to ensure the implementation of its provisions, including those for international verification of compliance with the Treaty and to provide a forum for consultation and cooperation among its Member States. The IMS consists of 321 monitoring stations and 16 laboratories built worldwide to monitor the planet for any sign of a nuclear explosion conducted on Earth – underground, underwater or in the atmosphere and polar. The radionuclide network comprises 80 measuring stations, of which more than 60 are certified. At a global level, radionuclide stations aim to monitor radioactive aerosols and radioactive noble gases. Another example of a cosmogenic radionuclides repository (such as ⁷Be) is the Radioactivity Environmental Monitoring Database (REMDB) https://rem.jrc.ec.europa.eu/RemWeb), which is maintained by the Joint Research Centre of the European Commission, located in Ispra, Italy. Further details on this database are given in the box on the right.

8.2.4 An overview of research activities on beryllium-7

This section provides an overview of research activities undertaken by the scientific community based on beryllium-7 (⁷Be) activity concentration data. These results represent attempts to understand the distribution of ⁷Be better, as well as its use as a tracer of different atmospheric processes. Here, we focus on ⁷Be because:

- Its high activity concentration in the air (troposphere), the highest one for any cosmogenic radionuclide (see Table 8.1),
- Its wide use in understanding the roles of transport and/or scavenging in controlling the behaviour of radioactivity active gases and aerosols (research of 1996),
- And its contribution, however small, to annual effective doses: 0.035 μSv (UNSCEAR, 2000).

Briefly, ⁷Be is a cosmogenic radionuclide generated by cosmic-ray spallation reactions with nitrogen and oxygen (Lal et al, 1999). It is produced, mainly in the stratosphere (67%) and secondarily in the upper troposphere, where ⁷Be rapidly attaches to ubiquitous submicron aerosol particles in the ambient air (e.g. Ioannidou et al, 2005). Aerosols are transported by wind and redistributed via gravitational sedimentation and are ultimately removed mainly by wet and secondary by dry deposition in the lower troposphere. Therefore, in addition to its radiocative decay, ⁷Be is removed from the atmosphere by the same depositional mechanisms as for fine aerosols.

Several factors affect ⁷Be distribution in surface air (Field et al, 1989), such as air-mass exchange between the stratosphere and troposphere, vertical transport in the troposphere, horizontal transport described by trajectories and mid-latitudes to the tropics and polar regions, as well as regional-local meteorological conditions and their seasonal variations (e.g. rainfall, temperature and winds). All these parameters make it difficult to describe ⁷Be activity in surface air.

Because of its global distribution in surface air, its unique source and sink characteristics, ⁷Be is considered as a suitable tracer for atmospheric dynamics. For example, Teréz & Kalinowski (2017) analysed ⁷Be activity concentrations from the International Monitoring System (IMS) to visualise the location of the Hadley-Ferrel circulation zone (HFZ), the Polar-Ferrel circulation zone (PFCZ) and the Intertropical Convergence Zone (ITCZ) through ⁷Be maps covering the whole world and demonstrating the seasonal shift of these zones at longitudinal bands over the course of one year. Usoskin et al. (2009) analysed short-term production and synoptic influences on atmospheric ⁷Be concentration by using a series of daily measurements of ⁷Be concentration in near-surface air at eleven sites all around the world.

Many studies have described airborne ⁷Be activity concentrations and temporal evolution in Europe (in italics are indicated works carried out at high-altitude stations):

- Croatia: Franic et al. (2008);
- Czech Republic: Rulík et al. (2009), Pochsl et al. (2010);
- Finland: Leppanen et al. (2010, 2012); Leppanen & Paatero (2013); Ajtyt et al. (2016), Sarvar et al. (2017);
- France: Bonhomme et al. (2016);
- Greece: Papasterianou & Ioannidou (1991); Gerassopoulos et al. (2003); Ioannidou et al. (2005); Papandreou et al. (2011); Ioannidou (2012); Ioannidou et al. (2014);
- Greenland: Dibb (2007);
- Italy: Toffolo et al. (2014); Brattich et al. (2017a,b); Cannizzaro et al. (2020a,b);
- Monaco: Pham et al. (2011), Pham et al. (2013);
- Portugal: Carvalho et al. (2013);
- Russia: Burenin et al. (2007);
- Serbia: Todorovic et al. (1999, 2005, 2010); Krmar et al. (2007), Ajtyt et al. (2013), Saroalvarez et al. (2014); Radoja et al. (2016);
- Slovak Republic: Durana et al. (1996); Sykora et al. (2017);
- Spain: Rodenas et al. (1997); Azahra et al. (2003, 2004); Lozano et al. (2011, 2012); Dueñas et al. (2009, 2011); Piñero García et al. (2012); Rodas Ceblanos et al. (2015); Grossi et al. (2016); Bas et al. (2016, 2017); Gordo et al. (2015); Hernandez-Ceballos et al. (2017);
- Sweden: Alldan et al. (2001); Kulén (2006);
- Switzerland: Zans et al. (1999); Gerassopoulos et al. (2005), Steinmann et al. (2013);
- United Kingdom (England only): Dash et al. (2005); Likuku (2006).

In addition to the previous studies, several others deal with long-term distribution of the cosmogenic isotope ⁷Be in surface air all over Europe. Kulén et al. (2006) analysed ⁷Be collected on collecting filters over three decades, 1972-2003, at five sampling stations located in Sweden, the Czech Republic and France. At European level, Hernandez-Ceballos et al. (2015) characterised the spatial and temporal distribution of the ⁷Be activity concentration in surface air for 54 sampling sites available in the REMdb using data from 1984 to 2011. Moreover, Hernandez-Ceballos et al. (2016) applied a cluster analysis to identify spatial patterns in ⁷Be concentrations in Europe. Results showed the presence of three distinguishable cluster groups (south, central and north of Europe, respectively).
clearly differentiated in terms of both intensity and time trends of concentration levels, and with a latitudinal distribution of the sampling stations. These regions were also identified in an analysis of seasonal and spatial patterns of extremely high 7Be surface concentrations (values exceeding the 95th percentile in each site) recorded over the 2001–2010 period across Europe (Ajtić et al., 2017). This study reported that most of the extremes occur during the March–August period, while at least 10% of the total number of extremes takes place during autumn and winter (Figure 8-4). The extreme 7Be events are thought to be caused by particular meteorological conditions, different from the average European patterns (Ajtić et al., 2017; Hernández-Ceballos et al., 2017). In the northernmost parts of Europe, the Scandinavia teleconnection index seems to be a good indicator of these occurrences (Ajtić et al., 2016, 2018).

Furthermore, some of the extremely high 7Be surface concentrations in Scandinavia during winter were linked to a perturbed Stratosphere–Troposphere Exchange (STE) that accompanies sudden stratospheric warmings of the Arctic polar vortex (Ajtić et al., 2018). Hernández-Ceballos et al. (2016) investigated the connection between 7Be activity concentrations and heat-wave events in Spain. On average, the 7Be activity concentrations during these events show an increase of around 20% in central and southern areas of Spain and a decrease of 13% in northern parts. This increase was associated with the arrival of distant westerly air masses.

The behaviour of 7Be activity concentrations at high altitude sites, under the direct influence of air masses from the free troposphere, has often been investigated to understand stratosphere-to-troposphere exchange dynamics (Gerasopoulos et al., 2001, 2005; Zanis et al., 2003; Bourou et al., 2011; Jasuiuolus & Werhofen, 2005; Simon et al., 2009; Tositti et al., 2014; Brattich et al., 2017; Cristofanelli et al., 2018). In particular, Gerasopoulos et al. (2001) characterised the climatological features of 7Be in combination with a set of meteorological and atmospheric parameters such as the tropopause height, relative and specific humidity, and with 3D back-trajectories at four European high-altitude sites. Because of the latitudinal variation of 7Be production, 7Be activity concentrations in northern Europe have also been extensively analysed. For example, Leppanen & Paatero (2013) analysed the surface air 7Be concentrations in Finland according to solar cycle. Sarvan et al. (2017) investigated a 7Be dataset for Helsinki, Finland, that spanned 25 years and found that over short time intervals, the activity concentrations were strongly autocorrelated, while over longer intervals, there were periods of anticorrelation in the data records, which led them to conclude that changes in the activity concentrations of this radionuclide and events with time-scales of several years. Ajtić et al. (2016) also analysed the Helsinki 7Be records, but from a perspective of extremely high values occurring during the colder half of the year. In these works, the impact of higher tropopause height (TPH) on 7Be and therefore on the spatial distribution of 7Be in Europe, was also suggested. Further, a number of studies have shown a strong link between temperature and 7Be surface concentrations (Ajtić et al., 2018; Iarocci et al., 2005) that, in turn, suggests that this radionuclide could be one of the climate change indicators. A study of Jiwen et al. (2013) showed a decreasing trend of 7Be activity concentration over 1970–1997, which could be a result of changes in vertical transport, caused by changes in temperature, but also changes in precipitation patterns.

The impact of the 11-year solar modulation on the 7Be concentrations in air is well known. As 7Be is produced in the atmosphere through interaction of cosmic rays with atmospheric molecules, its production rate varies with solar modulation of galactic cosmic rays invading the heliosphere (Masarik & Beer, 1999), which is controlled by the solar magnetic field and, in turn, by solar activity (Figure 8-5). Therefore, the 7Be concentration is inversely related to the number of sunspots.

At surface layers, 7Be activity concentrations may vary due to various atmospheric processes. Generally, the increase in 7Be in ground level air from March to May is ascribed to the more efficient and higher frequency of STE, whereas the further increase in 7Be during summer is due to the stronger convective mixing and TPH. The influence of the tropopause height on 7Be was investigated in detail by Iarocci et al. (2014), where the time-lag between the elevation of tropopause and the concentration of 7Be in near-surface air is defined. Following the same methodology, Hernández-Ceballos et al. (2016) addressed the impact of tropopause height on 7Be distribution and evaluated the time-lag between tropopause height and 7Be at European level. These results show a larger tropopause height influence on 7Be during summer and a larger spatial variability of TPH on 7Be levels with a clear gap between southern and northern Europe in the area of the polar front jet. 7Be has been used as an indicator of parcels of stratospheric air that have entered the troposphere, especially in connection with other tracers to investigate ozone (O3) behaviour and to investigate vertical transports from the stratosphere to the troposphere. In fact, in atmospheric studies, 7Be has been used to investigate STE and STT (Stratosphere-to-Troposphere Transport) events, starting from the pioneering work of Reiter et al. (1983) at Zugspitze in Germany. STE events, sometimes associated with mid-latitude tropopause folds, are characterised by anomalously high potential vorticity (PV), high ozone, and low water vapour mixing ratio. Previous studies carried out at high-mountain sites especially within the VOTALP (Vertical Ozone Transport in the Alps) and STACATD (Influence of STE in A Changing Climate on Atmospheric Transport in the Alps) (e.g., Zanis et al., 1999; Cristofanelli et al., 2006, 2009) indicate that air mass transport from the stratosphere to surface levels occurs either in a direct way, with vigorous vertical transport (tropospheric age < 2 days), or in an indirect way, with a multi-step of synoptic and regional transport processes when the STT area is located thousands of kilometres away (longer tropospheric age). Several studies present case of concurrent STE events down to the surface in which high concentrations of the cosmogenic radionuclide 7Be are measured. While Gerasopoulos et al. (2006) presented a complex case in northern Greece, Hernández-Ceballos et al. (2017) identified vigorous stratospheric to-tropospheric events in Spain; Galari et al. (2003) investigated STE events over the southeastern Mediterranean region, during 2000–2002. An overview of 7Be data collected simultaneously at four high altitude stations in Europe (Monte Cimone, Italy; Sonnblick, Austria; Jungfraujoch, Switzerland; and Zugspitze, Germany) (Gerasopoulos et al., 2001) have provided a tool for analysing STE characteristics on a larger-than-usual spatial scale.

Using 7Be together with other tracers such as the 137Cs nuclide, which like 7Be, travels attached to fine aerosols and therefore follows the same rate of fine stable aerosol (Brattich et al., 2016), proved useful (especially used as activity ratio) for understanding regional circulation processes, as well as processes controlling PM10 variability at the Monte Cimone site (Tositti et al., 2014; Brattich et al., 2017b; Cristofanelli et al., 2018).

In addition to its use as radiotracer in atmospheric studies or to regional circulation understanding, 7Be has been used as a tracer in studies of soil erosion (e.g. Walsburg & Murray, 1996; Deconinck et al., 2012) or soil redistribution (Schuller et al., 2006), even though the Food and Agriculture Organization (FAO) of the United Nations and IAEA with a dedicated joint research programme indicated 137Cs as tracer to measure soil erosion (FAO, 2017). Also, soil redistribution (Schuller et al., 2006) measured 7Be concentration in soils and grass in the Thessalonia area of Northern Greece in order to study their fate in natural ecosystems. Iurian et al. (2013) analysed the spatial distribution of 7Be in soils of Lower Austria after heavy rains to estimate the erosion rates, based on the assumption that the deposition of 7Be fallout associated with the erosive event is spatially uniform.
8.2.5 Conclusions

All living organisms are continuously exposed to a background radiation from the air (cosmic-ray and cosmogenic radionuclides), soil, rock, water, and building materials. The amount of background radiation differs as a function of elevation, the amount of nuclei in the soil, and the geographical conditions of different regions.

The source functions, together with a wide range of different physical and chemical properties and half-lives of the cosmogenic radionuclides, are fairly well known. Hence it is possible to select the most appropriate tracer, depending on the specific study to be carried out, and, specifically, in order to understand better the physical, chemical, geological and biological processes at hand.

For example, cosmogenic radionuclides can be used to determine directly the timing of events and rates of change in the Earth’s surface. This is achieved by measuring their production due to cosmic-ray-induced reactions in rocks and sediments. Numerical simulations of atmospheric production rates of radionuclides, as a function of altitude, latitude, solar and geomagnetic fields, have recently progressed; this has helped to understand this production process better.

Due to the importance of cosmogenic radionuclides as tracers and their contribution to natural background radiation, they are measured and the results are compiled and managed in databases. The purpose is threefold to provide critical input for evaluating environmental radionuclide levels at regional and global scale; to deliver information on temporal trends of radionuclide levels; and to identify gaps in available information. This will foster a better understanding of the past, which is key to predicting the future.

Since it appears to be an excellent tracer for atmospheric circulation, $^{7}\text{Be}$ is measured routinely at surface monitoring stations all around the world. Temporal variations in surface $^{7}\text{Be}$ radioactivity have been reported from many of these sites. Considering its relatively short half-life of 53.3 days, it is a useful tracer for studying air mass motions on short timescales in the atmosphere, as well as processes controlling its activity concentration in surface air, such as wet and dry removal.
Case study: An overview of beryllium-7 concentrations in Europe in 2006

The following case study analyses beryllium-7 (7Be) concentration in a number of EU Member States using data from 2006 as submitted to the REM Database. This year has been chosen as reference because it has the highest number of 7Be measurements of all those covered by the annual monitoring reports on environmental radioactivity prepared by the Joint Research Centre of the European Commission. Only the stations that reported at least one result per month have been considered (Figure 8-6).

The frequency distribution shown in Figure 8-7 indicate the existence of a large variability in 7Be activity concentrations over these countries. All sampling stations display a positive asymmetrical distribution (positively skewed) of the values, as the upper quartile (P75) is farther from the median than the lower one (P25). This fact confirms the greater variability observed for higher values (P50 upward) than for lower values (P50 downward). This result is also confirmed by observing that the mean is always larger than the median, implying the dominance of low 7Be values as well as the large impact of occasionally high values.

The seasonal variability of surface-air 7Be concentration is displayed for each station in Figure 8-8. We point out the similarity of observed trends in all stations of increasing activity in spring and summer and decreasing in winter and autumn. Therefore, this indicates the existence of a strong seasonal pattern for 7Be. Different reasons for the seasonal variations in the surface-air 7Be concentrations (Figure 8-8) include:

1. seasonal variations in the amount of precipitation;
2. increased stratosphere-to-troposphere exchange during the late winter and early spring; and
3. increased vertical transport of 7Be from the upper troposphere to the middle and lower troposphere, due to decreased stability of the troposphere during summer months.

Figure 8-6. Map of the sampling stations for 7Be concentration in airborne particulates, as reported by EU Member States to the REM Database (reference year 2006).

Figure 8-7. Box-plots of 7Be frequency distribution at different sampling stations in a number of EU Member States for 2006. The stations are ordered by latitude from low (left side) to high (right side). P stands for Percentile. The rectangle represents 50% of the data (interquartile range from 25th to 75th percentile), the continuous horizontal line inside the rectangle identifies the median (50th percentile), the small circle and square identify the 10th and 90th percentiles respectively, and the whiskers extend each end of the box to the 5th and 95th percentiles, respectively.

Figure 8-8. Seasonal average of 7Be concentrations at the different sites. The stations are ordered by latitude from low (left side) to high (right side).

The seasonal variability of surface-air 7Be concentration is also confirmed by observing that the seasonal average of surface-air 7Be concentration is higher in spring and summer and decreasing in winter and autumn. Therefore, this indicates the existence of a strong seasonal pattern for 7Be. Different reasons for the seasonal variations in the surface-air 7Be concentrations (Figure 8-8) include:

1. seasonal variations in the amount of precipitation;
2. increased stratosphere-to-troposphere exchange during the late winter and early spring; and
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