Cosmogenic $^7$Be: Atmospheric Concentration and Deposition in Japan

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Interactions between cosmic rays and atmospheric components produce various nuclear fragments. Cosmogenic $^7$Be distributes uniformly in the atmosphere which covers all over the earth. Thus, the vertical and horizontal transport of $^7$Be in the stratosphere as well as troposphere will work as an effective tracer with half life of 53.3 days. Many studies have been conducted on $^7$Be atmospheric concentration and deposition onto the ground. Generally, the atmospheric $^7$Be concentration and the $^7$Be deposition show seasonal and yearly variations which are controlled by solar activity, cosmic ray intensity, atmospheric circulation and other mechanisms such as "washout" and "rainout". This paper presents atmospheric $^7$Be concentration and $^7$Be deposition data obtained by the authors as well as other investigators. The variations of atmospheric $^7$Be concentration and $^7$Be deposition and their influential factors are also reviewed.

KEY WORDS: Beryllium-7, Cosmogenic Nuclide, Stratosphere, Tropopause, Troposphere, Seasonal Variation, Deposition.

I INTRODUCTION

Earth is surrounded by various particles called cosmic rays, composed of electrons, protons and alpha particles.1) Cosmic rays into the earth's atmosphere, born in explosion of super nova and the sun, partly born as secondary particles, are composed of highly energetic particles (protons, alpha particles and heavier ions). But they do not move freely due to Cut-off effects of the geomagnetic field, of which energy is below several MeV, but cosmic rays of above this energy allow particles enter into the atmosphere along the geomagnetic lines of force.

About 90% of the particles are composed of protons, and the remainders consist of charged alpha particles. These charged particles bear electrons as well as neutrons through cascade process when they collide with atoms of upper atmosphere. When protons and/or neutrons collide with atmospheric components like carbon, oxygen, nitrogen, argon and so on, they produce various nuclear fragments like $^1$H, $^7$Be, $^{10}$Be, $^{14}$C, $^{22}$Na, $^{32}$P, $^{33}$P and $^{35}$S.2, 3) These cosmogenic nuclides reach to the earth continuously. Among all, $^7$Be is most important cosmogenic nuclide of beta decay (electron capture) as $^7$Be emit gamma rays of 0.478 MeV (branching ratio: 10.5%, and decay constant: $1.513 \times 10^{-8}$ s$^{-1}$), which is easily detectable. Beryllium-7 is produced according to the following reactions $^4$−$^6$(Fig. 1):

Maximum concentration of $^7$Be is found in the upper stratosphere.7) And $^7$Be also depends on geomagnetism.

Production rate of $^7$Be in troposphere and total atmosphere are respectively $2.7 \times 10^{-2}$ atoms cm$^{-2}$ sec$^{-1}$, and $8.1 \times 10^{-2}$ atoms cm$^{-2}$ sec$^{-1}$, and global inventory is 3.2 g.7) Thus produced $^7$Be are attached to aerosol, and conduct dispersion and movement with mean residence time of about 7.4−8.9 days.8)

Beryllium-7 was found for the first time in rain by Arnold and Al-Salih.9) After this, Cruikshank et al.10) reported that $^7$Be was detected in atmospheric aerosol. There have been lots of reports on $^7$Be, in which $^7$Be were detected in atmosphere as well as in rain.

Beryllium-7 distributes uniformly in the atmosphere which covers all the earth. Therefore, $^7$Be's vertical and horizontal transport in the stratosphere as well as troposphere will work as an effective tracer with half life of 53.3 days, both providing space and temporal information. Here, environmental movement and morphological characteristic are reviewed based on continuous measurement of atmospheric concentration of $^7$Be and its deposition.

Fig. 1 Generation equation of $^7$Be atom by proton and neutron.

II ATMOSPHERIC $^7$Be CONCENTRATION

To know $^7$Be concentration and its latitudinal distribution, periodicity of seasonal and yearly variations, effectiveness of $^7$Be with regard to inflow mechanism to troposphere from...
stratosphere, and effectiveness of $^7$Be as a tracer of stratospheric air are examined. Atmospheric $^7$Be concentration is examined by gamma ray spectrometry of air samples, collected on quartz fiber seat of a high volume air sampler.

1. Distribution of $^7$Be concentration

Atmospheric $^7$Be concentration shows minimums at along the equator, area between 50°N – the Arctic and area between 40°S – the Antarctic. It also makes the maximum at middle latitude. Various sampled points and data are summarized in Fig. 2 and Table 1.

Beryllium-7 concentration in Japan are 0.3 – 9.8 mBq/m$^3$, and mean are 3.97 – 5.90 mBq/m$^3$. Such values in foreign countries, of which latitudes are similar to Japan, are 0.32 – 18.3 mBq/m$^3$ and mean are 4.16 – 5.02 mBq/m$^3$. In lower latitudes, reported values distribute at around 0.20 – 14.92 mBq/m$^3$ and mean are 4.10 – 5.21 mBq/m$^3$. In this way, $^7$Be concentration in low and middle latitude areas are similar each other. In high latitude, values are at around 0.042 – 8.16 mBq/m$^3$ and mean are 1.89 – 2.50 mBq/m$^3$ as reported. The value in high latitude area seems to be lower than the values in low

Table 1  Summary of atmospheric $^7$Be concentrations (mBq/m$^3$).

<table>
<thead>
<tr>
<th>Period</th>
<th>Place or Country</th>
<th>Latitude</th>
<th>Mean or Median, (Range)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994 – 1998</td>
<td>Kuwait</td>
<td>29°N</td>
<td>5.21, (0.20 – 14.92)</td>
<td>AI-AMZI et al. (2001)</td>
</tr>
<tr>
<td>1999 – 2007</td>
<td>Dazaifu</td>
<td>33°N</td>
<td>4.3, (0.3 – 9.8)</td>
<td>Present study</td>
</tr>
<tr>
<td>1979 – 1992</td>
<td>Sakai</td>
<td>35°N</td>
<td>5.43, (1.8 – 9.6 )</td>
<td>MATSUMI and MEGUMI (1994)</td>
</tr>
<tr>
<td>1992 – 1999</td>
<td>Spain</td>
<td>36°N</td>
<td>4.16, (2.5 – 6.0)</td>
<td>DUENAS et al. (2005)</td>
</tr>
<tr>
<td>1995 – 2002</td>
<td>Italy</td>
<td>38°N</td>
<td>4.94, (0.32 – 15.3)</td>
<td>CANNIZZARO et al. (2004)</td>
</tr>
<tr>
<td>1987 – 2001</td>
<td>Greece</td>
<td>40°N</td>
<td>5.02, (0.47 – 12.70)</td>
<td>IOANNIDOU et al. (2005)</td>
</tr>
<tr>
<td>1996 – 2001</td>
<td>Serbia</td>
<td>44°N</td>
<td>(0.6 – 18.3)</td>
<td>TODOROVIC et al. (2005)</td>
</tr>
<tr>
<td>1975 – 2000</td>
<td>Sweden</td>
<td>67°N</td>
<td>1.89, (0.042 – 8.16)</td>
<td>KULAN et al. (2006)</td>
</tr>
</tbody>
</table>

The part of shadow shows measurement points in Japan.
and middle latitude areas. Though production rates of $^7$Be is higher in high latitude, altitude of tropopause becomes lower as the latitude becomes higher, and air exchange between stratosphere and troposphere becomes less. In addition, based on measurements on the mean meridional circulation, upward air motion in low and high latitude in troposphere forms large scale circulation entering into stratospheric interior. And air falls down to middle latitude stratosphere, and finally reach to 30°–50° latitudes in troposphere. Therefore, $^7$Be concentration in middle latitudes (30°–50°) is about 30% higher than that in low latitudes (0°–30°). And, the concentration in high latitudes (60°–90°) is about 20% lower than that in low latitudes. All these facts clearly indicate that the maximum $^7$Be concentration in atmosphere appears in middle latitudes.

Yearly variation of $^7$Be concentration in the atmosphere observed in Dazaifu (33°N), obtained by NARAZAKI, is shown in Fig. 3. The concentration in the atmosphere in 1999–2007 are 0.3–9.8 mBq m$^{-3}$ and mean is 4.3 ± 1.9 mBq m$^{-3}$, and about 82% lie between 2.0–8.0 mBq m$^{-3}$. This mean value is not largely different from the worldwide mean 3.5 mBq m$^{-3}$, based on 79 stations.

The value is similar to $^7$Be concentration in other areas in Japan, and in various countries in middle latitudes. All these facts indicate that, at least in Japan, no large difference of atmospheric concentration of $^7$Be exists, and that values are in the similar level unless there is large change of meteorological factors like rain.

2. Seasonal variation of $^7$Be concentration

Decrease of atmospheric $^7$Be is considered due to decrease of aerosol adsorbed $^7$Be by rain, and due to shorter residence time when atmospheric aerosol is increased. Moreover, atmospheric $^7$Be concentration is influenced by topography and atmospheric pressure as well as other meteorological factors. These are caused due to inflow of stratospheric air, variation of atmospheric stability in troposphere, variation of air mass and air flow, and scavenging by rain. It is also pointed out that flow of stratospheric air to troposphere is associated with formation of low-pressure trough.

Atmospheric $^7$Be concentration in Dazaifu has got significant monthly variation, of which power analyses give 6 months and 12 months variation (Fig. 4, left). Inverse Discrete Fourier Transform provides 6 months and 12 months cycles and the composed value of thus obtained sinusoidal wave function well reflects real time variations, of which frequency of $^7$Be concentration well coincides with the monthly variation of $^7$Be (Fig. 4, right). Namely, atmospheric $^7$Be concentration is relatively higher in winter, spring and fall compared to summer. That is due to formation of trough, downward air motion by Hadley circulation, deposition of $^7$Be from the stratosphere through folding and gaps of tropopause.

On the other hand, in summer when stable high air pressure over Pacific, which stagnates over tropical sea, covers throughout Japan, $^7$Be concentration decreases largely from the yearly mean. Harvey and Mathews pointed out a strong inverse correlation between $^7$Be concentration and precipitation. In summer in Japan, when there is lots of rain, aerosol to which $^7$Be is adsorbed causes decrease of $^7$Be concentration, which
is called “washout” effect. In summer, airflow from south or south-west overwhelms, and its gradient of air pressure becomes small, and fallout of aerosol becomes weakened in wet updraft over ocean, tropopause becomes high, and frequency of formation of trough is also decreased. Therefore, $^7$Be concentration is decreased to the lowest in a year all over Japan.

Dutkiewicz and Husain\cite{39} pointed out that temperature increase in summer is accelerated vertical movement in troposphere, and maximum $^7$Be concentration at $30^\circ$–$70^\circ$ N tends to appear at around June–July. But such increase of $^7$Be concentration in summer is popular in the foreign countries, though the decrease of $^7$Be in summer is seen in Japan.\cite{17, 21, 40}

Abe\cite{41} pointed out there exist regular double peaks of $^7$Be concentration in spring and fall in Japan. In eastern areas from Kansai such as Osaka,\cite{16} Tsuruga,\cite{17} Miyagi,\cite{42} Tsukuba\cite{43} and Tokyo,\cite{44} the regular double peaks clearly appear in spring and fall. Such double peak variation is seen in middle latitudes, and is associated with apparent decrease of $^7$Be concentration in winter, especially in January as well as summer. The decrease in winter is considered due to capture by snow and nature of air mass.\cite{42} And, in Kyushu district including Dazaifu, decrease in summer is seen, although such decrease in January, when snowfall is limited, has not been seen.\cite{15} In this way, seasonal variation of $^7$Be concentration depends on each area and local meteorology.

3. Yearly variation of $^7$Be concentration

Narazaki, by two-way factorial of variance analyses of data, showed that significant variation is seen in yearly variation of $^7$Be concentration (private communication). Beryllium-$^7$ which had been decreased since 1999 reached to the minimum in 2001–2002, and then turned to increase, of which increment was 41% in 2007 (Fig. 5).

Intensity of cosmic rays, a cause of $^7$Be production, varies with 11-year period of variation of solar activity.\cite{45} Cosmic rays cannot reach to the earth’s neighborhood when the sun is active, and when production of $^7$Be decreases. And inverse correlation between atmospheric $^7$Be concentration and sunspot number is found. This solar activity is related to the decrease of atmospheric $^7$Be concentration and sunspot number is described. Cosmic ray intensity has got a relation with the sunspot number, which varies with 11 years, as pointed out.\cite{50} Larsen\cite{49} noted that decrease of $^7$Be concentration is found when the sunspot number is increasing in global scale. The maximum solar activity appeared in 2000 in the 11 year period, but the decreasing tendency of cosmic ray intensity could be seen until 2003.\cite{50}

Since then cosmic rays increased, and $^7$Be atmospheric concentration also showed an increasing tendency.

Cosmic ray intensity in the atmosphere is weak when solar activity is active, resulting in small production of $^7$Be concentration. This provides a proof that increment of $^7$Be concentration occurs with decrease of solar activity, while behavior of cosmic ray intensity is opposite to the latter. Such is very important in determining yearly variation.

4. Inflow of stratospheric atmosphere

Stratospheric atmosphere, which comes down to the upper troposphere by turbulence of jet stream, invades into the troposphere through a folding of tropopause. This could be seen through observing the upper atmosphere.

Based on meteorological data in upper atmosphere, Narazaki shows that there exists an inverse correlation between $^7$Be concentration and specific humidity at 850 hPa, irrespective of season, and also points out that the stratospheric descending air gives influences on $^7$Be concentration on the ground (private communication). Specific humidity, defined as the ratio between mass of water vapor and mass of wet air, is generally low in the stratosphere. However, as Fig. 6 shows, specific humidity decreases even in lower troposphere when dry air of stratosphere descends.\cite{33} Increase of $^7$Be concentration on the ground level is strongly correlated with the decreases of specific humidity and air temperature, and is due to descending stratospheric air. Current of air by analysis of backward trajectory comes from north in September-May most frequently, in which $^7$Be concentration increases. As for air mass from the

**Fig. 5** Comparisons of the observed monthly atmospheric $^7$Be concentration in Dazaifu and simulated ones by signature function approximation. The annual mean of $^7$Be concentration (■) and the standard deviation (longitudinal line), and sin curve by signature function approximation are shown.

**Fig. 6** Altitude distribution of specific humidity from 8 to 20 on September, 2007 in Dazaifu.
north, descending motion with dozens m h\(^{-1}\) along the isothermal plane is expected.

As for a mechanism which ozone comes down from stratosphere to the ground, WAKAMATSU et al.\(^5\) explained that air in stratosphere is carried down through tropopause to upper troposphere and to the ground by successive descending air of high pressure. Based on observation at the top of Mt. Fuji, TSUTSUMI et al.\(^5\) explained that stratospheric ozone concentration is corresponding to decrease of water vapor and to increase of \(^{10}\)Be concentration. TSUTSUMI and MAKINO\(^5\) and HATAKEYAMA et al.\(^5\) made the ozone transport in the stratosphere clear by airplane observation, and they pointed out that descending motion of stratospheric air brings \(^{10}\)Be, and increase of stratospheric ozone concentration on the ground surface. Furthermore, DUTKIEWICZ and HUSAIN\(^3\) collected on monthly basis, being concentrated and surrendered to gamma ray spectrometric measurements. Furthermore, from artificial radionuclide and deposited non-sea-salt sulfate ion (nss-SO\(_4^{2-}\)) deposition has got specific concentration and regional distributions. Therefore obtained value well agreed to the calculated value using a chemical transport model of the whole earth.\(^5\)

### III DEPOSITION OF \(^{10}\)Be

Seasonal variation of \(^{10}\)Be deposition in Japan can be classified into 4 patterns by comparing monthly variations of measurements. Furthermore, from artificial radionuclide and deposition of non-sea-salt sulfate ion (nss-SO\(_4^{2-}\)), factors which cause seasonal variation of \(^{10}\)Be are identified. Here fall-out deposition was collected on a large scale stainless steel basin (area: 0.5 m\(^2\)), from which rain and aerosol samples were collected on monthly basis, being concentrated and dried, and were surrendered to gamma ray spectrometric measurements.

#### 1. Countrywide distribution

Beryllium-7 atoms born in the stratosphere as well as upper troposphere attach to aerosol particles of 0.4 – 2.0 μm\(^2\),\(^5\)\(^,\)\(^6\)\(^,\)\(^7\) as forms of \(^{7}\)BeO or \(^{7}\)Be(OH)\(_2\).\(^3\)\(^,\)\(^9\). And then, they fall due to eddy diffusivity or gravity. After adsorption, condensation and grow occurs, and then they fall to the ground by dry deposition or wet deposition as rain or snow. Beryllium-7 wet deposition includes rainout, in which aerosol is removed by rain or snow as nuclei of raindrops, or removed by washout in which aerosol is captured by rain or snow.\(^2\),\(^5\)\(^,\)\(^7\) By virtue of deposition mechanism and change of \(^{10}\)Be concentration in rain, \(^{10}\)Be deposition has got specific concentration and regional distributions.

Annual deposition of \(^{10}\)Be at 45 points in Japan (26°18’N – 43°05’N, 127°54’E – 141°27’E) in 1989 – 1995 is 290 (Gifu) – 6,500 Bqm\(^{-2}\) (Ishikawa), and mean is 1,500 ± 820 Bqm\(^{-2}\).\(^5\)\(^,\)\(^8\) These values roughly coincided with 1,600 Bqm\(^{-2}\) year\(^{-1}\) derived from the BROST et al. global model,\(^3\)\(^\)\(^4\) but in Japan there are slightly large statistical deviation and local differences.

Reported annual \(^{10}\)Be depositions are presented in [Table 2]. Japanese reported values are 290 – 7,400 Bqm\(^{-2}\). In foreign countries which are in the similar latitudes, values are 359 – 2,670 Bqm\(^{-2}\). In the southern hemisphere, the mean value of 1,030 – 6,350 Bqm\(^{-2}\) is observed. And in Antarctica, a value of 700 Bqm\(^{-2}\) is reported.\(^6\)\(^,\)\(^9\) From these, one can know whether annual \(^{10}\)Be depositions are large or small.

While most of \(^{10}\)Be come from stratosphere and upper troposphere, there exists no similarity between values in each sampling point, and it has no significant relation to geomagnetic latitude. And \(^{10}\)Be deposition is specially large in Japan Sea side, and attains the maximum in Hokuriku district, from which the values are decreasing towards both north and south. On the other hand, in the Pacific Ocean side values are high in

<table>
<thead>
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<th>Period</th>
<th>Place or Country</th>
<th>Latitude</th>
<th>Mean,(Range)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 – 2003</td>
<td>Kumamoto</td>
<td>32° N</td>
<td>(1486 – 1693)</td>
<td>MOMOSHIMA et al. (2006)(^5)(^)(^3)</td>
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<tr>
<td>1979 – 1992</td>
<td>Kuma tori</td>
<td>34° N</td>
<td>(1042 – 1831)</td>
<td>MATSU NAMI and MEGUMI (1994)(^5)(^)(^6)</td>
</tr>
<tr>
<td>1983 – 1997</td>
<td>Osaka</td>
<td>35° N</td>
<td>1313</td>
<td>MEGUMI et al. (2000)(^5)(^)(^6)</td>
</tr>
<tr>
<td>1986 – 1993</td>
<td>Tsukuba</td>
<td>36° N</td>
<td>(876 – 1780)</td>
<td>IGARASHI et al. (1998)(^5)(^)(^9)</td>
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<td>2000 – 2005</td>
<td>Rokkasho</td>
<td>40° N</td>
<td>(2160 – 3300)</td>
<td>AKATA et al. (2008)(^5)(^1)</td>
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<td>1989 – 1993</td>
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<td>(539 – 1242)</td>
<td>PAPASTEFANOU et al. (1995)(^5)(^)(^2)</td>
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<td>Italy</td>
<td>44° N</td>
<td>(843 – 1581)</td>
<td>BETTOLE et al. (1995)(^5)(^)(^3)</td>
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<td>1984 – 1987</td>
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<td>47° N</td>
<td>2670</td>
<td>SCHULER et al. (1991)(^5)(^4)</td>
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<td>1988 – 1989</td>
<td>Australia</td>
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<td>1030</td>
<td>WALLBRINK and MURRAY (1994)(^5)(^)(^5)</td>
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<td>1985 – 1986</td>
<td>New Zealand</td>
<td>42° N</td>
<td>6350</td>
<td>HARVEY and MATTHEWS (1989)(^5)(^)(^8)</td>
</tr>
<tr>
<td>1985 – 1986</td>
<td>Antarctica</td>
<td>70° N</td>
<td>700</td>
<td>NISHURUKAR and RAO (1993)(^5)(^)(^6)</td>
</tr>
</tbody>
</table>

The part of shadow shows measurement points in Japan.
East Japan, while they are relatively low in West Japan. However, deposition of $^7\text{Be}$ is relatively small in basin areas surrounded by backbone mountains, as well as coastal areas of the Inland Sea area, surrounded by Chugoku mountains and Shikoku mountains, due to poor supply of both $^7\text{Be}$ and precipitation (Fig. 7).

Japanese Islands are surrounded by sea, of which characteristic is abundant rain especially among middle latitudinal areas. Besides in locations along Japan Sea side, annual $^7\text{Be}$ deposition is more than 2001 Bq/m$^2$, and winter values attain the maximum in a year. This large amount of rain in winter gives a reason why $^7\text{Be}$ deposition is increased, and that $^7\text{Be}$ concentration in rain is outstandingly high in winter compared to other region gives another reason (Fig. 8).

In winter, when air pressure is often low in East Japan and high in West Japan, descending air motion to center of Siberian high pressure, which stagnates at around latitudes of 50$^\circ$N, is considered to accelerate downward velocity of high $^7\text{Be}$ concentration which is made in upper stratosphere. At the same time, air stream, considered as seasonal wind from north-west, accelerates inflow to a migratory cyclone and/or trough, which are often seen in Hokuriku district of Japan Sea.

Heat provided by Tsushima ocean current (warm current), which moves northward in Japan Sea, thus bears updraft, and wet air born there brings lots of snow due to cold temperature in upper air, and so Hokuriku district becomes to be a world-known heavy snow area. Beryllium-7 is adsorbed to aerosol as coagulation nucleus, which causes increases of $^7\text{Be}$ with increases of rain in the period in Japan Sea side. The phenomenon agrees to the situation of New Zealand which faces to west wind with South Alps mountains on her back, which brings annual deposition of 6,350 Bq/m$^2$. High concentration of $^7\text{Be}$ in rain in winter as well as large amount of rain in winter causes larger $^7\text{Be}$ deposition in Japan than that in foreign countries and difference of the geographic distribution.

2. Seasonal variation in each locality

It is reported that $^{90}\text{Sr}$ fallout, originated in atmospheric nuclear weapon tests, and stagnated in stratosphere, shows the maximum in winter in Japan Sea side, and in spring in Pacific Ocean side. Beryllium-7, stratospheric fallout, also receives local influence, and its seasonal variation can be classified into four (spring peak, double peaks, winter peak and non peak) patterns (Fig. 9). At the spring peak and double peaks their $^7\text{Be}$ deposition in spring increases. And due to leak through gap in tropopause or mean meridional circulation, atmospheric $^7\text{Be}$ concentration increases in this period. However, $^7\text{Be}$ deposition in spring has got low correlation with rain amount and $^7\text{Be}$ concentration in rain, but stagnation in rainy season promotes washout increase of the $^7\text{Be}$.

Areas, where $^7\text{Be}$ deposition becomes maximum in spring, can be classified into two groups; one has peak only in spring, and the other has double peaks also in September. The former
distributes in West Japan, and the latter in East Japan (Fig. 10). In September, when pressure direction turns to reverse, north-eastern air current becomes easy to enter, and autumnal rain front also stagnates in south-eastern sea of Japan, which brings lots of rain in the Pacific Ocean side of East Japan. This local increase of rain brings large $^7$Be deposition in September, which results in double peaks there.

Winter peak, at which $^7$Be deposition eminently increases, is considered due to rainout by rain,18, 42) and is distributed in Japan Sea side such as Hokuriku district. No large seasonal variation is shown throughout a year in areas of stable atmosphere, sandwiched by backbone mountains running north-south direction, and of a little rain (Non peak). In August, when Pacific oceanic high air pressure, stagnating in south ocean, covers all Japan, atmospheric $^7$Be concentration and rain amount are relatively low, and then $^7$Be deposition becomes minimized throughout a year all over Japan.

3. Factors of seasonal variation
About 67% of cosmogenic $^7$Be exists in stratosphere, and the remainders in upper troposphere.2) On the other hand, $^{90}$Sr and $^{137}$Cs after 1981 are due to their injection caused by atmospheric nuclear weapon tests into a stable layer in the stratosphere. As a result, both cosmogenic radionuclides and fission products coexist.

In middle latitude of northern hemisphere, air exchange between stratosphere and troposphere proceeds in spring. When stratospheric air is carried into troposphere, $^7$Be, $^{90}$Sr and $^{137}$Cs behave similarly as fallout, and are deposited on the ground. Both $^{90}$Sr and $^{137}$Cs increase in spring, and decrease in summer and fall, by which clear spring peaks appear.67) Such is a popular phenomenon if $^{90}$Sr and $^{137}$Cs coexist in stratosphere. On the other hand, $^7$Be increase in spring is also seen almost everywhere, which implies that the increase then is mainly due to fallout from stratosphere.69)

In areas where $^7$Be deposition increase is recognized in winter and in September, deposition is influenced by local meteorology and geomorphology. In areas of Japan Sea side, in winter when high (west) and low (east) pressure distribution appears, and seasonal wind from north-west direction dominates, nss-SO$_4^{2-}$ deposition is increased in seasonal variation, which is a result of long distance transport of sulfur oxides released into the atmosphere from north China.70) These areas well agree to the areas where $^7$Be deposition becomes high in winter, and well coincide with air mass route

Fig. 9  Variation pattern for normalized monthly deposition of $^7$Be and precipitation. A straight-line (■) represents mean of monthly average deposition of $^7$Be and a step line represents mean of monthly average precipitation.

Fig. 10  Distribution of variation patterns for monthly deposition of $^7$Be in Japan. 10 stations having the Spring peak, 25 stations having the Double peaks, 8 stations having the Winter peak, 3 stations having the Non peak of monthly average deposition of $^7$Be.
of high atmospheric \(^{7}\text{Be}\) concentration coming from north.

On the other hand, in September and October when atmospheric pressure direction is reversed, wind from north dominates in upper atmosphere of Japan. It follows that air from middle latitude comes to enter easier, and atmospheric \(^{7}\text{Be}\) in East Japan reaches the maximum in October. In September when northward wind dominates, typhoons also most frequently occur, and they reach to coastal areas of Pacific Ocean. Moreover, autumnal rain front which stagnates in south-eastern sea brings lots of rain, and the areas receive the largest rain throughout a year. It is possible that the increase of \(^{7}\text{Be}\) deposition is a resultant of washout of aerosol to which \(^{7}\text{Be}\) is attached, although exact correlation between \(^{7}\text{Be}\) deposition and amount of rain is not seen.

4. Yearly variation

Cosmic ray intensity had been decreased in 1985–1990 year period when magnetic field was strengthened by solar activity.\(^{6,9}\) Later, cosmic ray intensity recovered to normal level as solar magnetic field became weakened,\(^{7,1~73}\) and \(^{7}\text{Be}\) concentration on the ground level showed increasing tendency.\(^{16,59}\) The same tendency of \(^{7}\text{Be}\) was recognized in Greece\(^{8}\) and Italy.\(^{63}\)

In yearly variation, however, of \(^{7}\text{Be}\) deposition in 1990-1995, observed at 45 points in Japan, no such tendency could be recognized, and there were three groups of significantly increasing, decreasing, and no variation points.\(^{74}\) Although most \(^{7}\text{Be}\) are fallout which come from stratosphere and upper troposphere, no such general feature of yearly variation is seen, as \(^{7}\text{Be}\) amount of deposition increases with cosmic ray intensity.

Of all locations where annual deposition of \(^{7}\text{Be}\) increases significantly, Niigata, Ishikawa, Toyama, Fukui, Tottori and Shimane prefectures are all along Japan Sea side, and their contributions of January – February and November – December are large in annual \(^{7}\text{Be}\) deposition. Characteristic increase of \(^{7}\text{Be}\) concentration in rain in this period is due to decrease of rain, but due to supply of newly born \(^{7}\text{Be}\).

Namely, air mass movement in winter, seen in Japan Sea side, is mainly due to horizontal transport from Siberia, and cosmic ray intensity in Irkutsk, located in the center of Siberian high pressure, is stronger than that in Tokyo. The increase of cosmic ray intensity in Irkutsk in 1990–1995 is corresponding to such increase of \(^{7}\text{Be}\) concentration in rain on Japan Sea side, which indicates a possibility that the \(^{7}\text{Be}\) is transported from Siberian high pressure area.\(^{59}\)

In locations of insignificant annual variation of \(^{7}\text{Be}\) deposition, the \(^{7}\text{Be}\) is related to amounts of rain in West Japan, and the amount of \(^{7}\text{Be}\) deposition depends on the amount of rain. On the other hand, annual \(^{7}\text{Be}\) deposition decreased in Tokyo and Osaka where yearly decrease of \(^{7}\text{Be}\) concentration in rain occurred, and the reason is considered due to decrease of supply of \(^{7}\text{Be}\) to rain. Capture of \(^{7}\text{Be}\) in rain is not uniform, but it depends on how water vapor is coagulated in air mass, and it also depends on season, rain period and rain intensity. Local convection of atmospheric boundary layer and dry air made by “heat island” may also contribute to \(^{7}\text{Be}\) capture and deposition decline.

IV CONCLUSION

Geographically, Japan has got quite different nature between Japan Sea side and Pacific Oceans side. And dust transport in early spring, rainy season in spring to summer, approach and hits of typhoons, and later seasonal wind and snowfall in winter, all of which belong to most variable natural phenomena, make the problem complex. Such natural phenomena give influence on air circulation, distribution of fallout, or material transport from the continent, and are of interesting interdisciplinary subjects.

Influences on human health and plants due to oxidant (mostly ozone) and aerosol (PM2.5 etc) transported from China, of which economical growth has been eminent, have been pointed out. Indeed people are facing at environmental problems which should be studied with international cooperation. Transition mechanisms of occurrence of air pollutants followed by dispersion and deposition need chemical tracers as well as time tracers, and, in this meaning, radioactive materials are indispensable to conduct researches. Especially \(^{7}\text{Be}\), one of cosmogenic radionuclides, is important because its deposition is known quantitatively, and is used to clarify transportation of ozone from upper atmosphere (ozonosphere), and that of aerosol. That is important because \(^{7}\text{Be}\), born in stratosphere and transported through tropopause, reflects transport of other substances in stratosphere to troposphere. It is expected that researches on \(^{7}\text{Be}\) contribute a lot in investigating natural scientific subjects, especially atmospheric subjects.

This review is an extract of what have been done, and does not cover all the researches on associated subjects. Some important references might have been missing, for which authors must apologize.

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102 Yukinori N Arazaki and Kazunobu Fujitaka


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