# A statistical analysis of the relationship between the number of daily earthquakes (M≥5) in the world and the daily beryllium-7 concentrations in the surface air at each of 69 radionuclide monitoring stations in the world

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**Research Article**

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# A statistical analysis of the relationship between the number of daily earthquakes (M≥ 5) in the world and the daily beryllium-7 concentrations in the surface air at each of 69 radionuclide monitoring stations in the world

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## Abstract

The relationship between the number of daily earthquakes (M$\geq$ 5) in the world and the daily Be-7 concentrations in the surface air at each of 69 stations in the world from September 9, 2001, to December 31, 2017, was statistically analyzed. Aftershocks were not included in the analysis. The number of certified radionuclide stations increased from 5 in 2001 up to 69 in 2017.

(1) The median of the numbers ($n$) of daily earthquakes (M$\geq$5) in the world during the period was 3. Therefore, the observation days of the Be-7 concentrations of each station were classified by $n \geq 4$ or $n \leq 3$. The number of stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was greater was 43, and the number of stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ were smaller than or equal to that on days of $n \leq 3$ was 26. In more stations (significantly $(p = 0.0147)$ by the binomial test), the median of the Be-7 concentrations of each station on days of $n \geq 4$ was greater than that on the days of $n \leq 3$. In 14 years of total 17 years, in more stations, the median of the Be-7

concentrations of each station on days of $n \geq 4$ were greater than that on the days of $n \leq 3$.

(2) For $r$ = 1 ~ 12 and 15, the observation days were classified into two types, $n \geq r$ and days of $n \leq r - 1$. For 11 classifications of total 13 classifications, the median of the Be-7 concentrations of each station on days of $n \geq r$ was greater than that on days of $n \leq r - 1$ in more stations. For each of 7 classifications, it was significant ($p < 0.05$) by the binomial test.

(3) For each station, the inclination of the regression line of the daily Be-7 concentrations with respect to the numbers of daily earthquakes(M≥5) in the world was calculated. In more stations (almost significantly ($p$=0.074) by the binomial test), each inclination was positive.

The Be-7 concentrations in the surface air in the world, as a whole, may increase on days when the daily number of earthquakes(M≥5) in the world increase.

Key words: Number of daily earthquakes (M≥5) in the world,
Daily Be-7 concentrations in surface air at each station in the world,
Statistical analysis, Cosmogenic radionuclides

## 1. Introduction

It was previously reported that the Be-7 concentrations in the surface air at Takasaki statistically significantly decreased on days of earthquake (a day when one or more earthquakes of *M*5 or greater occurred in Japan and its vicinity) during the period from August 25, 2003 to December 28, 2008 (net 3.3 years). Earthquakes which were deemed aftershocks were not included. The Be-7 concentrations decreased on days of earthquakes both precipitation and non-precipitation, respectively (Ichihashi (2011)).

Morozova *et al.* (2000) reported that variations of cosmic rays are one of the possible causes of air pressure variations and one of the possible earthquake precursors by studying variations of the air pressure, cosmic ray fluxes, sun spot numbers, and interplanetary magnetic field (IMF) in connection with large earthquakes ($M \geq 7.0$) occurring from 1961-1996 in the world.

Beryllium-7 (half-life 53.29d) is one of the radionuclides produced by spallation of cosmic rays with light atmospheric nuclides, such as carbon, nitrogen and oxygen. It is mainly produced by interaction between cosmic-ray produced secondary neutrons and nitrogen or oxygen. About 70% of Be-7 is produced in the stratosphere and about 30% is produced in the troposphere. Beryllium-7 rapidly associates with submicron-sized aerosol particle. A residence time is estimated about a year in the stratosphere and about six weeks in the troposphere. Most of the Be-7 that are produced in the stratosphere don't reach the troposphere except during spring when seasonal thinning of the tropopause take place at midlatitudes, resulting in air exchange between stratosphere and troposphere. Gravitational settling and precipitation processes largely accomplish transfer to the earth's surface. A large part of surface Be-7 are of tropospheric origin (Sugihara *et al.* (2000); Yoshimori (2005)). It was reported previously that the long-term variation of the Be-7 concentrations in the surface air corresponds to the variation of cosmic ray intensity. When the sun spot numbers increase and the IMF becomes large, galactic cosmic rays become less and the Be-7 concentrations decrease (Ishikawa *et al.* (2005)). It was also reported previously that the daily variation of Be-7 concentrations is large and is related to local meteorological conditions (in particular, rainfalls) and pressure patterns (Abe (1995)).

In this study, the relationship between the number of daily earthquakes (M$\geq$ 5) in the world and the daily Be-7 concentrations in the surface air at each of 69 stations of CTBTO in the world from September 9, 2001, to December 31, 2017, was statistically analyzed. Aftershocks were not included in the analysis. The number of stations was 5 in 2001 and totally 69 during the period. During the period, the numbers ($n$) of daily earthquakes(M≥5) in the world were from 0 to 12, and 15.

(1) The median of the numbers ($n$) of daily earthquakes (M≥5) in the world during the period was 3. Therefore, the observation days of the Be-7 concentrations of each station were classified by $n \geq 4$ or $n \leq 3$.

Next, each station was classified according to whether the median of the Be-7 concentration of the station on days of $n \geq 4$ was greater than that on days of $n \leq 3$. The binomial test was performed on which type of station is more in the world. The analysis was performed for the total period, and for each year from 2001 to 2017.

(2) Next, for $r$ = 1 ~ 12 and 15, the observation days of each station are classified into two types, $n \geq r$ and days of $n \leq r - 1$. All the stations were classified into 13

different two types from the classification of days of $n \geq 1$ and $n \leq 0$ to the classification of days of $n \geq 15$ and $n \leq 14$. The binomial test was performed on which type of station is more in the world for each two types.

(3) For each station, the inclination of the regression line of the daily Be-7 concentrations with respect to the numbers ($n$) of daily earthquakes(M≥5) in the world was calculated. The binomial test was performed on which was more in the world, the stations with positive inclinations or the stations with negative inclinations.

## 2. Data

### 2.1 Earthquakes in the world

The catalog of the earthquakes in the world was obtained at the Web site of the USGS. The earthquakes of *M*5 or greater in the world were analyzed. Days are in UTC.

The periods longer than the periods when the probabilities that any aftershock of *M*5 or greater occur are more than or equal to 0.01/day were used as the lengths of aftershock periods. The probabilities were calculated by the method in Utsu (1999). The coefficients for earthquakes of $5 \leq M < 6$ obtained in Hosono and Yoshida (1992) and the coefficients for earthquakes $M \geq 6$ obtained in in Matsu'ura (1993) were used. Those coefficients were obtained from aftershocks in Japan and its vicinity. It was assumed that these coefficients are applicable to aftershocks in the world. Concretely, it was assumed that the lengths of aftershocks were 10 days for $5 \leq M < 5.8$; 30 days for $M5.9 \leq M < 6.4$; 90 days for $6.5 \leq M < 7.1$; 130 days for $M7.2$ and $M7.3$; 200 days for $M7.4$ and $M7.5$; 250 days for $M7.6$ and $M7.7$; 300 days for $M7.8$; 360 days for $M7.9$; 460 days for $M8.0$; 570 days for $M8.1$; 700 days for $M8.2$; 870 days for $M8.3$; 1070 days for $M8.4$; 1300 days for $M8.5$;1600 days for $M8.6$ ; 2400 days for $M8.8$; 4600 days for $M9.1$. It was assumed that earthquakes of $M \geq 5$ which occurred within the aftershock periods in the following areas are aftershocks: in the area of 1° in latitude and $1/\cos(\theta)°$ ($\theta$ : latitude of epicenter) in longitude from epicenters for the mainshocks of M<8; in the area of 2° in latitude and $2/\cos(\theta)°$ in longitude from epicenters for the mainshocks of 8≤M≤8.5; in the area of 3° in latitude and $3/\cos(\theta)°$ in longitude from epicenters for the mainshocks of 8.6≤M≤8.8; in the area of

4° in latitude and $4/\cos(\theta)°$ in longitude from epicenters for the mainshocks of 8.9≤ M≤9.1. Earthquakes which were deemed aftershocks were not included in the analysis. Earthquakes which were deemed aftershocks of earthquakes which occurred before September 9, 2001, were not included in the analysis, either.

## 2.2 The Be-7 concentrations in the surface air at each station in the world

The data of the Be-7 concentrations in the surface air of all the 69 radionuclide monitoring stations in the world during the period from September 9, 2001, to December 31, 2017, were provided by the CTBTO. The number of certified radionuclide stations increased from 5 in 2001 up to 69 in 2017. The names and locations (latitudes and longitudes) of the stations are shown in Table 2. The days are in UTC. The location map of the radionuclide monitoring stations is shown in Figure 1.

The Be-7 concentrations at each station were obtained by the analysis of the radionuclides in the filter which was removed once a day from an air sampler. The data of each day shows the Be-7 concentrations for the about 24 hours before the removal of the filter. The UTC's of removal of filters are not necessarily the same among the stations.

## 3. Results

### 3.1 Number of daily earthquakes (M≥ 5) in the world and the median of the of the Be-7 concentrations in the surface air at each station

(1) Table 1 shows the distribution of the numbers ($n$) of daily earthquakes(M≥5) in the world during the period from September 9, 2001, to December 31, 2017. The median of the numbers ($n$) of daily earthquakes (M≥5) in the world during the period was 3. Therefore, the observation days of Be-7 concentration at each station were classified according to the number ($n$) of daily earthquakes (M $\geq 5$) in the world, $n \geq 4$ or $n \leq 3$. The observation lengths are not necessarily the same among the stations because the dates when stations started observation are not necessarily the same.

Secondly, each station was classified according to whether the median of the Be-7 concentration of the station on days of $n \geq 4$ was greater than the median of the Be-7 concentration of the station on days of $n \leq 3$.

(2) The medians of the Be-7 concentrations of each station on days of $n \geq 4$ and on days of $n \leq 3$ are shown in Table 2. The number of stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was greater than the median of the Be-7 concentrations of each station on days of $n \leq 3$ was 43. The number of stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was smaller than or equal to the median of the Be-7 concentrations of each station on days of $n \leq 3$ was 26. It was significant $(p = 0.0147)$ by the binomial test that there were more stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was greater than that on days of $n \leq 3$.

In Figure 1, the mark "○" shows the location of the station where the median of the Be-7 concentration of each station on days of $n \geq 4$ was greater than the median of the Be-7 concentration of each station on days of $n \leq 3$. The mark "△" shows the location of the station where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was smaller than or equal to the median of the Be-7 concentrations of each station on days of $n \leq 3$.

In Table 3, a “station (Be-7Median >)” denotes a station where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was greater than the median of the Be-7 concentrations of each station on days of days of $n \leq 3$. “A station (Be-7Median≤) denotes a station where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was smaller than or equal to the median of the Be-7 concentrations of each station on days on days of $n \leq 3$. The numbers of stations (Be-7Median>) and the numbers of stations (Be-7Median≤) for the classification of days of $n \geq 4$ and days of $n \leq 3$ in each year are shown in Table 3. In 14 years out of 17 years in total, there were more stations (Be-7Median>) than stations (Be-7Median≤). It is statistically significant $(p = 0.0012)$ by the binomial test that there were more years when there were more stations(Be-7Median>) than stations (Be-7Median≤) for the classification of days of $n \geq 4$ and days of $n \leq 3$.

(3) In the same way, for $r$ = 1 ~ 12 and 15, the observation days of each station are classified into two types, $n \geq r$ and days of $n \leq r - 1$. Here, a “station(Be-7Median>) ” denotes a station where the median of the Be-7 concentrations of each station on days of $n \geq r$ is greater than the median of the Be-7 concentrations of each station on days of $n \leq r - 1$. A “station(Be-7Median≤)” denotes a station where the median of the Be-7 concentrations of each station on days of $n \geq r$ is smaller than or equal to the median of the concentrations of each station on days of $n \leq r - 1$.

Table 4 shows the number of stations(Be-7Median>) and the number of stations (Be-7Median≤) in the world for all the 13 classifications from the ‘classification of days of $n \geq 1$and days of $n = 0$’ to the ‘classification of days of $n \geq 15$ and days of $n \leq 14$.’ (The numbers of stations for the ‘classification of days of $n \geq 13$ and days of $n \leq 12$’ and the ‘classification of days of $n \geq 14$ and days of $n \leq 13$’ are not shown because there was no day of $n = 13$ and $n = 14$. ) The result shows that, in each of the 11 categories out of the 13 categories, stations (Be-7Median>) were more than stations (Be-7Median≤). Furthermore, in 7 of these 11 categories, the number of stations (Be-7Median≥) was larger than that of stations (Be-7Median≤), which was statistically significant (p <0.05) in the binomial test. The 7 classifications are as follows: ‘classification of days of $n \geq 3$ and days of $n \leq 2$’, ‘classification of days of $n \geq 4$ and days of $n \leq 3$’, ‘classification of days of $n \geq 7$ and days of $n \leq 6$’, ‘classification of days of $n \geq 8$ and days of $n \leq 7$’, ‘classification of days of $n \geq 9$ and days of $n \leq 8$’, ‘classification of days of $n \geq 10$ and days of $n \leq 9$’, and ‘classification of days of $n \geq 12$ and days of $n \leq 11$’.

These results suggest that the Be-7 concentrations increase at more stations on days when the number of $M \geq 5$ earthquakes in the world increases.

### 3.2 Regression analysis between numbers of daily earthquakes ($M \geq 5$) in the world and the daily Be-7 concentrations at each station

In order to analyze how the Be-7 concentration of each station in the world changed on days when the number of earthquakes in the world ($M \geq 5$) increased, regression analysis was performed between the number of daily earthquakes ($M \geq 5$) and the daily Be-7 concentration at each station. Table 5 shows the inclination of regression line of the Be-7 concentrations at each station of all 69 the stations with respect to the numbers ($n$) of daily earthquakes (M$\geq 5$) in the world. The inclinations of 40 stations are positive and the inclinations of 29 stations are negative. There was no station where the inclination is 0. It is almost statistically significant ($p = 0.0740$) by the binomial test that there were more stations where the inclinations were positive. For the stations where the observation days were $\geq 20$ days, the inclinations of 40 stations are positive and the inclinations of 27 stations are negative. There was no station where the inclination is 0. For the stations where the observation days were $\geq 20$ days, it is significant ($p = 0.0432$) by the binomial test that there were more stations where the inclinations were positive. These regression analyses also suggest that the Be-7 concentrations increase at more stations in the world on days when the number of earthquakes(M≥5) in the world increase.

## 4 Discussion

(1) The above results suggest that the Be-7 concentrations increase at more stations in the world on days when the number of earthquakes(M≥5) in the world increase. However, it is necessary to recognize that there were also the stations where the Be-7 concentrations decreased on days when the number of earthquakes(M≥5) in the world increased. It is speculated that, because of the global atmospheric flow, the B-7 concentration increased at some points in the world and decreased at some points on days when the number of earthquakes(M≥5) in the world increased. However, it seems reasonable to hypothesize that the Be-7 concentrations in the world as a whole increased on days when the number of earthquakes(M≥5) in the world increased.

There are some factors which influence the Be-7 concentrations at stations in the world. They are such as: (a) The Be-7 concentrations in the surface air increase when the cosmic rays increase. (b) The Be-7 concentrations in the surface air vary when the atmospheric flow varies. (c) The cosmic rays decrease when the sunspots increase.

When we consider the mechanism by which the Be-7 concentrations in the world as a whole increase on days when the number of earthquakes(M≥5) in the world increase, it may be useful to note that there is difference between the northern hemisphere and the southern hemisphere. As an example, for the ‘classification of days of $n \geq 4$ and days of $n \leq 3$’, there were 22 stations (Be-7Median>) and 20 stations (Be-7Median≤) in the northern hemisphere, and there were 21 stations(Be-7Median>） and 6 stations (Be-7Median≤) in the southern hemisphere. It is significant (p=0.00336) by the $\chi^2$ test that there were relatively more stations(Be-7Median>） than stations (Be-7Median≤) in the southern hemisphere than in the northern hemisphere, for the ‘classification of days of $n \geq 4$ and days of $n \leq 3$’

It seems necessary to continue to obtain the long-term data and to consider the physical mechanism of the possible relationship between the number of daily earthquakes in the world and the daily Be-7 concentration in the surface air in the world.

## 5. Conclusion

The relationship between the number of daily earthquakes of M$\geq 5$ in the world and the daily Be-7 concentrations in the surface air at each of the 69 stations for the CTBTO International Monitoring System in the world during the period from September 9, 2001, to December 31, 2017, were statistically analyzed. The median of the numbers ($n$) of daily earthquakes (M≥5) in the world during the period was 3. Therefore, the observation days of the Be-7 concentrations of each station were classified by whether $n$ on the observation days were $\geq 4$ or $\leq 3.$ Next, each station was classified according to whether the median of the Be-7 concentration of the station on days of $n \geq 4$ was greater than the median of the Be-7 concentration of the station on days of $n \leq 3$. The number of stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was greater than the median of the Be-7 concentrations of each station on days of $n \leq 3$ was 43. The number of stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was smaller than or equal to the median of the Be-7 concentrations of each station on days of $n \leq 3$ was 26. It was significant $(p = 0.0147)$ by the binomial test that there were more stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ were greater than that on days of $n \leq 3$.

In 14 years out of 17 years in total, there were more stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was greater than that of each station on days of $n \leq 3$. It is statistically significant ($p = 0.0012$) by the binomial test that there were more years when there were more stations where the median of the Be-7 concentrations of each station on days of $n \geq 4$ was greater for the classification of days of $n \geq 4$ and days of $n \leq 3$.

In the same way, for $r$ = 1 ~ 12 and 15, the observation days of each station are classified into two types, $n \geq r$ and days of $n \leq r - 1$. In each of the 11 categories out of the 13 categories, there were more stations where the median of the Be-7 concentrations of each station on days of $n \geq r$ was greater than that of each station on days of $n \geq r - 1$. Furthermore, in 7 of these 11 categories, it was statistically significant ($p < 0.05$) by the binomial test.

For each station, the inclination of the regression line of the daily Be-7 concentrations with respect to the numbers ($n$) of daily earthquakes(M≥5) in the world was calculated. There were 40 stations with a positive inclination, and 29 stations with a negative inclination. It was almost significant ($p$=0.074) by the binomial test that there were more stations with a positive inclination. It was significant ($p$=0.043) by the binomial test for the 67 stations where the observation days were $\geq 20$ day.

These results suggest that the Be-7 concentrations increase at more stations in the world on days when the number of earthquakes(M≥5) in the world increase. The Be-7 concentrations in the surface air in the world, as a whole, may increase on days when the daily number of earthquakes(M≥5) in the world increase.

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## Disclaimer

The views expressed in this study are those of the author and do not necessarily represent the views of the CTBTO Preparatory Commission.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable on individual person's data.

The institutional consent for publication has been obtained from CTBTO and Tokyo Seitoku University High School.

### List of abbreviations

station (Be-7Median>)

station (Be-7Median≤)

### Availability of data and materials

The datasets are available from the author on request.

### Competing interests

Not applicable.

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**Authors' contributions**

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  (During this time, the author was engaged in the “Earthquake Frontier” project.)
- Chief Senior Engineer, Nuclear Nonproliferation Science and Technology Center, Japan Atomic Energy Agency (2005-2010)

(The study on the relationship between the Be-7 concentrations in the surface air at Takasaki and earthquakes in Japan and its vicinity was performed during this period.)

- Senior Researcher (part time), Space Environment Group, Japan Space Development Agency (2010-2012)

**Endnotes**

Not applicable.

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**Figure legends**

Figure 1. The map of stations in the world for during the period from September 9, 2001, to December 31, 2017.

**Table legends**

Table 1. The distribution of the numbers ($n$) of daily earthquakes(M≥5) in the world during the period from September 9, 2001, to December 31, 2017.

Table 2. The medians of the Be-7 concentrations in the surface air at each station respectively on days of earthquakes(n≥4) and on days of earthquakes (n≤3) during the period from September 9, 2001, to December 31, 2017 (UTC).

Table 3 The numbers of stations(Be-7Median>) and the number of stations (Be-7Median≤) in the world for 'classification of days of $n \geq 4$ and days of $n \leq 3$' in each year during the period from September 9, 2001, to December 31, 2017.

Table 4. The number of stations(Be-7Median>) and the number of stations(Be-7Median≤) in the world for all the classifications from 'classification of days of $n \geq 1$ and days of $n = 0$' to 'classification of days of $n = 15$ and days of $n \leq 14$' during the period from September 9, 2001, to December 31, 2017.

Table 5. Regression coefficients of the regression line of the Be-7 concentrations in the surface air at each station with respect to $n$ during the period from September 9,2001, to December 31,2017. Days are in UTC. ( $y = ax + b$. $a$ : inclination of Be-7 with respect to $n$. $x = n$)

# Figures

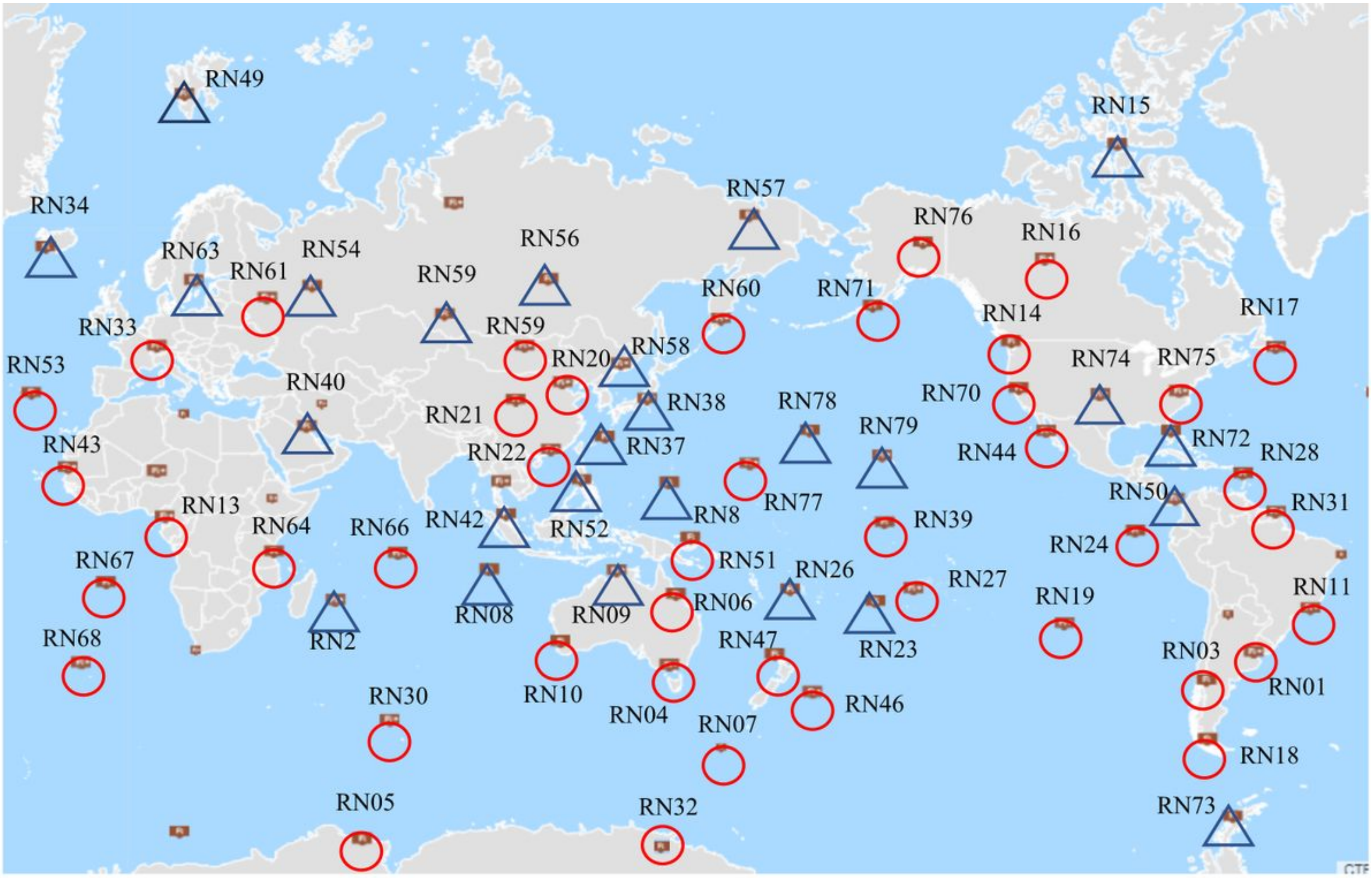


Figure 1. The map of stations in the world during the period from September 9, 2001, to December 31, 2017.

### Figure 1

The map of stations in the world during the period from September 9, 2001, to December 31, 2017.

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