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A STUDY ON TEMPORAL AND SPATIAL DISTRIBUTIONS OF LOW PRECIPITATION BY DEPTH-AREA-DURATION ANALYSES

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SYNOPSIS

The DAD (depth-area-duration) analysis has been used for many years to study the general characteristics of temporal and spatial distributions of heavy rainfall. A similar analysis was applied to 'low precipitation' which is a small amount of precipitation during relatively a long period and is a major factor in causing droughts. First, an analysis similar to the conventional DD (depth-duration) analysis (which is simply referred to as 'DD analysis', and it is the same for 'DA' and 'DAD') was carried out using 'daily precipitation' (which is not 'normalized precipitation' mentioned later). Consequently, it was found that the data of daily precipitation were not appropriate for analysis, and that the data of normalized precipitation should be used instead. First, a polynomial approximation curve as a DD relationship was obtained by the DD analysis. Secondly, by using the DD curve and the results of DA (depth-area) analyses, DAD curves that closely represent the data were obtained.

In addition, the degree of severity of the drought was evaluated statistically by a method that is similar to the DDC (drought-duration curve) method.

INTRODUCTION

Due to the seriousness and the frequency of its occurrence, it is clear that drought is one of the most serious natural disasters from the viewpoint of disaster prevention, and analyzing and clarifying the mechanism of drought is essential for conserving water resources for society and activities, not only in arid countries but also in Japan. Although contributing factors include a variety of natural and man-made phenomena; that is, low precipitation, high temperature in summer, problems with water supply systems, low precipitation is clearly the main factor in causing droughts from the viewpoint of hydrology. In recent years, much research has been done in the field of civil engineering as well as meteorology, in which precipitation is treated as a purely physical process (for example (4)). A stochastic and statistical method of analyzing drought and low precipitation is, however, appropriate at the present stage because drought occurs over a relatively large time-space scale.

Recent examples of extreme drought years are 1978, 1984, and 1994. Takara et al. (6)(8) carried out statistical analyses on temporal and spatial distributions of drought by employing the DDC (drought-duration curve) method (9)(10). For example, in the literature (6), DDCs obtained from monthly rainfall data over a period of about 100 years at 46 surface meteorological observation stations in Japan were compared with 'rainfall intensity' (which is depth of precipitation divided by its duration of accumulation of precipitation) in 1994, and the seriousness of this drought was evaluated.

On the other hand, disasters caused by heavy rainfall are quite the opposite of disasters caused by low precipitation or drought, and the DAD (depth-area-duration) analysis (see, for example, Linsley et al.(3), Gilman (2), and Raudkivi(5)) is frequently employed as an analytical technique since it is an effective way of clarifying general characteristics of temporal and spatial distributions of heavy rainfall. In this paper, an analysis of temporal and spatial distributions of low precipitation is attempted by applying a similar method to the DAD. In addition, the seriousness of droughts is evaluated using probability of occurrence, that is, a technique analogous to the DDC.

DATA

The data used in this study consists of daily precipitation records of AMeDAS (Automated Meteorological Data Acquisition System), taken over a 24-year period (1976–1999), provided by the Japan Meteorological Agency. An additional meteorological data set was provided by the Japan Meteorological Agency; namely, 'Surface Meteorological Observation System', whose spatial resolution is lower than AMeDAS' but whose observation period is much longer than that of AMeDAS. Since we needed high spatial resolution for the DA analysis; that is, the analysis of the spatial distribution of precipitation, we adopted the former one.

Initially, actual daily precipitation data were sorted out to yield a time series comprising 8766 data of daily precipitation (from January 1, 1976 to December 31, 1999) at all the observation points (1578 points where at least one datum is available). Note that a large number of non-observation days is included in the data. In the process of analyzing the data, the non-observation days were treated as days with extremely heavy rainfall. This means that precipitation which includes such non-observation days is excluded from analyses. This was done to avoid making the wrong conclusion that long-term non-observational period corresponded to the occurrence of low precipitation.

DD ANALYSIS USING DAILY PRECIPITATION DATA

The DD analysis was carried out using the time series data on daily precipitation. The purpose of the DD analysis is to find the relationship between the duration of precipitation (here, duration means 'duration of accumulation of precipitation depth' for low precipitation, which is mentioned below) and the depth of the minimum point precipitation, in contrast with the DD analysis for heavy rainfall in which the maximum point precipitation is used. A period of time ranging from 10 to 1100 days (about three years) was selected for the accumulation. A period of time less than 350 days is, however, adopted for DA or DAD analyses. Hereafter, 'duration of accumulation of precipitation' or 'duration of integration of precipitation' is referred to as 'duration of precipitation'. The analyses were carried out in the following manner:

1) The moving sum of values of precipitation over d days (d-day precipitation) was first obtained at each observation point using the time series for daily precipitation data comprising 8766 data. The minimum value of the moving sums was then obtained. Hereafter, d represents the duration of precipitation within the range between 10 and 1100 days. $min_i^{(d)}$ denotes the minimum value for a certain d and a certain observation point i.
2) $min^{(d)}$, the minimum value of $min_i^{(d)}$ for all i is the value that defines a DD curve. The DD curve is the relationship between d and $min^{(d)}$.

The black line linked by circles in Fig.1 denotes a DD curve calculated using the method mentioned above. It indicates

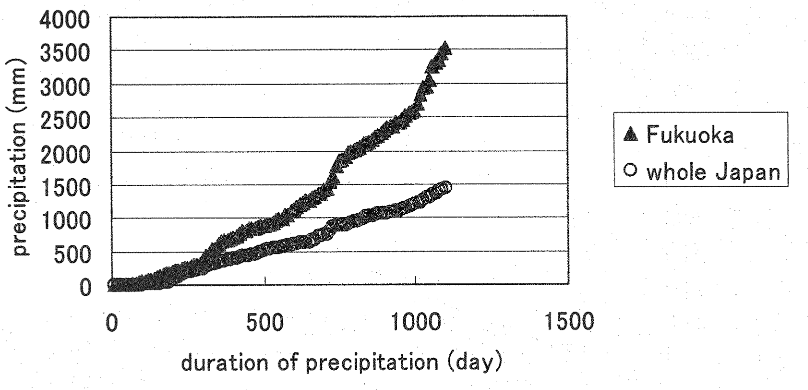


Fig.1 Dependence of precipitation on the duration of precipitation

the trend in the minimum point precipitation, that is, the DD relationship, in Japan overall. However, from the viewpoint of analyzing drought disasters, it provides no useful information. The reason for this is that the curve mainly represents the data for a certain observation point in the Hidaka District in Hokkaido over the range of d <240, and the curve represents the data for another observation point in Abashiri District in Hokkaido in the other range. The gray curve linked by triangles in the same figure indicates a similar DD curve obtained by using the same method for the data within Fukuoka Prefecture only, where many serious drought disasters have occurred. The former DD curve in Fig.1 clearly reflects only the characteristics of areas with low precipitation, regardless of the degree of risk of experiencing drought. Therefore, we proceeded with our analysis based on precipitation normalized by mean annual precipitation (hereafter, referred to as 'normalized precipitation').

ANALYSES USING NORMALIZED PRECIPITATION

(1) Normalized precipitation

Hereafter, the basic data employed are normalized precipitation by a mean annual precipitation at each observation point. The concept of 'mean annual precipitation' has a similar meaning to 'normal value' provided by the Japan Meteorological Agency, but the values are calculated employing the data for 24 years at the longest for averaging, using the following method:

1) First, the observation points are narrowed down using the following conditions. That is, 'available year' must contain effective ('effective' means that a datum exists) daily precipitation data more than 26 days in February and more than 28 days in other months, and observation points which have more than 20 available year are an 'available observation point'.
2) Values of mean annual precipitation are then calculated for the above selected observation points by using values of the annual precipitation for all available years.
3) Note that an available year still contains non-observation days. Therefore, the annual precipitation is obtained by adding the values of monthly precipitation corrected using the following equation: monthly precipitation (corrected) = (sum of the values of daily precipitation for effective days) × (number of total days in the month) / (number of effective days).

Normalized precipitation is defined as the value obtained by dividing the time series of daily precipitation data, which comprises 8,766 values for each observation point, by the previously described mean annual precipitation, and then

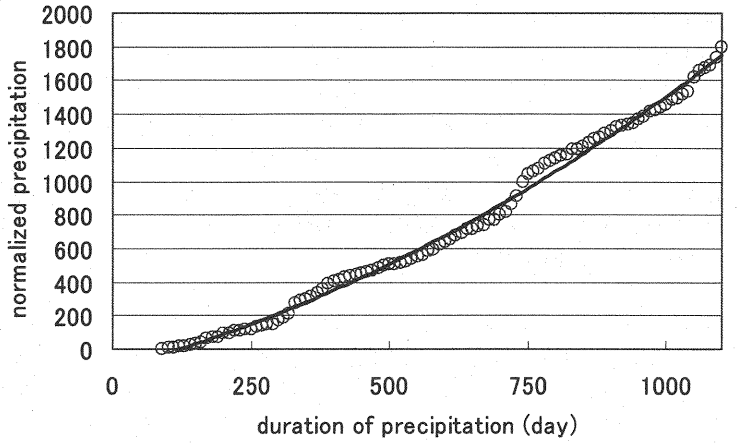


Fig.2 Dependence of normalized precipitation on the duration of precipitation

multiplying by 1,000. For the sake of simplicity, the normalized precipitation is sometimes called 'precipitation' hereafter. The number of observation points that satisfy the above-mentioned condition for the mean annual precipitation is found to be 606 (refer to Fig.7 for their positions). The data on these points only are employed hereafter.

(2) DD relationship

Another DD curve was calculated using the normalized precipitation in a similar manner to the previous section (circle-lined curve in Fig.2). The solid line in the figure denotes an approximate line based on the secondary polynomial approximation. The relationship between the precipitation (p_0; mm) and the duration of precipitation (d; day) is expressed as:

$$p_0 = 0.0008d^2 + 0.8671d - 116.05 \quad (p_0 \geq 0) \tag{1}$$

This is a relationship for d ≤ 1,100. For the relationship with d ≤ 360, the following equation is obtained. Later DA (depth-area) analyses employ Eq. (2).

$$p_0 = 0.0032d^2 - 0.3741d + 15.845 \quad (360 \geq d \geq 90) \tag{2}$$

(3) Evaluation of the seriousness of drought based on probability of occurrence

In this section, evaluations of the scale or the seriousness of droughts in 1978, 1984, and 1994 are carried out using their probability of occurrence. Discussions in this section refer to Yoshikawa and Takeuchi (10), and Takeuchi (9). The DD curve obtained in the previous section was based on all the time series data from 1976 to 1999. Probability of occurrence is first calculated from the DD relationship in each year. The procedure is as follows:

1) Assuming that r_{ij} is a daily precipitation (note that it is the normalized precipitation) at i (observation point number) on the day whose day number is j (starting from 1 for January 1, 1976 and ending in 8,766 for December

31, 1999), the following statistical quantity (Eq. (3)) is obtained for the duration of precipitation d in the year n (n = 1976, 1977, ... 1999).

$$x_n^{(d)} = \min_{\substack{j1 \in J \\ i \in I}} \left\{ \sum_{j=j1}^{j2(=j1+d-1)} r_{i,j} \right\} \tag{3}$$

Here 'I' denotes a set of observation points, 'J' a set of day numbers corresponding to year n, and '$j1$' is the day number which corresponds to January 1 to December 31 of year n.

2) Supposing the number of $x_n^{(d)}$ obtained is N (which depends on d and is 21 or 23 as mentioned later) for a certain d, probability of occurrence of the k-th smallest $x_n^{(d)}$ is expressed as "k-th among N".

Yoshikawa and Takeuchi (10) discussed the DDC regarding the non-exceeding probability, namely $P_k = k/(N+1)$, as the degree of risk. Takara and Ikebuchi et al. (6) evaluated the degree of risk or the seriousness of drought using the return period that is given by $T_k = 1/P_k = (N+1)/k$. The employed data were as long as 40–50 observation years for the former, and about 100 years for the latter. By contrast, the data in this discussion was limited to a period of 20-24 years, which called into question the suitability of using these return periods to evaluate the seriousness of droughts. Therefore, we use, henceforth, the expression "k-th among N".

Fig.3 illustrates the dependence of $x_n^{(d)}$, namely, the normalized precipitation on d. Each line in the figures shows the relationship between the duration of precipitation and the normalized precipitation whose seriousness (of drought or low precipitation) is 'k-th among N'. In the legends, only values "k" are shown. Note that 23 items of $x_n^{(d)}$ are obtained at $d \leq 365$, and smaller numbers of $x_n^{(d)}$ are obtained at larger d values depending on the number (N) because of the definition of $x_n^{(d)}$. When d is less than 360, there are 23 $x_n^{(d)}$ and an initial point for calculating $x_n^{(d)}$ is one of 23 years (1976-1998). However, with larger d values, the initial point is one of 21 years (1976–1996). This means that polygonal unbroken line corresponds to "k-th among 23" in the former; and "k-th among 21" in the latter. These figures show the relationship between the seriousness of drought expressed in terms of probability and the duration of precipitation. Using the relationship in the figures, we attempted to determine the seriousness of droughts in the years 1978, 1984, and 1994. First, the relationships between the duration of precipitation and the accumulated precipitation depth were calculated for each of the three years. However, to obtain $x_n^{(d)}$ for the three years, the following equation (Eq. (4)) was employed instead of Eq. (3).

$$x_n^{(d)} = \min_{\substack{(j1 \in J) \cup (j2 \in J) \\ i \in I}} \left\{ \sum_{j=j1}^{j2(=j1+d-1)} r_{i,j} \right\} \tag{4}$$

The reason for using Eq. (4) here is that $x_n^{(d)}$ as given by Eq. (3) cannot include the following case. That is, an accumulated precipitation whose duration includes a part of year n is very small because of low precipitation in year n, but the duration of precipitation is somewhat longer and the starting point of it is in year n-1. However, it should not contain any cases which are not related to low precipitation in year n.

The thick unbroken line in Fig.3 denotes the relationship between the duration of precipitation and low precipitation in 1978. From these figures, the following conclusions are deduced:

1) Under the conditions of $d \leq 60$ days, the precipitation is zero, indicating the lowest precipitation in the last 23 years.
2) With increasing d values up to $d = 250$, the value indicates about fifth low precipitation.
3) Further at $500 \leq d \leq 930$, the value generally indicates records of low precipitation at more than the third class,

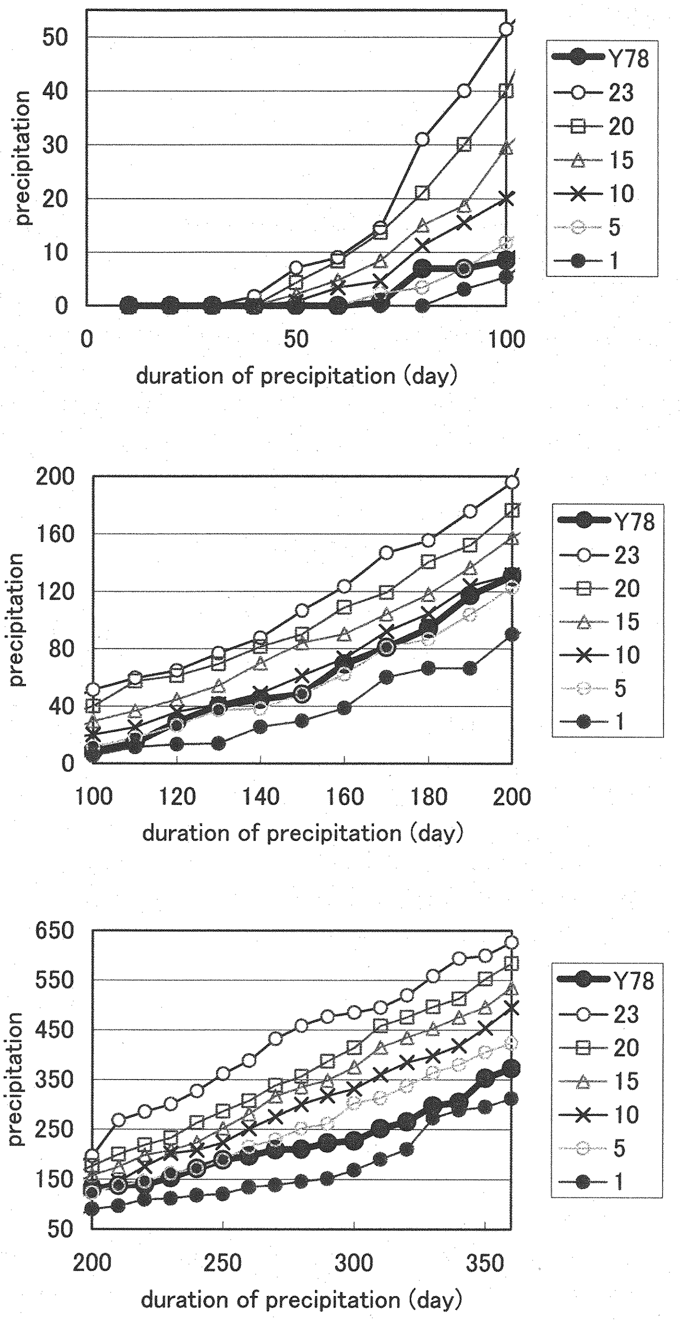
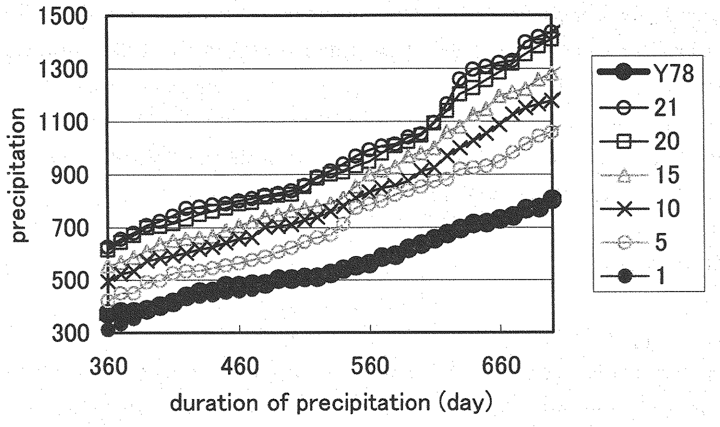


Fig.3-1 Normalized precipitation versus the duration of precipitation (The seriousness of drought can be evaluated statistically using these figures. The relationship is divided into four sequences depending on the duration.)



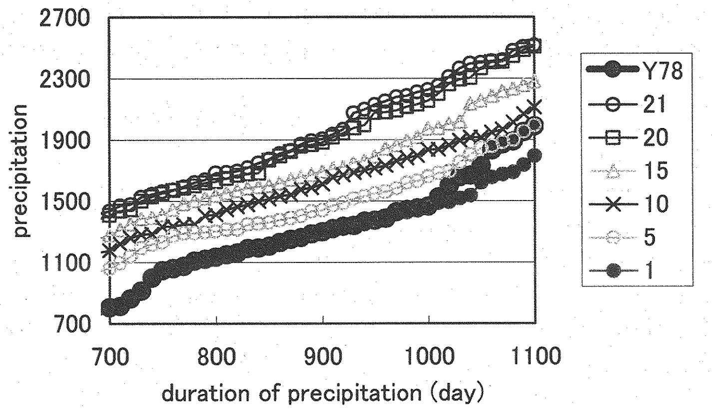


Fig.3-2 Normalized precipitation versus the duration of precipitation (The seriousness of drought can be evaluated statistically using these figures. The relationship is divided into four sequences depending on the duration.)

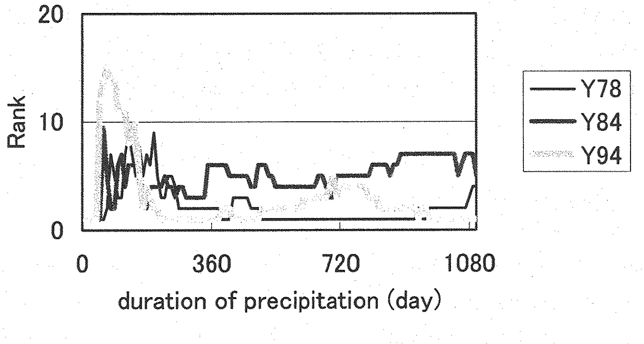


Fig.4 Temporal changes in the seriousness of drought for 1978, 1984, and 1994

while occasionally reaching the first class. However, there is not a substantial difference between the first class and the third class.

The abnormally low precipitation in 1978 was assessed in detail in this way. Similar figures were generated for the other two abnormal years of 1984 and 1994. Although discussions concerning these years are omitted, changes of *k* values for these three years are investigated. The changes in the seriousness of drought (Y axis) or ranks of *k* (*k*-th among *N*) were examined for the duration of precipitation (X axis) for the three drought years. The findings are shown in Fig.4. In none of the years did the precipitation show significant abnormality under conditions of $d \leq 200$, but with longer *d*, especially in 1978 and 1994, it exhibited a distinct scarcity abnormality.

(4) DA and DAD relationships

In the DAD analysis, which focuses mainly on heavy rainfall, it is a standard practice to obtain DA curves illustrating the relationships between the areal size of a region and the maximum areal rainfall in the region (7). Since the objective of this study is to analyze low precipitation, the dependence of the areal size of a region (in practical use, the 'radius of a scanning circle' which ranges between 20 km and 500 km is employed for reasons described later) on the minimum areal precipitation in the region was investigated by using the following procedures:

1) Precipitation values were obtained for all observation points over a specified period of which accumulated precipitation established the DD curve in section 4-(2). Note that 'precipitation' means 'normalized precipitation' again.
2) The minimum areal precipitation was calculated in a scanning circle of radius *r* according to the 'fixed area method' (7) which will be described later. 'Areal precipitation' means the value obtained by averaging precipitation values which are included in a certain scanning circle, and 'minimum' means the smallest value among the values of 'areal precipitation' obtained by moving the circle.
3) For example, the minimum point precipitation for a 50-day precipitation is 0 (mm), while the same values are found at 376 cases which differ in either the observation point or the starting point of the low precipitation of 0(mm) for $d = 50$ days. Therefore, the smallest value among the values of the 'minimum areal precipitation' determined in 2) was adopted as the 'minimum areal precipitation for *d* and *r*' (hereafter we simply refer to this as the 'minimum areal precipitation').
4) The dependence of the lowest areal precipitation on a radius *r* was plotted by parameterizing the duration of precipitation.

The 'fixed area method', which was employed by Takara et al. (7) for the DAD analysis of heavy rainfall, divides the designated area using a grid, and defines a precipitation value at each grid point. A circle of a specified area is then made to shift over the whole range of the catchment area to obtain areal rainfall in the circle from the precipitation at the grid points within it. By shifting the circle, the maximum areal rainfall can also be determined. Note that although wet use the grid points when the circle shifts, we do not calculate the precipitation value at each grid point. The areal precipitation values are obtained by simply arithmetically averaging the precipitation values in the circle. If the circle contains fewer than 6 observation values, it is not included in our calculations. By means of this method the amount of available areal precipitation becomes relatively small when the radius of the scanning circle (hereafter, it is simply referred to as 'radius') is small. In cases of the radius under 100 km, the minimum areal precipitation is calculated by setting the grid distance to 1 km. On the other hand, for larger radii, the distance is set to 5 km owing to limitations in computation resources.

The purpose of the DA analysis for heavy rainfall is to determine depth-area relationships. However, in this study, the DA method was modified and not the area of region; namely, the area of a scanning circle, but the radius of a scanning circle is employed to investigate the relationship with the precipitation. The reasons for doing this are as follows: 1) in this study, setting a relatively large spatial scale was necessary to allow the investigation of DA

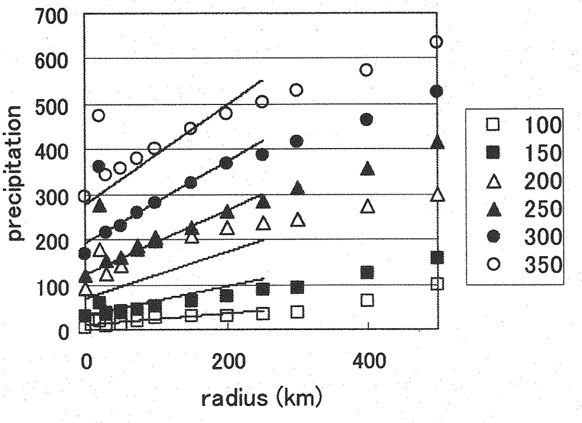


Fig.5 Dependence of the radius of a scanning circle on the minimum areal precipitation. Figures in the legend indicate the duration of precipitation (days). Approximated lines based on a linear regression are also shown in the figure.

relationships for low precipitation; 2) due to the arcuate form of Japanese islands, and due to the large spatial scale, scanning circles of the fixed area method will include many sea areas where precipitation data are not available; 3) because of 2), evaluation of the 'area' is difficult. Regardless of the method, it is necessary to evaluate the 'area' for the DA analysis. However, evaluating the 'area' is difficult because of the existence of sea; namely, the arcuate form of Japanese land and because of the large spatial scale. In view of this, we evaluate spatial scale by the radius of a scanning circle.

During the actual execution of the DA analyses, the observation points, that is, AMeDAS observation points were plotted on a plane of two-dimensional x-y coordinates (1). On this occasion, the origin is set at 33°N/129°30'E (refer to Fig.7). The scanning circle is shifted within a square diagonalized with (0, -300) and (1400, 1400) points. The entire circle should be included in the square.

Fig.5 shows the relationships revealed by the procedure described above with the horizontal axis the radius (km) and the vertical axis the minimum areal precipitation. The scale runs at intervals of 50 days showing the duration of precipitation from 100 days to 350 days. The minimum point precipitation obtained by the DD analysis is plotted on the position of the radius of 0 km. At a radius of 20 km, high precipitation values are shown for each value of the duration of precipitation. The same tendency is found for other duration values (days) in other figures that are not shown in this paper. Considering the grid distances for AMeDAS observation points and the radius, the condition mentioned above that necessitates including more than 6 observation points within scanning circles may seem relatively severe for a radius of 20 km. In fact, the number of scanning circles that satisfy this condition ranges between 400 and 1,800. (This number varies with the number of available observation points depending on the duration of precipitation.) This number is smaller by one order than for the radius of 30 km. The reason for the large precipitation values at the radius of 20 km is that the distances between AMeDAS observation points are relatively long compared to the radius of scanning circles, that is, 20km.

Except for the case where the radius is 20 km, the minimum areal precipitation increases linearly with increasing radius of the scanning circle for each value of the duration of precipitation. The curves obtained with the range of the radius from 0 km to 500 km reveal negative values in the secondary differential, indicating an upward convex tendency. We assume that the DA relationship allows linear approximation within a range of 0 km to 250 km for the radius of a scanning circle. As mentioned previously, the case of the radius of 20 km is excluded. Therefore, the approximated linear relationship is expressed by the following Eq.(5).

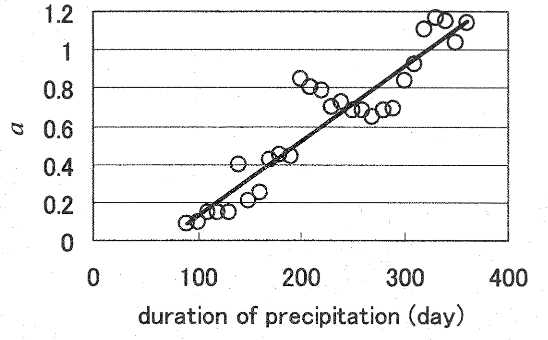


Fig.6 Dependence of constant *a* in quation (5) on the duration of precipitation (*d*)

$$P = ar + b \tag{5}$$

Here, *P* denotes precipitation, and *r* denotes the radius of a scanning circle in km. The constant *b* is calculated from the relationship (Eq.2) between the minimum point precipitation and the duration of precipitation, as shown below.

$$b = 0.0032d^2 - 0.3741d + 15.845 \quad (360 \geq d \geq 90) \tag{6}$$

Then DA curves like Fig.5 are plotted for *d* that satisfies the condition of $90 \leq d \leq 360$, which then yields a regressive equation using Eqs. (5) and (6), namely the constant *a* in eq.(5). The relationship found between *d* and *a* is shown in Fig.6. It is approximated by the following Eq. (7).

$$a = 0.0039d - 0.2646 \tag{7}$$

By means of the procedures described above, Eqs.(5), (6), and (7) are obtained for the DAD relationship shown in Fig.5 by solid lines. It shows that the obtained DAD relationship closely reproduces the plotted data in Fig.5 within the range of $90 \leq d \leq 360$ and $0 \leq r \leq 250$. The detailed physical significance of the DAD relationship shown here needs to be examined in future studies, but conclusions heretofore are:

1) The capability of expressing the DD relationship by means of a quadratic polynomial (eqs.(1) and (6)) which indicates a downward convex tendency, is due to diminishing low precipitation tendencies with increasing temporal scale.
2) Monotone increasing of the DA relationship can be attributed to the diminishing low precipitation tendencies with increasing spatial scale.

Finally, the relationship between the region where the tendency of low precipitation is remarkable and 'scale' was investigated in order to clarify the temporal and spatial structures of low precipitation and to verify the finding mentioned above. In the context of this study, a 'scale' means either a temporal scale (the duration of accumulating precipitation) or a spatial scale (the radius of a scanning circle). Specifically, we confirm the position of the scanning circles by which the values of minimum areal precipitation are calculated for the duration of precipitation (temporal scale) and the radius of a scanning circle (spatial scale). Fig.7 illustrates the scanning circle giving the minimum areal precipitation (hereafter referred to as 'circle of the smallest precipitation'). From these figures as well as from the

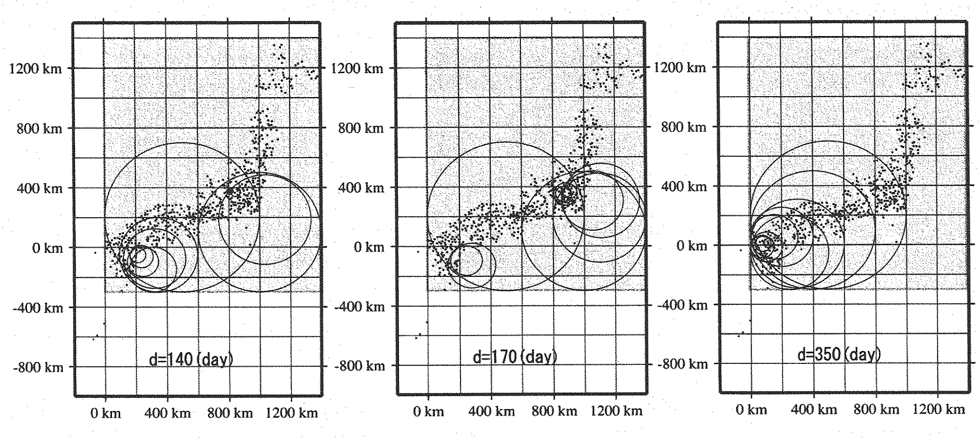


Fig.7 The location of AMeDAS observation points (shown as grids in the figure) and the circle of smallest precipitation. (The durations of precipitation are shown in the figures. The values of the radius of a scanning circle are set to 500, 400, 300, 250, 200, 150, 100, 75, 50, 30, and 20 km. The scanned range is shown by a shaded area.)

results of other values of the duration of precipitation which are not shown here, the following conclusions are drawn:

1) Except for the cases of d = 200 and 210 days, the circle of the smallest precipitation, with a radius of 500 km, comes into contact with the southwest corner of the scanned range. This indicates that a tendency of low precipitation is remarkable in the southwestern part of Japan if the radius of a scanning circle, that is, the spatial scale is large and is around 500 km. Contact of the circle of the smallest precipitation with the southwest corner also indicates that the circle may shift further to the southwest if conditions for the scanning range are altered. In cases of d = 200 and d = 210 days, the circle of the smallest precipitation, with a radius of 500 km, was shown to shift slightly to the east with its center on (775, 200).
2) In case of d = 220 days, the circles of the smallest precipitation with a larger radius contact with the southwest corner, and many of the circles of the smallest precipitation with smaller radii, except for 20 km radius, contact with the west side corner with their center around y = 0 km. Note that all the centers of the circles whose radius are 20km are located in the Kinki region when d is 220 days or larger. Some of the circles of the smallest precipitation which have a radius of 30 km or 50 km are located quite close to the western corner, but do not contact it. These results suggest that southwestern Japan shows marked tendency to experience low precipitation at scales of less than 400 km radius when the duration of precipitation is 220 days or larger. Similar to 1), the possibility of the circle of the smallest precipitation shifting to the west remains when conditions for the scanning area are altered. However, tendency of the circles of the smallest precipitation whose radii are 30 and 50 km indicates that the region where there is a remarkable tendency of low precipitation is the western side of Kyushu's central northern region at these spatial scales. (That is, it does not necessarily shift further to the west.)
3) When d is smaller than 210 days, there is a remarkable tendency of low precipitation in two areas; namely, an area whose center is around the east of the Kyushu region and an area whose center is around the Kanto region under the condition where a radius or spatial scale is smaller than 300km.
4) Some of the circles of the smallest precipitation slant noticeably towards the sea area. This phenomenon may be due to the scanning range of the circle; and it reveals problems which require further research. However, since many

of these circles contain observation points of Tokyo's isolated islands, and most of scanning circles contain sea areas more or less due to the peculiar shape of the Japanese topography, these deviations are unlikely to cast doubt on the conclusions of this study.

CONCLUSIONS

The DAD analysis method has been applied to analyze temporal and spatial characteristics of heavy rainfall. We applied a similar DAD analysis method to low precipitation. If raw data of daily precipitation was used, the DD relationship was defined by the data for areas where the annual volume of precipitation is originally small. Therefore, we used the normalized precipitation by the mean annual precipitation. The findings of this study reveal the following:

1) The relationship between the minimum point precipitation and the duration of accumulating precipitation was obtained.
2) The dependence of the minimum areal precipitation on the radius of a scanning circle was investigated under conditions of the values of duration of precipitation from 90 to 360 days and the radius of a scanning circle of less than 250 km.
3) The DAD equation was calculated using these results. It was found to reproduce closely the original plotted data.
4) The seriousness of the low precipitation for major drought years was evaluated stochastically and statistically.
5) The relationship between low precipitation and scale was deduced from the circle of the smallest precipitation obtained by means of the DA analysis.

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