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A STUDY OF DEPENDENCE PROPERTIES OF RAINFALL DISTRIBUTION ON TOPOGRAPHIC ELEVATION

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SYNOPSIS

For the purpose of making a stochastic model of rainfall distribution, an attempt was made to determine their dependence properties on topography in mountainous regions. Special attention was focused on “the Dependence Line on Topographic Elevation (DLTE)”, which is one of characteristic properties of rainfall distribution. DLTE represents the correlation between rainfall distribution and topographic elevation. Through the analysis of the data observed by a weather radar in Japan, conditions required for establishing the relation of DLTE were determined, and the stochastic properties of rainfall distribution were made clear by analyzing the fluctuation of DLTE and the variance around DLTE of rainfall distribution. Much attention was also focused on “the Temporal Accumulation Process of Rainfall distribution (TAPR)”, which means how the properties of rainfall distribution fluctuate with temporal accumulation of rainfall. The TAPR was conceptually modeled by classifying it into three stages according to an accumulation time scale: the boundaries of the accumulation time scale between the stages and the properties of rainfall distribution in each stage were determined through the analysis of DLTE. Moreover, the primary factor that causes the emergence of topographic effects on rainfall distribution was determined through the analysis of the three indexes which represent the properties of rainfall distribution considering the types of rainfall.

1. INTRODUCTION

One of important subjects on hydrology is determining the properties of spatial-temporal rainfall distribution considering topographic features in a target region. In this paper, for the purpose of making a stochastic model of rainfall distribution, an attempt was made to determine their dependence properties on topography in mountainous regions.

1.1 Study Background

It is well-known that rainfall distribution depend on topographic elevation: rainfall amount increases as topographic elevation increases. Yamada et al.[1], for example, observed rainfall amount with rain gauges located in mountainous regions in Japan at intervals of a few kilometers to ten kilometers, and analyzed the relation between rainfall distribution and topographic elevation. It was found that the degree of the dependence of rainfall on topographic elevation increases as accumulated rainfall amount increases.

On the other hand, spatial-temporal scales of rainfall distribution are great significant to the researches on the dependence properties of rainfall distribution. Oki et al.[2], for example, explained clearly how topographic effects on accumulated rainfall distribution are related to the spatial-temporal scales of rainfall. They concluded that the topographic effects become very significant in an accumulation time scale of one rainfall event or a-few-days rainfall when the spatial scale is supposed to be the scale of a basin. Ninomiya[3] reported similar

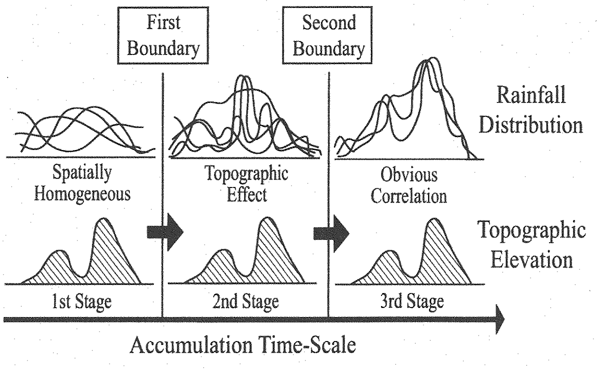


Fig. 1 Schematic figure of the Temporal Accumulation Process of Rainfall Distribution (TAPR) in mountainous regions, which is the process of how the properties of rainfall distribution fluctuate with temporal accumulation of rainfall.

findings by analyzing the geographic distribution of extreme values of rainfall intensity in Japan. He reached the following conclusions. In the case of a short-time scale, the extreme values show spatially homogeneous features. By contrast, in a time scale of one-day rainfall, they show a large bias toward mountainous regions: they depend obviously on topography.

We agree with these conclusions. It seems certain that topography has some effect on rainfall distribution in an accumulation time scale of over one rainfall event. However, in such an accumulation time scale, it is difficult to determine the properties of rainfall distribution because the topographic effects on rainfall vary greatly with each meteorological disturbance. Therefore, it is necessary to investigate the topographic effects from a different viewpoint from past studies for the purpose of estimating them precisely.

Here, Nakakita et al.[4],[5],[7] investigated the topographic effects on rainfall distribution in a longer accumulation time scale than that of one rainfall event (i.e., in a time scale of monthly rainfall). As a result, they concluded that in such an accumulation time scale, it is possible to find a universal relation between rainfall distribution and topography which is independent of meteorological disturbances. They called the relation "hierarchical time-scale structure in the dependence of rainfall distribution on topography". This result suggests that an effective approach is taking such a long time scale into consideration that covers the scale of multiple meteorological disturbances for the purpose of determining the universal properties of topographic effects on rainfall distribution.

1.2 Study Overview

From the standpoints mentioned above, our research was conducted according to the following flow of analysis.

(1) Special attention was focused on topographic elevation as a main topographic factor which is related closely to rainfall distribution to make clear the correlation between them.

(2) The authors found characteristic properties of rainfall distribution, which we call "the Dependence Line on Topographic Elevation (DLTE)". Thus, our research attempted to determine the dependence properties of rainfall distribution on topographic elevation by modeling the stochastic fluctuations of DLTE.

(3) Much attention was also focused on the process of how the properties of rainfall distribution fluctuate with temporal accumulation of rainfall, which we call "the Temporal Accumulation Process of Rainfall Distribution (TAPR)". By determining the properties of the process through the analysis of DLTE, the stochastic properties of rainfall distribution can be made clear.

(4) Moreover, as an analysis from physical aspects, our research investigated how the stochastic properties of DLTE differ between convective rainfall and stratiform rainfall (i.e., how the topographic effects on rainfall distribution differ between the types of rainfall) for the purpose of making clear what is the primary factor of the topographic effects.

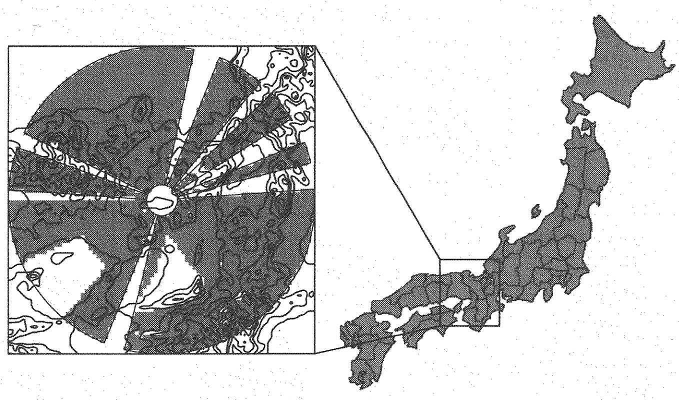


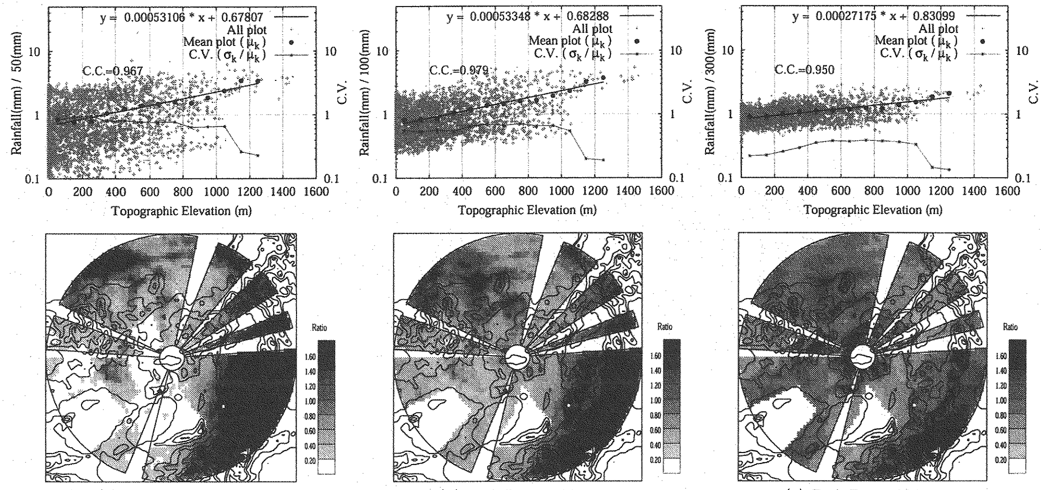
Fig. 2 Target region of this paper in the Kinki region of Japan, which is shown with gray color inside a circular range with a 120 km radius. The regions which have the possibility of even a little problem of ground clutter or shadow were excluded.

Here, we give a complete description of TAPR. As Nakakita et al.[4],[5],[7] suggested, although rainfall distribution accumulated in a short time scale (i.e., in a time scale of one rainfall event) has various fluctuations with holding their dependence on topography, universal relation between rainfall and topography can be found when attention is turned to those in a relatively long time scale (i.e., in a time scale of weekly or monthly rainfall). On the other hand, according to past studies, topographic effects cannot be recognized on the rainfall distribution in a time scale of hourly rainfall because the stochastic properties of topographic effects on such distribution are spatially homogeneous. In other words, although such rainfall distribution is affected by topography, the topographic effects disappear because the random fluctuations of the effects on individual rainfall events dominate the relation between rainfall distribution and topography. However, in the case of the rainfall distribution accumulated in over a time scale of daily rainfall, topographic effects become gradually noticeable.

Based on the above findings, it can be concluded that rainfall distribution in an accumulation time scale has different stochastic properties from that in a different accumulation time scale. In this paper, the process during which the properties of rainfall distribution change with the temporal accumulation of rainfall is called TAPR, and the properties of rainfall distribution in all accumulation time scales are investigated for modeling them. The authors think that TAPR can be classified into three stages according to the accumulation time scale: each stage corresponds approximately to a time scale of hourly rainfall, daily rainfall and monthly rainfall respectively. Thus, it is important to determine the boundary time scales of TAPR and the properties of rainfall distribution in each stage for the purpose of modeling the stochastic structure of rainfall distribution. The concept of TAPR is represented in a schematic form in **Fig. 1**.

1.3 Data Description

As mentioned above, the focus of this paper is to make clear the spatial properties of rainfall distribution. Therefore, our research was conducted using the data observed by a weather radar in Japan to obtain spatially continuous information of rainfall. In detail, the used data were observed by the Miyama radar raingauge, which is located in the Kinki region in Japan. It was managed by the old Japanese Ministry of Construction and is now managed by the Japanese Ministry of Land, Infrastructure and Transport. The observation period of the data is from June to October in 1988 to 1990 and in 1998 (except June in 1998): the total length of the period is 19 months. The observation range is the inside of a circular range with a radius of 120 km. The spatial resolution is 3 km and the temporal resolution is 5 minutes. In this paper, the raw data arranged by polar coordinate were converted to 80×80 grid data arranged by Cartesian coordinate. Since our research focused much attention on the rainfall distribution accumulated for a relatively long period, the regions which have the possibility of even a little problem of ground clutter or shadow were excluded to be adequately on the safe side. As a result, the target region of our research is the region shown in **Fig. 2** with gray color.



(a) R.A.R. = 50 mm (1998.9.1 - 9.15)

(b) R.A.R. = 100 mm (1998.9.1 - 9.16)

(c) R.A.R. = 300 mm (1998.9.1 - 9.22)

Fig. 3 The relation between accumulated rainfall amount and topographic elevation in the three cases of regional average rainfall (R.A.R.) (upper figures), and the spatial distribution of accumulated rainfall in each case (lower figures). In the upper figures, the abscissa represents a topographic elevation and the ordinate represents an accumulated rainfall amount, which is normalized with the R.A.R., on a logarithmic scale.

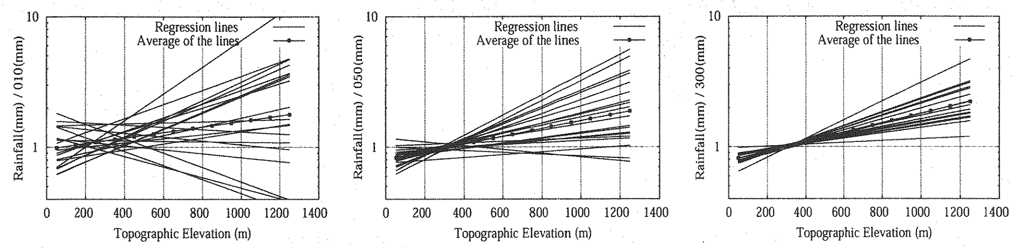
2. DEPENDENCE PROPERTIES OF RAINFALL DISTRIBUTION ON TOPOGRAPHIC ELEVATION

2.1 The Relation between Rainfall Distribution and Topographic Elevation

The relation between accumulated rainfall distribution and topographic elevation in September 1998 in the Kinki region is shown in **Fig. 3**. The lower figures show the spatial distribution of accumulated rainfall in the cases of 50 mm, 100 mm and 300 mm of regional average rainfall (R.A.R.) respectively. In the upper figures, small plots represent each grid in the target region, and the abscissa represents a topographic elevation and the ordinate represents an accumulated rainfall amount, which is normalized with the R.A.R., on a logarithmic scale. In this paper, R.A.R. is used to represent the criterion of the time scale of rainfall accumulation, although the real-time scale was used in the researches of Nakakita et al.[5],[7].

Here, we give a detailed description of DLTE, which was found to exist through our research (Nakakita et al.[6]). **Fig. 3** shows that the relation between accumulated rainfall amount and topographic elevation is so widely dispersed as a whole that no clear correlation can be recognized. However, when attention is turned to the stratified sampling averages of accumulated rainfall amount and topographic elevation with the stratification of the latter at appropriate intervals, a definite correlation between them can be recognized. It is found from the figures that the stratified sampling averages of them show a definitely linear relation with high correlation coefficient of over 0.9 on a semilogarithmic plot as represented with black circles in the figures, where the intervals of stratification are 100 m of topographic elevation. This linear relation between averaged topographic elevation and the logarithmic value of averaged rainfall amount in each class of elevation is refered to as "the Dependence Line on Topographic Elevation (DLTE)" of rainfall distribution. This linear relation of DLTE is one of noticeable properties which represent the dependence properties of rainfall distribution on topographic elevation. The authors ascertained that the same relation between them exists in the southern Kyushu region in Japan. Thus, DLTE is not the characteristic properties only in the Kinki region in Japan.

Furthermore, it is found in **Fig. 3** that the dispersion of the whole small plots decreases and the plots gather gradually around the DLTE with temporal accumulation of rainfall (i.e., as R.A.R. increases). Thus, the dependence properties of rainfall distribution can be explained by taking into account the following two properties.



(a) R.A.R. = 50 mm (b) R.A.R. = 100 mm (c) R.A.R. = 300 mm

Fig. 4 The fluctuations of the slope of DLTE in the three cases of R.A.R. The ordinate represents an accumulated rainfall amount, which is normalized with the R.A.R., on a logarithmic scale.

(1) the average properties represented with DLTE

(2) the properties of variance (degree of dispersion) around DLTE

The temporal accumulation process of rainfall distribution (TAPR) is the process during which these properties change with temporal accumulation of rainfall (i.e., as R.A.R. increases). In the following subsection, the properties of fluctuation of DLTE are determined. The properties of variance of DLTE and the properties of TAPR are investigated in the Section 3.

2.2 The Properties of Fluctuation of DLTE

In this section, the formulation of DLTE is described as follows. First, DLTE can be expressed by the following equation,

$$\ln\left\{\frac{\mu_k(T)}{\mu(T)}\right\} = a \cdot Z_k + b\ , \tag{1}$$

where $\mu(T)$ (mm) = R.A.R in the accumulation time scale T; $\mu_k(T)$ (mm) = spatial average of accumulated rainfall amount in the class k of elevation; Z_k (m) = spatial average of topographic elevation in the class k of elevation; and a,b = parameters. When it is assumed that the relation between the logarithmic values of spatial averages of accumulated rainfall amount ($\ln\{\mu_k(T)\}$) and spatial averages of topographic elevation (Z_k) is completely linear (i.e., the correlation coefficient of DLTE is equal to 1), the R.A.R. which is computed from the equation of DLTE (**Eqs. 1**) is equal to the R.A.R. which is computed from the observation data. Thus, the following equation can be derived.

$$\mu(T) = \left\{\sum_k \mu_k(T) \cdot V_k\right\} \Big/ \sum_k V_k\ , \tag{2}$$

where V_k (km^2) = area in the class k of elevation. From the equations of **Eqs. 1** and **Eqs. 2**, DLTE is eventually expressed using the following equation (Nakakita et al.[6]),

$$\ln\left\{\frac{\mu_k(T)}{\mu(T)}\right\} = a \cdot Z_k + \ln\left\{\frac{\sum_k V_k}{\sum_k \exp(a \cdot Z_k) \cdot V_k}\right\}\ . \tag{3}$$

In the next stage of this investigation, about 19 samples of rainfall distribution which has a specific R.A.R. in various accumulation periods were produced for various cases of R.A.R. to analyze the properties of fluctuation of DLTE. The linear lines of DLTE which were obtained from all samples are shown in **Fig. 4** in the cases of 10 mm, 50 mm and 300 mm of R.A.R. respectively. The abscissa and the ordinate represent the same as those of upper figures in **Fig. 3**. Two characteristic features described as follows can be found in **Fig. 4**:

(1) the fluctuation of the slope decreases as R.A.R. increases,

(2) all of the DLTE tend to intersect almost a unique point of around 300 m of topographic elevation.

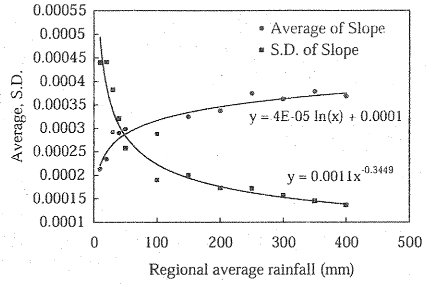


Fig. 5 The average value and the standard deviation (S.D.) of the slope of DLTE in various cases of R.A.R.

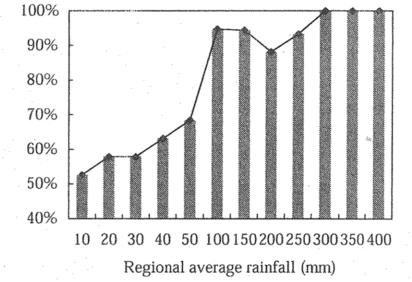


Fig. 6 The percentage of the samples which have the C.C. over 0.8 in each case of R.A.R.

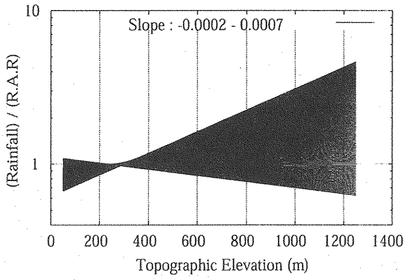


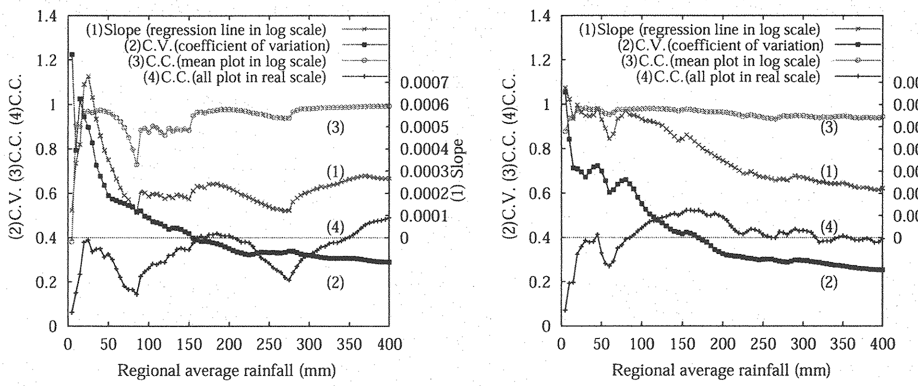
Fig. 7 Sensitivity analysis for the formula of DLTE. The slope was changed from -0.0002 to 0.0007. The ordinate represents an accumulated rainfall amount, which is normalized with the R.A.R., on a logarithmic scale.

To investigate feature (1) in detail, the average value and the standard deviation of the slope of DLTE were computed in various cases of R.A.R. The results are shown in **Fig. 5**. They indicate that the variance of the slope decreases as R.A.R. increases and then converges into an almost constant value when the R.A.R. is more than the value from 200 to 250 mm. At the same time, the variance is extremely large at less than 50 mm of R.A.R., and the same feature can be found in **Fig. 4**.

Moreover, the correlation coefficient (C.C.) of DLTE in each sample distribution was also computed in various cases of R.A.R. The percentage of the samples which had the C.C. over 0.8 in each case of R.A.R. is shown in **Fig. 6**. Findings show that over 90 percent of the samples had the C.C. over 0.8 in the case that the R.A.R. was more than 100 mm, and that most samples in the case that the R.A.R. was less than 50 mm had only a relatively smaller value of the C.C.

These results lead us to the following conclusion. In the figure of **Fig. 4** (a), where the R.A.R. is 50 mm, the variance of the slope of DLTE is extremely large because the linear relation of DLTE cannot be established with high correlation in the case of such a small R.A.R. Therefore, it is said that one of conditions required for establishing the linear relation of DLTE is that R.A.R. should be more than the threshold value from 50 to 100 mm.

On the other hand, a sensitivity analysis for the formula of DLTE of **Eqs. 3** was conducted by changing the parameter a which represents the slope of DLTE after the data of topographic elevation in the target region were assigned to Z_k. The case where slope a was changed from -0.0002 to 0.0007 is shown in **Fig. 7**, in which the abscissa and the ordinate represent the same as those in **Fig. 4**. Almost the same feature as feature (2) in **Fig. 4** can be found in **Fig. 7**: all of the DLTE tend to intersect almost at a unique point of around 300 m of topographic elevation. This result means that the feature (2) is one of the characteristic features under the condition that the linear relation of DLTE is established with high correlation: R.A.R. is more than the threshold value from 50 to 100 mm. At the intersection point of DLTE, where the topographic elevation is around 300 m, the value of the ordinate in **Fig. 4** and **Fig. 7** is almost equal to 1: (rainfall amount)/(R.A.R.) = 1. This means that the value of averaged rainfall in the area with around 300 m of topographic elevation always corresponds approximately to R.A.R. in the target region. It is, however, supposed that the intersection point of 300 m of topographic elevation is dependent on the spatial distribution of topographic elevation in the target region, and varies from region to region.



(a) Accumulation from 1990.9.1

(b) Accumulation from 1998.9.1

Fig. 8 The stochastic properties of rainfall distribution in various cases of R.A.R. (1) the slope of DLTE, (2) the C.V., which is the average of the C.V. in all classes of elevation, (3) the C.C. of DLTE, and (4) the C.C. between accumulated rainfall distribution and topographic elevation.

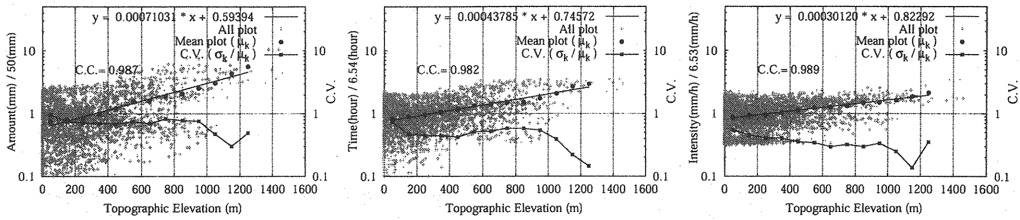
3. THE TEMPORAL ACCUMULATION PROCESS OF RAINFALL DISTRIBUTION (TAPR)

In this section, we describe our analysis of the temporal accumulation process of rainfall distribution (TAPR) on the basis of our research carried out on the linear relation of DLTE. When attention is focused on the relation between accumulated rainfall distribution and topographic elevation shown in **Fig. 3**, the findings confirm again that the dispersion of the whole plots decreases and the plots gather gradually around the DLTE as R.A.R. increases. This means, in the strict sense, that the dispersion decreases relatively to the average value in the target region because the accumulated rainfall amount which was normalized by the R.A.R. is plotted in **Fig. 3**. In this figure, as an index which represents the degree of the dispersion of the plots, the coefficient of variation (C.V.) of rainfall distribution in each class of elevation is also plotted with a broken line. This graph shows that the C.V. tends to decrease as R.A.R. increases. Note that these values of C.V. are not computed with the logarithmic values but with the real values of rainfall amount.

Moreover, **Fig. 8** shows how these stochastic properties of rainfall distribution change as R.A.R. increases. In this figure, four indexes which represent the properties of rainfall distribution are plotted in the two cases where accumulation of rainfall began on September 1 in 1990 and 1998. When attention is focused on (2) the C.V., which is the average of the C.V. in all classes of elevation, the average value of the C.V. decreases gradually as R.A.R. increases, which is the same feature as mentioned above. Special attention has to be focused on the fact that the average value of the C.V. converges into an almost constant value when the R.A.R. is more than the value from 200 to 250 mm. This indicates that it is possible to find definite dependence properties on topography when R.A.R. is more than the threshold scale from 200 to 250 mm because the fluctuation of the relation between rainfall distribution and topography becomes very small in such an accumulation time scale. In this sense, the R.A.R. from 200 to 250 mm can be taken as a boundary scale of the temporal accumulation process of rainfall distribution (TAPR) as shown in **Fig. 1**. Indeed, the real time scale which corresponds to the boundary scale from 200 to 250 mm of R.A.R. is about 20 to 30 days, and it is almost equal to the boundary scale of 20 days, which was found by Nakakita et al.[4],[5],[7] as a result of their research carried out on the hierarchical time-scale structure of rainfall distribution in the southern Kyushu region of Japan.

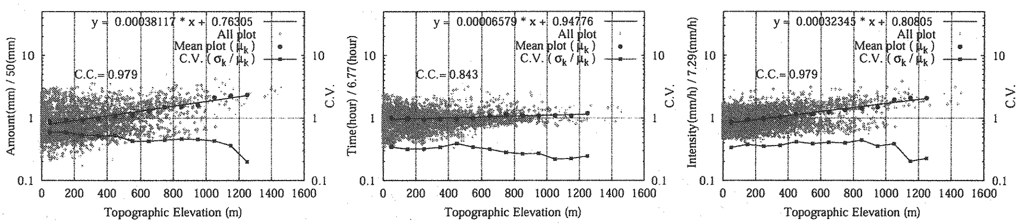
As described above, findings show that the properties of variance around DLTE of rainfall distribution change at the boundary scale from 200 to 250 mm of R.A.R. On the other hand, as described in the section 2, one of conditions required for establishing the linear relation of DLTE is that R.A.R. should be more than the threshold value from 50 to 100 mm. It was also described that the fluctuation of the slope of DLTE tends to converge into a constant value when R.A.R. is more than the threshold value from 200 to 250 mm. These findings lead us to the conclusion that the properties of rainfall distribution change at the accumulation time scales corresponding to the threshold values from 50 to 100 mm and from 200 to 250 mm of R.A.R., because establishing the linear relation of DLTE indicates the emergence of topographic effects on rainfall distribution.

As a result, the temporal accumulation process of rainfall distribution (TAPR) in mountainous regions



(a) accumulated rainfall amount (A.R.A.) (b) accumulated rainfall time (A.R.T.) (c) average rainfall intensity (A.R.I.)

Fig. 9 The relation between each index (A.R.A., A.R.T. and A.R.I.) and topographic elevation, and the linear line of DLTE on each distribution in August 10 in 1988 (a case of convective rainfall). The ordinate represents a value of each index, which is normalized with each regional average value, on a logarithmic scale.



(a) accumulated rainfall amount (A.R.A.) (b) accumulated rainfall time (A.R.T.) (c) average rainfall intensity (A.R.I.)

Fig. 10 The relation between each index (A.R.A., A.R.T. and A.R.I.) and topographic elevation, and the linear line of DLTE on each distribution in September 13 in 1989 (a case of stratiform rainfall). The ordinate represents a value of each index, which is normalized with each regional average value, on a logarithmic scale.

can be modeled as a process which can be classified into three stages, as shown in the schematic form of **Fig. 1**. The first boundary scale of TAPR is the value from 50 to 100 mm of R.A.R., and the second one is the value from 200 to 250 mm of R.A.R. The properties of rainfall distribution in each stage of TAPR can be described as follows:

(1) In the first stage (e.g., in a time scale of hourly rainfall), the linear relation of DLTE is not established because the random fluctuations of topographic effects on individual rainfall events dominate the relation between rainfall distribution and topographic elevation. Therefore, universal topographic effects on rainfall distribution are not recognized although there are various topographic effects in reality. The stochastic properties of rainfall distribution can be said to be spatially homogeneous.

(2) In the second stage (e.g., in a time scale of daily rainfall), topographic effects on rainfall distribution gradually emerge, and the relation of DLTE tends to be established although the fluctuation of rainfall distribution is still large.

(3) In the third stage (e.g., in a time scale of monthly rainfall), definite topographic effects can be recognized, and the relation of DLTE is completely established, because the variance (degree of dispersion) around DLTE of rainfall distribution becomes small and converges into a stationary state.

In this section, the properties of TAPR in mountainous regions were determined through the analysis of DLTE. Furthermore, the dependence properties of rainfall distribution are investigated from the viewpoint of their physical structure in the following section.

4. DEPENDENCE PROPERTIES ON TOPOGRAPHY CONSIDERING THE TYPES OF RAINFALL

As described in the section 2, the relation of DLTE can be established when R.A.R. is more than the threshold value from 50 to 100 mm. However, the slope of DLTE and the properties of variance around

Table 1 The sample averages of the slopes S_a, S_t and S_i of DLTE in convective or stratiform rainfall, which were computed using 6 samples of convective rainfall and 7 samples of stratiform rainfall

Slope ($\times 10^{-4}$)	convective	stratiform	convective / stratiform
S_a (A.R.A.)	5.354	2.585	2.071
S_t (A.R.T.)	4.359	0.603	7.232
S_i (A.R.I.)	1.063	2.049	0.518
S_t/S_a	0.8393	0.1843	
S_i/S_a	0.1683	0.8414	

Table 2 The sample averages of the C.V. in convective or stratiform rainfall, which were computed by averaging the average values of the C.V. in all classes of elevation

C.V.	convective	stratiform	convective / stratiform
V_a (A.R.A.)	0.5868	0.4692	1.251
V_t (A.R.T.)	0.4521	0.2813	1.607
V_i (A.R.I.)	0.3349	0.3340	1.003
V_t/V_i	1.350	0.842	

DLTE change considerably according to the types of accumulated rainfall events (i.e., convective or stratiform rainfall), because the properties of rainfall distribution differ with the types of rainfall events. Therefore, it is very important to determine the relation between the stochastic properties and the physical structure of rainfall distribution for the purpose of making a stochastic model of rainfall distribution.

Some samples of rainfall distribution which have 50 mm of R.A.R. were produced by accumulating one or two rainfall events whose type of rainfall could be clearly distinguished. Then, their dependence properties on topographic elevation were investigated on the basis of DLTE. The types of rainfall events were distinguished by means of past weather charts. In this paper, in order to determine the primary factor of topographic effects on rainfall distribution, spatial distributions of three types of indexes which represent the properties of rainfall distribution were computed and compared with each other. The three types of indexes are defined as follows.

(1) accumulated rainfall amount (A.R.A.): the total amount of rainfall accumulated at each grid as used in the above sections.

(2) accumulated rainfall time (A.R.T.): the total length of time when rainfall intensity at each grid is more than 1 mm/h.

(3) average rainfall intensity (A.R.I.): the intensity which is computed by dividing A.R.A. by A.R.T. (i.e., the average value of the rainfall intensity during the accumulated rainfall time (A.R.T.)).

Fig. 9 and **Fig. 10** show the relation between each index and topographic elevation in the case that the accumulated rainfall distribution has 50 mm of R.A.R. and an accumulation period of about one day. The linear line of DLTE on the distribution of each index is also shown in each figure. The ordinate represents the value of each index, which is normalized with each regional average value, on a logarithmic scale. The dominated type of rainfall in the case of **Fig. 9** is convective rainfall, which was caused by mainly a low pressure system on August 10, 1988. That in the case of **Fig. 10** is stratiform rainfall, which was caused by an autumnal rain front on September 13, 1989. In the following description, S_a, S_t and S_i represent the slope of DLTE on the distribution of A.R.A., A.R.T. and A.R.I. respectively.

First, attention should be focused on **Fig. 9** (a) and **Fig. 10** (a). By comparison between them, the slope S_a of DLTE on A.R.A. in the former figure (i.e., a case of convective rainfall) is larger than that in the latter figure (i.e., a case of stratiform rainfall). Therefore, it can be concluded that the A.R.A. of convective rainfall is dependent more highly on topographic elevation than that of stratiform rainfall is. Findings indicate that the variance around DLTE of the A.R.A. is relatively larger in the former. Secondly, attention should be turned to **Fig. 9** (b), (c) and **Fig. 10** (b), (c). A comparison among them indicates that the slope S_t of DLTE on A.R.T. is larger than the slope S_i of DLTE on A.R.I. in the case of convective rainfall in **Fig. 9**. On the contrary, in the case of stratiform rainfall shown in **Fig. 10**, the slope S_t is nearly zero and is smaller than the slope S_i. At the same time, the slope S_i in convective rainfall is a little smaller than that in stratiform rainfall.

Furthermore, the sample averages of the slopes S_a, S_t and S_i of DLTE were computed using more samples of rainfall distribution which has 50 mm of R.A.R. as shown in **Table 1**. Six samples of convective rainfall and seven samples of stratiform rainfall were used to compute them. Also, **Table 2** shows the sample averages of the C.V. of rainfall distribution, which were computed by averaging the average values of the C.V. in all classes of elevation. The findings discussed above, which were derived from **Fig. 9** and **Fig. 10**, can be confirmed through the results of **Table 1**. **Table 2** shows that the variance (degree of dispersion) on A.R.T. in convective rainfall is 1.6 times larger on average than that in stratiform rainfall. On the contrary, there is no significant difference in the variance on A.R.I. between the types of rainfall.

Here, when the values of A.R.A., A.R.T. and A.R.I. at each grid in the target region are represented by X_a, X_t and X_i respectively, the relation among the three values can be written as $X_a = X_t \times X_i$. Thus, a equation of $\log X_a = \log X_t + \log X_i$ is easily derived. Moreover, by considering the fact that the linear relation of DLTE is established on a semilogarithmic plot, the following equation concerning the slopes of DLTE on the three indexes can be derived almost exactly under the condition that the linear relation of DLTE is established with high correlation,

$$S_a = S_t + S_i \ , \tag{4}$$

where S_a = the slope of DLTE on A.R.A.; S_t = the slope of DLTE on A.R.T.; and S_i = the slope of DLTE on A.R.I. It can be confirmed that this relation among the three slopes is established clearly in **Fig. 9** and **Fig. 10**. However, such a relation among the intercepts of DLTE on the three indexes is not established in these figures because the ordinates are normalized with the regional average value of each index, although the slopes of DLTE are not changed by the normalization. Thus, in the case that the values of each index are not normalized, such a equation concerning the intercepts of DLTE is established approximately.

Because the slopes S_a, S_t and S_i can be interpreted to represent the degree of the dependence of each index on topographic elevation, topographic effects on rainfall distribution can be measured by the magnitude of the slope S_a, which is the summation of the slopes S_t and S_i. Thus, the contribution of A.R.T. and A.R.I. to the emergence of topographic effects can be estimated by the values of S_t/S_a and S_i/S_a. As shown in **Table 1**, the sample averages of these values were computed for each type of rainfall: convective rainfall and stratiform rainfall. **Table 1** shows that the contribution of A.R.T. is approximately four times larger than that of A.R.I. in convective rainfall, and that, on the contrary, the contribution of A.R.I. is approximately four times larger than that of A.R.T. in stratiform rainfall. These findings lead us to the following conclusions:

(1) In the case of convective rainfall, the degree of the dependence of A.R.T. on topography is very high: the rainfall time which is accumulated in the region with high elevation is much longer than that in the region with low elevation. Thus, it can be concluded that the primary factor that causes the emergence of topographic effects is the dependence of A.R.T. on topography. In other words, the dependence of rainfall distribution on topography is produced by the dependence of A.R.T. On the other hand, the variance (degree of dispersion) of rainfall distribution is also primarily derived from the distribution of A.R.T.

(2) In the case of stratiform rainfall, the emergence of topographic effects on rainfall distribution are caused mainly by the dependence of A.R.I. on topography, although the effects are estimated to be approximately half as large on average as those in convective rainfall.

The results of this study lead us to the following conclusion that the mechanism of the emergence of topographic effects on rainfall distribution can be understood as follows. In the case of convective rainfall, it is well-known that convective cells are more liable to be generated continually in the region with high elevation than in the region with low elevation. Also, because they tend to organize themselves to be a convective system which has a relatively large spatial-temporal scale, the life time of a rainfall event becomes longer in the region with high elevation. On the other hand, because the intensity of the self-organized convective system is determined mainly by the atmospheric conditions on a synoptic scale, once mountains take a role as a trigger for the convective system, the distribution of rainfall intensity does not have close correlation with topographic elevation. This is the reason why the dependence of A.R.I. on topographic elevation is much smaller than that of A.R.T.

In the case of stratiform rainfall, because rainfall depends mainly on the atmospheric conditions on a synoptic scale, the stochastic properties of the distribution of A.R.T. are almost uniform in space. Thus, the dependence of A.R.T on topographic elevation becomes very small on the whole. However, because moisture ascending along the slops of mountains strengthens rainfall intensity, the dependence of A.R.I. is only a little larger than that of A.R.T.

Nakakita et al.[5],[7] indicated that the dependence of the distribution of accumulated rainfall time on topography is very large in the case of convective rainfall, which corresponds to the results of our research.

5. CONCLUSION

In this paper, for the purpose of making a stochastic model of rainfall, an attempt was made to determine the dependence properties of rainfall distribution on topographic elevation in mountainous regions through the analysis of the data observed by a weather radar in Japan. The findings of this study are summarized as follows:

(1) Conditions required for establishing "the Dependence Line on Topographic Elevation (DLTE)", which characterizes the dependence properties of rainfall distribution on topographic elevation, were determined. The stochastic properties of rainfall distribution were also determined by analyzing the fluctuation of DLTE and the variance around DLTE of rainfall distribution.

(2) "The Temporal Accumulation Process of Rainfall distribution (TAPR)" was conceptually modeled by classifying it into three stages according to the accumulation time scale. Moreover, the boundaries of the accumulation time scale between the stages and the properties of rainfall distribution in each stage were determined on the basis of the properties of DLTE.

(3) It was demonstrated through the analysis of DLTE how the relation between rainfall distribution and topography varies according to the types of rainfall (i.e., between convective rainfall and stratiform rainfall). Moreover, the primary factor that causes the emergence of topographic effects on each type of rainfall distribution was determined through the analysis of three indexes which represent the properties of rainfall distribution.

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