

Numerical study of rainfall–topography relationships in mountainous regions of Japan using a mesoscale meteorological model

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Abstract Rainfall–topography relationships are investigated through numerical simulations using the mesoscale atmospheric model MM5. For a quantitative evaluation of topographic effects on rainfall distribution, a rainfall–elevation relationship, the Dependence Line on Topographic Elevation (DLTE) of rainfall distribution, was examined in four mountainous regions in Japan. The results confirmed that DLTE is one of the fundamental properties of rainfall distributions. The conditions required for the formation of DLTE were investigated as well as the fluctuation properties around DLTE in each region. The effects of wind on rainfall distribution were also examined to understand the mechanism of rainfall–topography relationships. The results show that there is a definite correlation between the strength of horizontal wind and the slope of DLTE, although the strength of the correlation differs from region to region.

Key words mesoscale meteorological model, MM5; numerical simulation; rainfall distribution; rainfall–elevation relationships; topographic effect

INTRODUCTION

For hydrological applications and water resources management, it has been required to understand the spatial and temporal structures of rainfall distribution related to topographic properties in a watershed. For understanding the mechanism of rainfall–topography relationships and developing a stochastic model of rainfall distribution, the rainfall–topography relationships are analysed through numerical simulations using the mesoscale meteorological model MM5.

The fluctuations of rainfall distribution depend on atmospheric conditions and topographic features such as moisture distribution, wind speed, wind direction, topographic elevation, slope orientation, barrier characteristics and scale of mountains. This study focuses on topographic elevation as one of the most significant factors because it has predominant effects on rainfall distribution on the spatial and temporal scale of meso β or meso α .

A great number of investigations on rainfall–elevation relationships have been conducted from the beginning of the twentieth century (e.g. Lee, 1911; Alter, 1919; Henry, 1919; Varney, 1920). According to these authors, it is already evident worldwide that rainfall amounts generally increase with topographic elevation. However, the quantitative nature of rainfall–elevation relationships has not yet been determined, and therefore analyses using weather radar were required for understanding the physical mechanism and for developing a rainfall model that well describes the stochastic properties. Recent studies investigate the relations between rainfall and topography using a numerical meteorological model (e.g. Colton, 1976; Alpert, 1986; Barros & Lettenmaier, 1994; Oishi *et al.*, 1996). The main factors that determine the amount and the distribution of rainfall were made clear to some extent through the simulations under various conditions of the height of a mountain, the slope of a mountain, the speed of synoptic wind, etc. These investigations, however, have not yet led us to a comprehensive discussion with consideration to the universality or the singularity of actual rainfall–topography relationships.

The authors investigated rainfall–elevation relationships through the analysis of the data from a weather radar in a mountainous region in Japan, which has an area of 240×240 km (Suzuki *et al.*, 2002). As a result, it was found that a definite linear relationship between stratified (piecewise) sampling averages of accumulated rainfall amount and topographic elevation was represented by a semi-logarithmic relation (i.e. rainfall–elevation relationships are exponential as a whole). This relationship is called the Dependence Line on Topographic Elevation (DLTE) of rainfall distribution. Figure 1 shows an example of rainfall–elevation plots and the linear relation of DLTE obtained from a weather radar observation in the Kinki region of Japan. The correlation between the stratified sampling averages represented by black circles and topographic elevation is more than 0.9. The topographic properties in the study region and the properties of rainfall events are well reflected in the value of the slope of DLTE. In other words, the linear relation of DLTE represents the fundamental and average properties of rainfall–elevation relationships in a study region. However, it has not been clarified whether the linear relation of DLTE is a universal property. In this paper, the characteristics of DLTE obtained through numerical simulations using a physically-based numerical model MM5 are investigated.

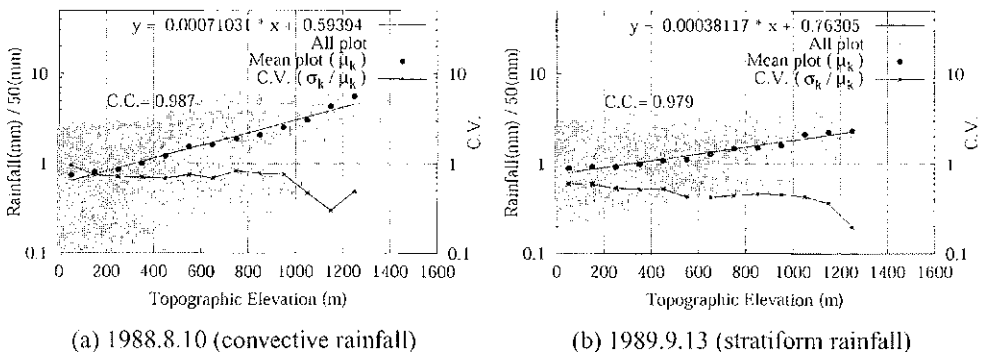


Fig. 1 Rainfall–elevation relationships and the linear relation of DLTE obtained by the Miyama radar rain gauge observation in the Kinki region of Japan.

DESCRIPTION OF SIMULATIONS IN THIS STUDY

MM5, the fifth-generation NCAR/Penn State mesoscale model, has a multiple-nest capability, non-hydrostatic dynamics and a four-dimensional data assimilation capability. The nesting method simulates several domains running at the same time with two-way interaction. In this study, three domains with the grid scales of 27 km, 9 km and 3 km (Domain 1, Domain 2 and Domain 3, respectively) were set in all simulations. Initial and boundary conditions were produced by interpolating the six hourly GPV data, including geopotential height, temperature, wind speed and humidity, which were provided by the Japan Meteorological Agency.

Simulations were carried out in the four mountainous regions of southern Kyushu, southern Kinki, Shikoku and Chubu in Japan. By comparison of simulation results among the regions, rainfall–topography relationships were investigated. For each region, 15 atmospheric simulations were conducted. The simulation period of each case was for 2 days.

DLTE OF RAINFALL DISTRIBUTION FROM NUMERICAL SIMULATIONS

Figure 2 represents the simulation results of 2-days-accumulated rainfall amount and rainfall–elevation relationships in each region. The figures show a linear relation is formed in every case between the stratified sampling averages of accumulated rainfall and topographic elevation. The linear relations of DLTE are found not only in observed rainfall but also in simulated rainfall fields. This means the DLTE is one of the universal properties which could be measured in various regions. This result leads us to the thought that DLTE is not one of the statistical properties of rainfall distribution, but one of the properties based on a physical mechanism of rainfall.

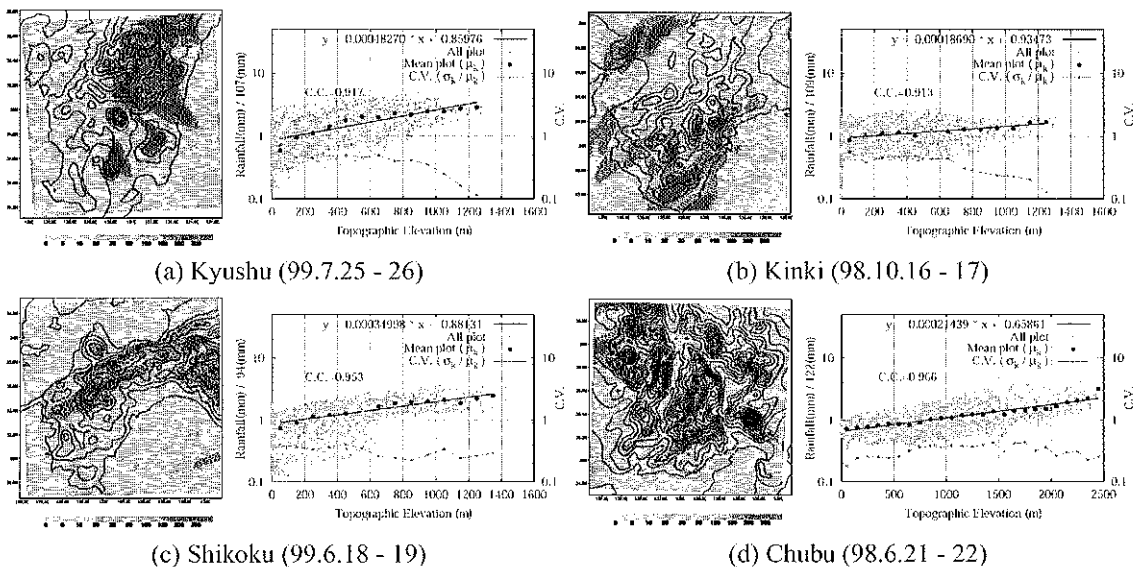


Fig. 2 Simulation results of 2-days-accumulated rainfall amount (mm) (left figures), and rainfall–elevation relationships (right figures).

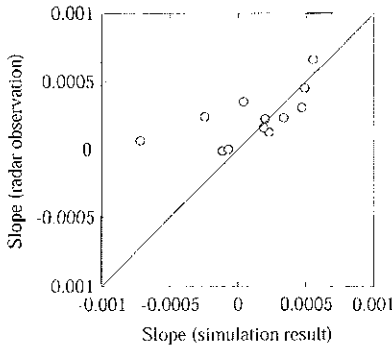


Fig. 3 Comparison between the slope of DLTE from the numerical simulations and that from the observations by Miyama radar raingauge in the Kinki region of Japan.

Furthermore, the slopes of DLTE from the simulation results were compared with those obtained from a weather radar in the Kinki region of Japan. The result is shown in Fig. 3. The slope of DLTE represents the degree of topographic effects on rainfall distribution. The figure shows that there is a strong correlation between the slopes from the numerical simulations and those from the radar observations, except for a few cases. Rainfall–elevation relationships shown by DLTE are reproduced with sufficient accuracy by a physically-based numerical model, even if the reproducibility of the position or the amount of rainfall is not so high. This also proves that DLTE is one of the universal properties of rainfall distribution.

The authors have found, through the analysis with a weather radar, that one of the conditions required for the formation of DLTE is a regional average rainfall (RAR) over 50–100 mm (Suzuki *et al.*, 2002). Here, RAR represents the scale of rainfall accumulation. In this study, the conditions in each region were investigated through the numerical simulations. The root mean square error (*RMSE*) of the stratified sampling averages against DLTE was used as the criterion for judging the formation of DLTE. The authors decide the DLTE is formed when the *RMSE* is less than 0.1. The *RMSE* was computed for 15 cases of the simulation results in each region, and the relation between RAR and the percentage of the cases which meet the conditions was investigated. Figure 4 shows that DLTE is formed on more than 90% cases when RAR

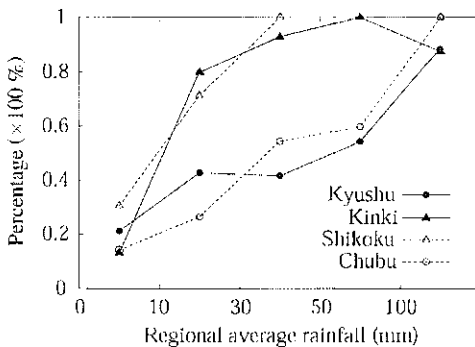


Fig. 4 The relation between regional average rainfall (RAR) and the percentage of the cases where *RMSE* of the stratified sampling averages against DLTE is less than 0.1.

is more than 30 mm in the Kinki and the Shikoku regions and more than 100 mm in the Kyusyu and the Chubu regions. DLTE is formed in most of the cases where RAR is over 100 mm in every region, which corresponds to the author’s previous analysis using radar observation.

EFFECTS OF WIND ON RAINFALL–TOPOGRAPHY RELATIONSHIPS

Various physical values such as wind speed, humidity and temperature, are obtained through numerical simulations. Among them, wind speed and wind direction have great impacts on rainfall distribution because they determine the strength and direction of ascending flows which could develop precipitation. The effects of wind on rainfall distribution are examined for understanding the mechanism of rainfall–topography relationships.

Relation between wind speed and rainfall distribution

The simulated results in Kyushu region in 13–14 June 1998 (case-1) and in 6–7 October 1998 (case-2) were analysed. In case-1 the slope of DLTE is relatively large and in case-2 small among the simulation results. Figure 5 represents the simulation

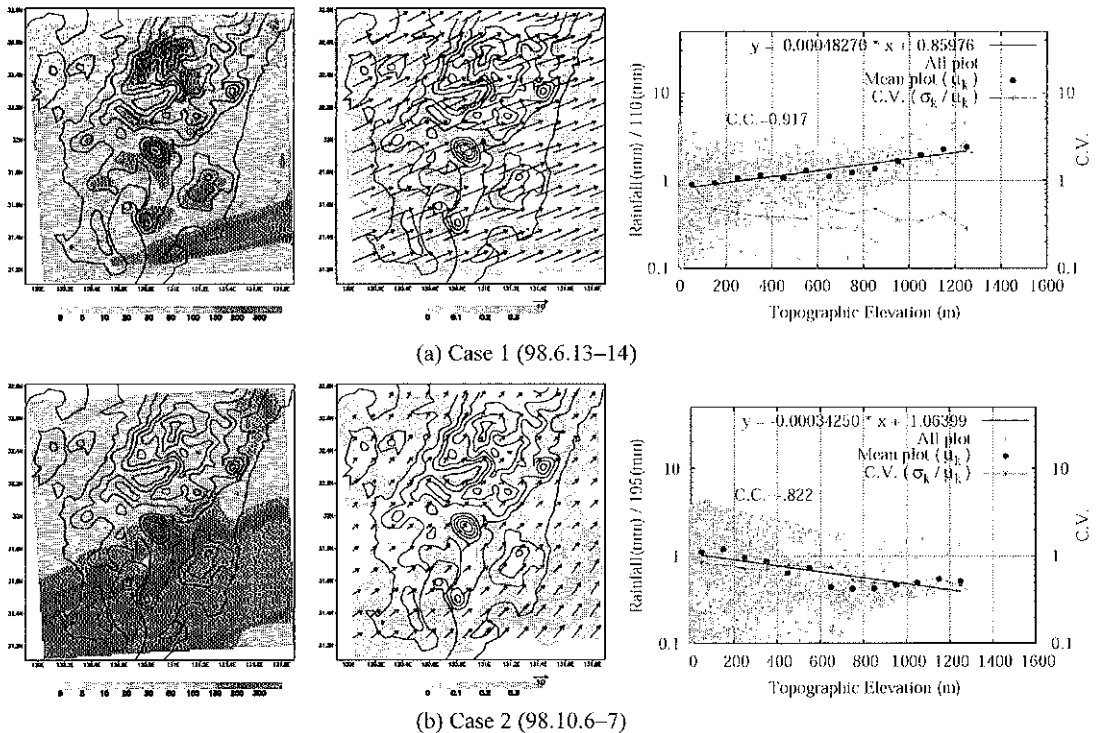


Fig. 5 Simulation results of 2-days-accumulated rainfall amount (mm) (left figures), two-days-averaged speed of horizontal wind (arrows) and vertical wind (contours) (m) (centre figures), and rainfall–elevation relationships (right figures) in the Kyushu region.

results of 2-days-accumulated rainfall, 2-days-averaged speed of horizontal and vertical wind fields, and rainfall–elevation relationships. The wind field data on an isobaric surface of 800 hPa (i.e. an altitude of about 2000 m) was used in this investigation.

In case 1, horizontal wind is strong as a whole and strong ascending flows occur on the windward side of mountains as shown in the centre figures. In case 2, horizontal wind is weak and ascending flows occur on the southeast sea far from mountains. In case 1, the rainfall distribution shown in the left figure has peaks on the top of mountains, and in case 2 much rainfall occurred on the southeast sea. The area with much rainfall corresponds well to the area with strong ascending flows, which occur above the mountains when horizontal wind is strong. This means that flows are forced to ascend along the slope of mountains when horizontal wind is strong and the height of mountains is high enough. The ascending flows then become convection that brings much rainfall. That is the reason why the slope of DLTE becomes large when horizontal wind is strong, and there is a strong correlation between the strength of horizontal wind and the slope of DLTE.

Relation between horizontal wind speed and the slope of DLTE

The relation between regional averaged speed of horizontal wind (H) and the slope of DLTE (S) were examined in each region. The value of H was obtained by averaging wind spatially in a study region and then averaging temporally during 2 days. Figure 6 shows that there is a definite correlation between H and S and the strength of the correlation differs from region to region. Correlation coefficient (CC) is high in the

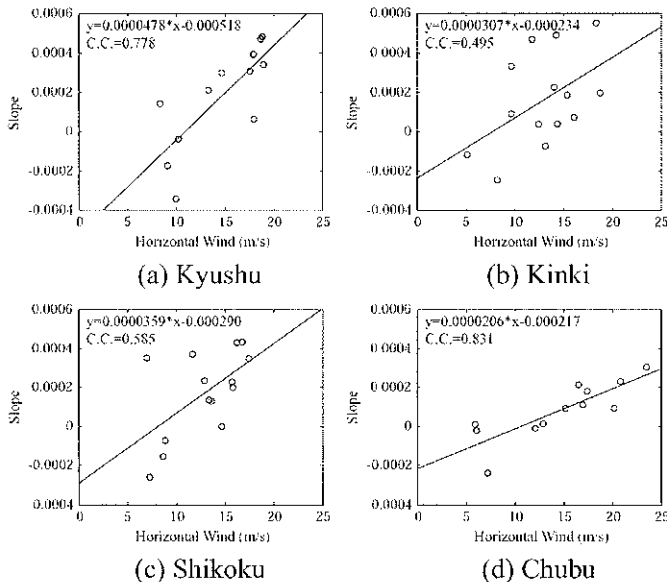


Fig. 6 The relation between regional averaged speed of horizontal wind and the slope of DLTE from the simulation results in each region.

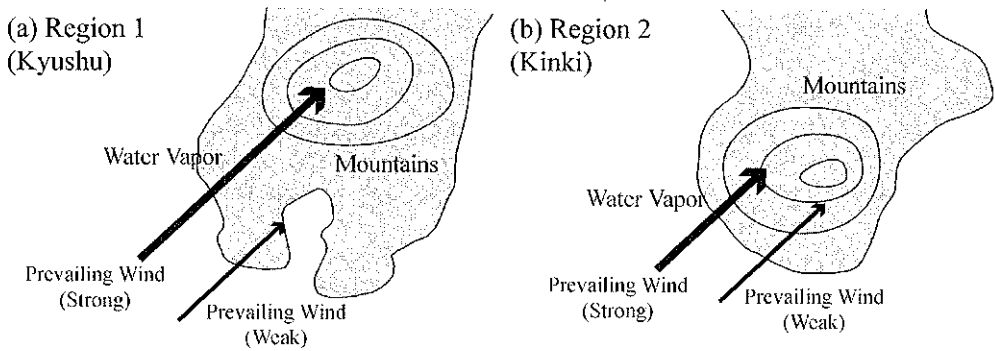


Fig. 7 Schematic of the transportation of water vapour in (a) Region 1 (Kyushu) and (b) Region 2 (Kinki).

Kyushu and the Chubu region (Region 1), and is not high in the Kinki and the Shikoku region (Region 2). This means that meteorological factors other than horizontal wind have relatively more effect on rainfall–elevation relationships in Region 2 than those in Region 1.

In Region 1, as represented in Fig. 2(a)–(d), mountains are located mainly far from the coast in a southwesterly wind direction, which is the prevailing wind in Japan. The amount of water vapour transported from the sea to the mountains varies with the strength of horizontal wind as a whole. This means that the degree of topographic effects on rainfall distribution depends on the strength of horizontal wind in each region, and that the spatial fluctuations of rainfall–elevation relationships become large. That is why the correlation between H and S is high, and much accumulation is required for the emergence of topographic effects in Region 1. On the other hand, water vapour is easy to transport from the sea to the mountains in Region 2 because most of the mountains are located near the seaside, as represented in Fig. 2(b) and (c). Thus, the atmosphere becomes saturated by even a few ascending flows forced by mountains because enough water vapour is supplied, even if horizontal wind is weak. The reason for the low correlation between H and S is that the degree of topographic effects is large according to the atmospheric conditions regardless of the strength of horizontal wind. Much accumulation is not, then, required for the emergence of topographic effects because the spatial fluctuations of water vapour in mountainous regions become relatively small as a whole. Figure 7 represents the of the transportation of water vapour in the regions.

The authors also investigated the effects of the direction of wind through numerical simulations in the four regions. A correlation was not found between the direction of wind and the degree of topographic effects.

SUMMARY AND CONCLUSIONS

This study analyses rainfall–topography relationships through numerical simulations using the mesoscale meteorological model MM5. For a quantitative estimation of topographic effects on rainfall distribution, rainfall–elevation relationships and the

Dependence Line on Topographic Elevation (DLTE) were investigated in four mountainous regions of Japan. The linear relation of DLTE represents the fundamental and average properties of rainfall–elevation relationships in a study region. When attention is focused on mesoscale (especially meso γ -scale) disturbances, rainfall–elevation relationships exhibit complicated behaviour. Thus, an analysis from a macroscopic viewpoint such as DLTE is important for clarifying the universal properties of the relationships.

The effects of wind on rainfall distribution were also investigated for understanding the mechanism of rainfall–topography relationships. The results showed that there is a definite correlation between the strength of horizontal wind and the slope of DLTE, although the strength of the correlation differs from region to region. This means that the strength of topographic effects depends on the distance from the coast to the mountains in each region because the amount of water vapour transported from the sea to the mountains fluctuates with the distance and the strength of horizontal wind. Therefore, the distance from the coast to the mountains plays a significant role in meso β -scale rainfall–topography relationships.

This study conducted diagnostic simulations under some actual conditions. The authors, in future, will conduct virtual simulations including various conditions of topography and the atmosphere for further determining the mechanism of rainfall–topography relationships.

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