NOTES AND CORRESPONDENCE

Relationship between Orographic Enhancement of Rainfall Rate and Movement Speed of Radar Echoes: Case Study of Typhoon 0709

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Abstract

It is well known that rainfall rate is enhanced over mountains due to orographic uplifting. It would be beneficial to rainfall nowcasting if the intensity of the orographic enhancement could be estimated using simple parameters. In the present study, we found a clear relationship between orographic enhancement of the rainfall rate and the movement speed of radar echoes in a case study of rainfall over mountains in the southwestern area of the Kanto District in Japan during Typhoon 0709, by using rainfall data derived from X-band polarimetric radar. The increasing rate of rainfall rate per unit altitude ($\Delta R/\Delta H$) showed a positive correlation ($r = 0.95$) with the movement speed of radar echoes (V) when $V > 10 \text{ m s}^{-1}$. Such a correlation suggests that V is an effective parameter for quickly estimating the orographic enhancement of rainfall, however, more case studies are required before it can be used in practical applications.

1. Introduction

Many researchers have pointed out that rainfall is sometimes strongly enhanced by orographic effects (Yoshino 1955; Sakakibara and Takeda 1973; Yamada et al. 1995). The ability to forecast the orographic enhancement of the rainfall rate is an important issue for disaster mitigation and management of water resources. Hence, there is a demand for a simple relationship that enables a quick calculation of orographic rainfall enhancement, in particular for nowcasting. The Japan Meteorological Agency (JMA) provides orographic precipitation data that is calculated using the method of Brown-

ing and Hill (1981) for forecasts longer than 1 h (Makihara 2007). In this method, wind direction and speed obtained from synoptic analysis are used, and the enhancement rate is calculated using a distribution map for each determined wind direction. However, this method is not used by JMA for nowcasting (forecasts less than 1 h) at present in order to save calculation time¹, and a simpler method for estimating orographic rainfall enhancement is desired.

It is hard to determine the rainfall distribution over mountains by using rain-gauge data since no dense network of rain gauges exists in these areas. An alternative method is the use of radar. With conventional radars, however, there is some difficulty in estimating the rainfall rate due to strong

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¹ http://www.jma.go.jp/jma/kishou/nowcast/kurashi/kotan_nowcast.html

rain attenuation and significant errors in the Z - R relationship. Therefore, studies on rainfall over mountainous areas by using radars have been restricted to qualitative arguments. On the other hand, X-band polarimetric radar systems have good accuracy for rainfall estimation and do not need correction by rain gauges because the R - K_{DP} relationship for rainfall estimation is less sensitive to rain attenuation and partial beam blocking by topographic elements (Park et al. 2005).

In the present study, we analyze the rainfall distribution over southwestern Kanto in Japan caused by Typhoon 0709, by using the X-band polarimetric Doppler radar (MP-X) that is operated by the National Research Institute for Earth Science and Disaster Prevention. The results indicate that there is a strong relationship between orographic enhancement of the rainfall rate and the movement speed of radar echoes (V), and that V is an effective parameter for estimating orographic rainfall enhancement.

2. Estimation of enhancement of rainfall rate by mountains

In the present study, MP-X radar located in Ebina City, Kanagawa Prefecture (35.3989°N, 139.3924°E), with a frequency of 9.375 GHz and an observation radius of 80 km (circles in Fig. 1), is used. This radar provides surface rainfall datasets at 5-min interval and at a $0.0055^\circ \times 0.0045^\circ$ (approximately $500 \text{ m} \times 500 \text{ m}$) horizontal resolution using the following procedures: 1) by applying a finite impulse response filter to the differential propagation phase (ϕ_{DP}); 2) by calculating the specific differential phase (K_{DP}) from ϕ_{DP} ; 3) by correcting the reflectivity factor Z_H for rain attenuation using K_{DP} ; 4) by estimating the rainfall rate by using the R - K_{DP} relationship when $K_{DP} < 0.3 \text{ km}^{-1}$ or $Z_H > 35 \text{ dBZ}$, and by using the Z - R relationship otherwise (Park et al. 2005), and 5) by converting ray-bin grids to longitude-latitude grids by Cressman interpolation.

There are several mechanisms involved with orographic enhancement of precipitation (Houze 1993). Among them, we focus our attention on processes that produce larger amounts of rainfall at high altitudes. A schematic diagram of the method used to estimate the rate of orographic rainfall enhancement from radar data is shown in Fig. 2. Here, we suppose that the rainfall at a time $t = 0 \text{ min}$ (R_0) at point A moves to point B by $t = 5 \text{ min}$ (R_5), where the horizontal and

vertical distances between A and B are ΔX and ΔH , respectively. In this case, the change in the rainfall rate over 5 min is $\Delta R = R_5 - R_0$. Here, ΔR includes both the orographic effects and the fluctuation of the rainfall disturbance itself. Assuming that the disturbances fluctuate randomly, they can be removed, leaving only the orographic effects (as will be shown in Section 4). R_0 and R_5 are acquired from the radar data, while ΔH is calculated from 250-m grid elevation data provided by the Geographical Survey Institute of Japan.

The movement speed of radar echoes (V) is calculated using the pattern matching method (De lanoy et al. 2005), which provides 5-min movement data in longitude and latitude grids by comparing the rainfall patterns at a given time with the patterns determined 5 min earlier. Pattern matching results with a correlation coefficient < 0.3 are not used because they introduce large errors into the calculation of V . In such cases, we estimate the value by linear interpolation using the before and after time. All data are then smoothed by using a simple 30-min moving average. The pattern matching was conducted using data over the plain to the east of the mountains (broken-outline square in Fig. 3), because rainfall systems sometimes become stagnant over mountains, making the calculation of their movement by pattern matching difficult for these regions.

The quantitative relationship $\Delta R/\Delta H = aV + b$ is assumed, where a and b are coefficients given by the following method. First, the data is divided into 2-m s^{-1} intervals of V . Then, linear regression between the topography gradient ($\Delta H/\Delta X$) and the change in rainfall rate per unit distance ($\Delta R/\Delta X$) is performed for each interval of V . The slope of the regression lines between $\Delta H/\Delta X$ and $\Delta R/\Delta X$ then indicates the increase in the rainfall rate per unit altitude ($\Delta R/\Delta H$) in each interval of V . Next, the regression $\Delta R/\Delta H = aV + b$ is performed by again using the least-squares method.

3. Study area

Hourly precipitation data obtained from the Automated Meteorological Data Acquisition System (AMeDAS) and rain gauges installed by Kanagawa Prefecture and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) were used to check the accuracy of the rainfall derived from the MP-X radar; the radar grids nearest to the rain gauges were used. The statistics used in the comparison were the normalized error (averaged hourly

Fig. 1. Distribution of rainfall rates observed by JMA radars at (a) 00 UTC on September 5, (b) 00 UTC and (c) 12 UTC on September 6 2007. Circles indicate the observation area of MP-X radar. (d) Accumulated rainfall (mm) from 16 UTC between 4 and 12 UTC on September 6 observed by MP-X radar.

error normalized by the mean value) and correlation coefficients. The distributions of normalized errors and correlation coefficients are shown in Fig. 3. From these results, a rectangular region where the normalized error is less than 50% and correlation coefficient is greater than 50% was chosen as the study area (the solid-outline region in Fig. 3). The area includes several mountain peaks higher than 1000 m in the northern and western part, and the plain and includes the sea in its south-eastern part.

Typhoon 0709 formed to the southeast of Minamitorishima Island at 00 UTC on August 29 2007 and reached the southern area of the Kanto District on September 5. After this time, the typhoon moved northward and changed into an extratropical cyclone at Ishikari Bay at 00 UTC on September 9. During this event, continuous rainfall and strong winds were observed in the Kanto District associated with the passage of typhoon. In the early stage of the event, scattered echoes were observed around the MP-X radar (Fig. 1a). Following this,

Fig. 2. Schematic figure of the method used to calculate orographic effects. A disturbance with a rainfall rate R_0 at $t=0$ moves a distance ΔX and has a rainfall rate R_5 over a mountain of height ΔH . In this case, the variation in the rainfall rate as the disturbance moves over 5 min is $\Delta R = R_5 - R_0$.

the outer rainbands landed (Fig. 1b) and the eye of the typhoon approached (Fig. 1c). Total rainfall reached 400 mm over the mountains and about 150 mm over the plain (Fig. 1d). Obvious rainfall enhancement was recognized by the MP-X radar over the mountainous area to the west of the radar site.

4. Results

Time variations of the magnitude and direction of V derived from the pattern matching method are shown in Fig. 4a. V increases as the typhoon approaches but suddenly decreases and its direction veers after 12:00 UTC on September 6. For comparison, the surface wind speed measured at Odawara by AMeDAS in the pattern-matching domain is shown in Fig. 4b. The wind speed shows the same increasing trend as V before 12:00 UTC on September 6, after that the two become inconsistent. This was most likely caused by the assumption made in the calculation of V that the rain area moves at a uniform velocity in the pattern-matching region. However, as the typhoon approaches, inhomogeneous movements of echoes around the typhoon vortex cannot be ignored and this makes the calculation of the movement speed difficult. For this reason, we did not use data after

Fig. 3. (a) Distribution of normalized errors (%) and (b) correlation coefficients (%) of radar-derived hourly rainfall relative to rain-gauge data. Positions of the radar, rain gauges, study area and the pattern matching area are indicated by a cross, black circles, a solid-outline rectangle and a broken-outline rectangle, respectively. Gray scale indicates the topographic altitude.

12:00 UTC on September 6. The effect of actually using such data is discussed in Section 5.

Examples of the relationship between $\Delta H/\Delta X$ and $\Delta R/\Delta X$ are presented in Fig. 5 for the wind intervals 11–13 m s^{-1} and 29–31 m s^{-1} . Each plot

Fig. 4. Time variations of (a) the movement speed and direction of radar echoes calculated by the pattern matching method and (b) wind speed and direction measured by AMeDAS at Odawara.

Fig. 5. Relationship between $\Delta H/\Delta X$ and $\Delta R/\Delta X$ for wind intervals (a) 11–13 m s⁻¹ and (b) 29–31 m s⁻¹.

was obtained using pairs of data at $t = 0$ and $t = 5$ min. For the wind interval 11–13 m s⁻¹, the values of $\Delta R/\Delta X$ are widely scattered relative to $\Delta H/\Delta X$. This is because ΔR contains the effects of fluctuating disturbances in addition to orographic enhancement. However, if such disturbances are distributed randomly with respect to $\Delta H/\Delta X$, they can be removed and the orographic effects can be extracted by the least-squares method. The values of $\Delta R/\Delta X$ are not as widely scattered for the wind interval 29–31 m s⁻¹, suggesting that the orographic effects are more dominant.

The relationship between $\Delta R/\Delta X$ and V at movement speed intervals of 2 m s⁻¹ is shown in Fig. 6. When V is less than 10 m s⁻¹, $\Delta R/\Delta H$ is small and sometimes negative, thus, the orographic effects are regarded as being too small to use in this analysis. The correlation coefficient between $\Delta R/\Delta H$ and V is 0.95, indicating a clear linear relationship.

Fig. 6. Relationship between the movement speed of radar echoes and the variation in rainfall rate per unit altitude. Error bars indicate the 95% confidence level.

Here, the regression line is obtained as $\Delta R/\Delta H = 8.44 \times 10^{-4} V - 9.13 \times 10^{-3}$, where the units of ΔR , ΔH and V are mm h^{-1} , m , and m s^{-1} , respectively.

5. Discussion

In the present study, a clear relationship was determined between the movement speed of radar echoes and the rate of increase of rainfall rate per unit altitude in a case study of rainfall over the western Kanto District during Typhoon 0709. This relationship can be interpreted as follows. Generally, orographic enhancement of rainfall is dependent on the vapor flux in the lower atmospheric layer, as well as topographic features (Alpert 1986). Thus the low-level wind velocity is an important factor for orographic precipitation. On the other hand, the movement speed of radar echoes is dependent on the wind velocity at a “steering” level, usually corresponding to the level around 700 hPa. Normally, wind direction does not change so much from the lower layer to the steering level, and thus the movement speed of radar echoes is closely correlated to the low-level wind velocity, and serves as a good index for orographic enhancement of precipitation.

Over real topography, orographic rainfall would also be dependent on the humidity of the air. We attempted to use the specific humidity data generated by the JMA Meso-Scale Model (JMA-MSM) to establish a more general relationship between V and $\Delta R/\Delta H$, but could not obtain reasonable results because of the coarseness of the humidity data in both time and space. For practical applications for nowcasting, we need to establish relationships between V and $\Delta R/\Delta H$ under many meteorological conditions to develop usable reference tables.

In addition, we could not calculate a valid movement speed of echoes after 12:00 UTC on September 6. This was due to inhomogeneous movements of echoes around the typhoon vortex after this time. For confirmation, we conducted the same analysis as that performed for the study period using the data after 12:00 UTC on September 6. The result also showed a high correlation between $\Delta R/\Delta H$ and V ; the correlation coefficient was 0.87. However, the regression parameters were different; the regression line was given by $\Delta R/\Delta H = 1.15 \times 10^{-3} V - 6.03 \times 10^{-3}$. This indicates that $\Delta R/\Delta H$ is underestimated by 46% if we use the data after 12:00 UTC on September 6 when $V = 15 \text{ m s}^{-1}$. One way to solve this problem is to im-

prove the pattern matching technique. For example, a smaller domain could be used when a vortex is approaching.

The high correlation between V and $\Delta R/\Delta H$ found in this study suggests that V is an effective parameter for quickly estimating the orographic enhancement of rainfall. More case studies are required before it can be used in practical applications.

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