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Probabilistic Estimates of Rainfall Extremes in the Republic of Korea during the Summer Season

Il-Kon Kim and Rafique Ahmed

Abstract

The summer season (June – September) in the Republic of Korea (South Korea) is warm and rainy. More than 60 percent of the total annual rainfall comes during the summer season. Because of high temperature and rainfall, summer is the main growing season in most of the country. Summer rainfall in the country varies from place to place and from year to year. Both high and low rainfall amounts have tremendous effects on agriculture and hydrology in the country. High rainfall causes soil erosion, flooding, and landslide. On the other hand, low rainfall amount causes drought; water shortage for industry, urban and domestic water uses.

This study presents the geographic distribution of the probabilistic amounts rainfall of various magnitudes and frequencies in South Korea, for each month of summer season (June – September) and for the summer season as a whole. Probabilistic amounts of both below-normal rainfall and above-normal rainfall have been determined for two time scales: (a) in 1 year out of 4 years, which is a relatively more frequent event; and (b) in 1 year out of 10 years, which is a relatively extreme event.

The results of this study may serve as an inventory of rainwater resources in the country during the summer season which will be useful to the agricultural planners, irrigation engineers, hydrologists, transportation engineers and local and regional planners for the proper utilization and management of the water resources and hazard potential.

1. Introduction

Precipitation is an important link in the hydrologic cycle. The importance of precipitation analysis has been highlighted in hydrological and climatological studies because of the increasing demand for freshwater use in all economic activities – agriculture, industrial, transportation, urban and domestic purposes (Carr, 1972; Chang, 1968; Lawlor, 1997; Lindqvist, 1997; Thornes, 1997; Whitehead, 1997.).

Precipitation varies over space and time. For the planning and management of water resources in various sectors such as agriculture, industry, and urban and domestic uses, it is essential to know the average amount and variability of precipitation. Variability of precipitation can be expressed in terms of its probabilistic occurrence (Ahmed, 1989). Especially important is the spatial variation of the probabilistic occurrence of extreme low and extreme high amounts – because these extreme amounts have tremendous effects on various sectors of the economy in a given region. Very high rainfall causes severe soil erosion, flooding, and landslide and other hazards. On the other hand, very low rainfall causes agricultural drought, and water shortages for industry, urban and domestic uses.

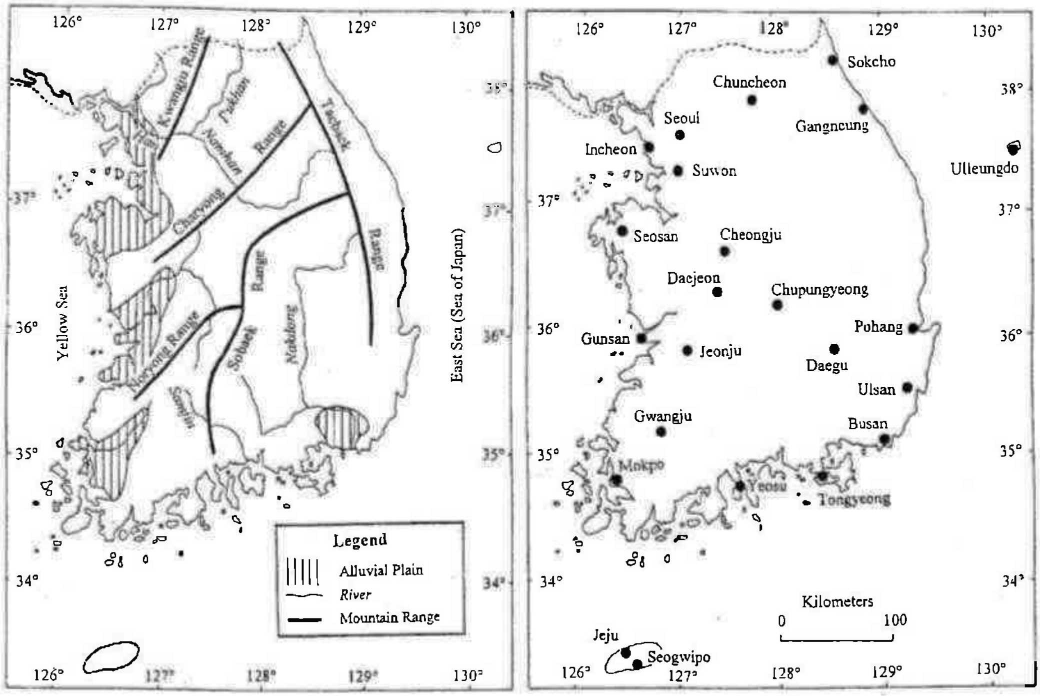
There are a number of studies published in recent years on various aspects of the summer climate in South Korea. Results of modelling extreme summer rainfall in the Korean Peninsula were presented by Park and others (Park, *et al.*, 2001). Association between the summer monsoon rainfall patterns over South Korea and the circulation features were discussed by Kim, *et al.* (Kim, *et al.*, 2002). One study analyzed the relationship between sea surface temperatures and the path of typhoons in summer around the Korean waters (Suh, *et al.*, 2002). Association between the Changma onset, East Asian summer monsoon circulation and summer rainfall characteristics was presented by Kim and others (Kim, *et al.*, 2005). A model experiment showed that excessive snow anomalies over the Tibetan Plateau in late spring caused excessive rainfall in the summer of 2003 in the Korean Peninsula (Hong and Seol, 2005). The inter-annual variability of summer rainfall in the Korean Peninsula was examined by using the impact of Bonin High, Okhotosk High and Tibet High on the onset and intensity of Changma index (Ha and Lee, 2005). Using decadal values, it was shown that the negative correlation between the East Asian summer monsoon and the western North Pacific summer monsoon was stronger in the 1994-2004 decade than the pervious decade (Jhun, 2005).

The effect of typhoons on the mixed layer temperature (MLT) and sea surface temperature (SST) were presented by Park *et al.*. (Park *et al.*, 2005). The characteristics and development of meso-scale convective complexes (MCC) in South Korea during the summer season were studied by Lee and Ryu (Lee and Ryu, 2005). One recent study analyzed the patterns of daily rainfall at four selected stations in South Korea (Busan, Gangneung, Gwangju and Seoul) during the wettest and driest summer in a 50-year period from 1951 to 2000 (Kim and Ahmed, 2005), and another recent study dealt with the long-term trend of summer rainfall at the above four stations in the same 50-year period (Kim and Ahmed, 2004).

Using 56 years' summer rainfall data (1951-2006), geographic distribution of the probabilistic monthly and seasonal rainfall in each month of the summer season (June -September), and in the summer season as a whole are presented in this paper. Probabilistic rainfall amounts were determined for both below-normal and above-normal amounts on two time scales – in 1 year out of 4 years which is a relatively more frequent event, and in 1 year out of 10 years which represents a relatively extreme event.

2. Location and Physiography

Geographically speaking, South Korea extends from 33° N to 38.5° N, and from 125.5° E to 129.5° E. It is surrounded by mountainous North Korea to its north, East Sea to its east and south, and the Yellow Sea to its west. The major factors that influence the climate of South Korea are: (a) topography of the Korean Peninsula, (b) seasonal reversal of wind direction between summer and winter, and (c) the adjacent water bodies, especially the Western Pacific.



(a) (b)

Fig. 1: (a) Physical setting of South Korea (adapted from Dege, 1999), (b) locations of station used in this study.

About 70 percent of South Korea consists of mountains, hills and narrow valleys, which is dissected by narrow streams (Jo, 2000; Kwon, 2000; Dege, 1999). The Taebaek Range is the main backbone of the South Korean mountain system, which runs in north-south direction in the eastern parts of the country (Fig. 1a). Other mountains branch out towards southwest from the Taebaek Mountain Range. From north to south, these mountains are Kwangju Range, Charyoung Range, and the Sobaek Range with its branch the Noryong Range. The elevations of the mountains in South Korea range from 800 m to 1000 m, with some peaks in excess of 1500 m (Mt. Taebaek: 1773 m, Mt. Chiri: 1915 m, not shown on the map). In addition to the mountains, hills and narrow valleys, there are a few alluvial plains in the western and southeastern part of the country (Fig. 1a).

3. General Climatic Conditions

The Republic of Korea (South Korea), located in the southern half of the Korean Peninsula, belongs to the mid-latitude climate (Lee, 2000) or warm temperate climate (Dege, 1999; Kim and Ahmed, 2004). However, because of the seasonal reversal of winds caused by the contrasting effects of Asian landmass and the Pacific Ocean, South Korea also belongs to the East Asian Monsoon Climate (Barry and Chorley, 2003; Oliver and Hidore, 2002).

According to the Köppen's classification of climates, the northern one-third of South Korea has a cold mid-latitude climate with dry winters (Dw), while the remaining two-thirds of the country has mild and moist mid-latitude climate with dry winters (Cw).

The climate of South Korea is dominated by two major seasons, summer (June-September) and winter (November-March). These two major seasons have transition seasons in between the two, spring season (April-May) and the brief autumn season (mid-September to October). The summer is very warm and moist and the winter is very cold and dry. As a result, summer is the growing season over most of the country. Mean annual rainfall in South Korea ranges from less than 1000 mm in the east central region to 1200 mm along the west coast, and 1700 mm in the Jeju Island (Lee, 2000; Kim and Ahmed, 2004).

A center of high pressure develops over the Pacific during the summer season resulting in sea-to-land wind. This is the typical summer monsoon in South Korea, which causes rainfall throughout the country. Summer rainfall accounts for more than 60% of the annual rainfall in the country. Moist air masses that travel from the western Pacific Ocean form the polar front in this region, which is known as the "Changma Front" in the Korean Peninsula. A series of cyclones that develop in the Yangtze River basin in China provide the main mechanism of rainfall during the summer season (Lee, 2000; Kim and Ahmed, 2004). These cyclones form at an interval of 2-3 days and enter South Korea along the Changma Front, which cause heavy rainfall in the country. July is the month of maximum rainfall in South Korea, after which rainfall generally decreases through the rest of the season (Lee, 2000; Kim and Ahmed, 2004).

Topography, direction of prevailing winds and the cyclone tracks determine the geographic distribution of summer rainfall in the country. Average summer rainfall in South Korea ranges from less than 700 mm in the northeast to 800 mm in the northwest and west, and 900 mm or more in the south and southwest (Kim and Ahmed, 2004). Rainfall is heavy in the southern coastal zone and in the adjacent mountains. Summer rainfall in these regions ranges from 800 mm to 900 mm or more. However, highest rainfall occurs in Jeju Island (900-1000 mm).

Relatively high rainfall (900 mm or more) in the south and along a strip from the Pukhan River Valley in the north to the Samjin River Valley in the south is caused by the additional effect of orographic uplifting of moist air by the mountain barriers. Northeastern part of the country receives relatively low rainfall in summer (less than 700 mm) because of the rain-shadow effect of the mountain ranges. The variability of summer rainfall ranges from less than 30% in the northeast part to 40% in the south.

It may be noted that typhoons from the western Pacific Ocean occasionally reach South Korea during the late summer season. Frequency of these typhoons is relatively low – occurring once every two years in the southern coastal region, and once every four years in the central region of the country (Lee, 2000; Kim and Ahmed, 2004). They cause torrential rainfall resulting in devastating soil erosion, landslides and floods, especially in the southern region of the country.

Summer is very warm in South Korea. August is the hottest month over most of the country. It is due to less cloud cover and rainfall in August than in July. Average monthly temperatures varies from 20-22°C in June to 22-25°C in July, 26-28°C in August and 18°C -20°C in September.

The autumn season in South Korea lasts from mid-September to October. High pressure begins to build up over Siberia in mid-September. A series of traveling anti-cyclones enter South Korea from China during this season. As a result, clear sky and pleasant weather prevail over the country during this period. In November, the high pressure over Siberia intensifies, which generates land-to-sea winds over the Korean Peninsula (Dege, 1999; Lee, 2000). This sets in the winter monsoon season in the country which lasts from November to March. Winter brings in bitterly cold and dry continental polar air mass (cP) from Siberia to South Korea (Dege, 1999; Lee, 2000). Average monthly temperatures in January range from about – 5°C in the north to 2-3°C in the south. Because of the land-to-sea wind in winter, the air is very dry, and precipitation is very low during this season. Winter precipitation in South Korea accounts for about 10% of the annual precipitation.

During the spring season (April-May) the Siberian high pressure weakens, and the weather in South Korea comes under the influence of the northern fringes of the extra-tropical cyclones. These cyclones cause some rainfall in the country which may account for 15-20% of the annual rainfall.

4. Methodology

Measures of variability of a distribution about the mean value are given as standard deviation () and coefficient of variation (CV). Methods of calculating and CV are given in any standard textbook on quantitative methods, such as that of Rogerson (Rogerson, 2006).

The probability of occurrence of a variable in an expected percentage is obtained by *Z*-score. This is written as (Rogerson, 2006):

$$x = \bar{X} \pm (Z)$$

where x is the probabilistic estimate of the variable (in this case, rainfall).

This method has been used in this study to obtain the probabilistic estimates of rainfall amounts in South Korea for each month of the summer season (June through September), and for the summer season as a whole. This was done both for below-normal and above-normal conditions as follows:

(1) Probabilistic amount of the below-normal rainfall that may occur in two different time scales are:

(a) Probabilistic amount of below-normal rainfall that may occur once in 4 years, which represents a relatively more frequent event, is given as:

$$x = \bar{X} - (Z \cdot 0.67).$$

(b) Probabilistic amount of below-normal rainfall that may occur once in 10 years, represents a relatively extreme event and is given as:

$$x = \bar{X} - (Z \cdot 1.28)$$

(2) Probabilistic amount of the above-normal rainfall that may occur in two different time scales are:

(a) Probabilistic amount of above-normal rainfall that may occur once in 4 years, which represents a relatively more frequent event and is given as:

$x = \overline{X} + (Z \cdot 0.67)$

(b) Probabilistic amount of above-normal rainfall that may occur once in 10 years, which represents a relatively extreme event and is given as:

$x = \overline{X} + (Z \cdot 1.28)$

5. Data

Data needed for this study include the monthly summer rainfall data for each month of June through September, for the 56-year period from 1951 to 2006. These data were collected for 23 stations,

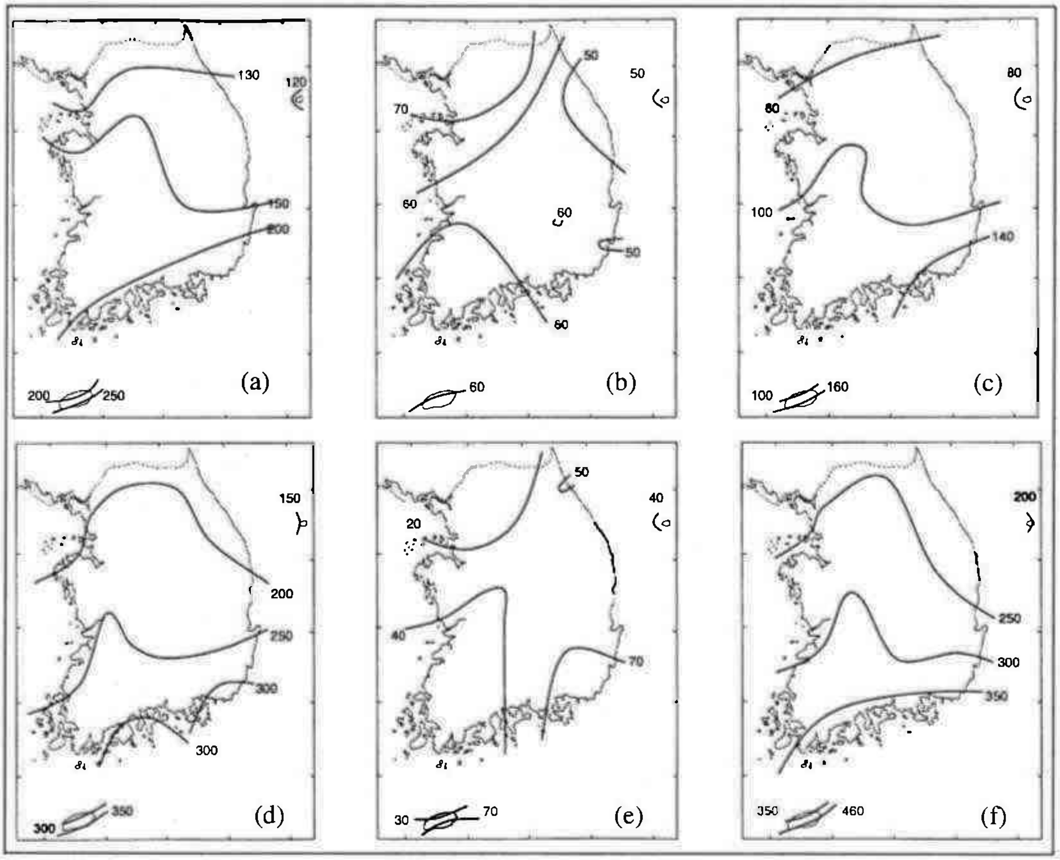


Fig. 2: **Rainfall in June**: (a) Mean rainfall (mm), (b) coefficient of rainfall variation (%), (c) probabilistic below-normal rainfall in 1 year out of 4 years (mm), (d) probabilistic above-normal rainfall in 1 year out of 4 years (mm), (e) probabilistic below-normal rainfall in 1 year out of 10 years (mm), and (f) probabilistic above-normal rainfall in 1 year out of 10 years (mm).

which are distributed over South Korea (Fig. 1(b)). These stations represent the diverse physio-climatic regions of the country. These stations are (in alphabetic order): (1) Busan, (2) Cheongju, (3) Chucheon, (4) Chupungyeong, (5) Daegu, (6) Daejon, (7) Gangneung, (8) Gunsan, (9) Gwangju,(10)Incheon,(11)Jeju,(12)Jeonju, (13) Mopko, (14) Pohang, (15) Seosan, (16) Seogwipo, (17) Seoul, (18) Sokcho, (19) Suwon, (20) Tongyeong, (21) Ulleingdo, (22) Ulsan, and (23) Yeosu. These data were collected from the Korea Meteorological Administration (KMA), Seoul, South Korea.

6. Results and Discussion

Maps have been drawn showing the distribution of mean rainfall, coefficient of rainfall variation, as well as the distribution of probabilistic rainfall amounts in the two time-scales on a monthly and seasonal basis, both for the below-normal and above-normal amounts.

6(A) Rainfall in June

Mean rainfall in June and its variability (coefficient variation, CV) are shown in Figure 2a and 2b, respectively. Mean rainfall in June varies from less than 130 mm in the north to more than 200 mm in the south (Fig. 2a), with the coefficient of variation ranging from less than 50% in the extreme northeast to 60% in the south and more than 70% in the northwest (Fig. 2b).

Probabilistic below-normal rainfall in 1 year out of 4 years in June varies from 60 mm in the north to more than 140 mm in the southeast ((Fig. 2c). On the other hand, probabilistic above-normal rainfall in 1 year out of 4 years varies from 200 mm in the north to 300 mm in the extreme south (Fig. 2d).

Probabilistic below-normal rainfall in 1 year out of 10 years varies from 20 mm in the northwest to more than 40 mm in the southwest and more than 700 mm in the southeast (Fig. 2e).

On the other hand, probabilistic above-normal rainfall in 1 year out of 10 years varies from 250 mm in the north and northeast to 350 mm in the extreme south (Fig. 2f).

6(B) Rainfall in July

Mean rainfall in July and its variability (CV) are shown in Figure 3a and 3b, respectively. Mean rainfall in July varies from 200 mm in the extreme east to 260 mm in the south and southwest, and 360 mm in the northwest (Fig. 3a), with the coefficient of variation ranging from less than 50% in the west and south to 60% in the east and in Jeju Island (Fig. 3b).

Probabilistic below-normal rainfall in 1 year out of 4 years in July varies from 120 mm in the east to more than 160 mm in the southwest, and more than 200 mm in the northwest (Fig. 3c). Probabilistic above-normal rainfall in 1 year out of 4 years varies from 300 mm in the extreme east and extreme southwest to 400 mm in the north, in the central region and in Jeju Island (Fig. 3d).

Probabilistic below-normal rainfall in 1 year out of 10 years in July varies from 20 mm in the extreme east to 30 mm in Jeju Island, and 100–140 mm in the northwestern part of the country (Fig. 3e). Probabilistic above-normal rainfall in 1 year out of 10 years varies from 360 mm in the southwest to 400 mm in the east (around Pohang),

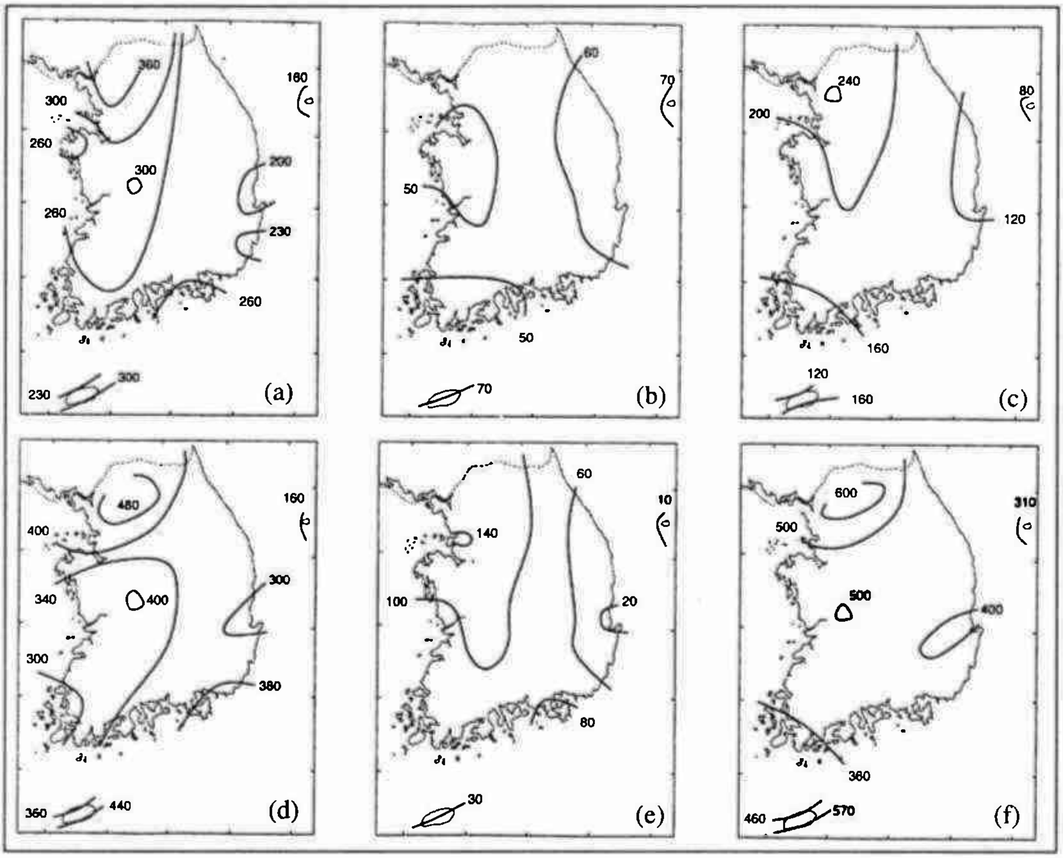


Fig. 3: Rainfall in July: (a) Mean rainfall (mm), (b) coefficient of rainfall variation (%), (c) probabilistic below-normal rainfall in 1 year out of 4 years (mm), (d) probabilistic above-normal rainfall in 1 year out of 4 years (mm), (e) probabilistic below-normal rainfall in 1 year out of 10 years (mm), and (f) probabilistic above-normal rainfall in 1 year out of 10 years (mm).

500 mm in the west-central region (near Daejon), and 500–600 mm in the north (Fig. 3f).

6(C) Rainfall in August

Mean rainfall in August and its variability (CV) are shown in Figure 4a and 4b, respectively. Mean rainfall in August varies from 200 mm in the extreme southwest (around Mokpo) to 240 mm in the east, 260 mm in the southeast, 280 mm in Jeju Island, and 280–350 mm in the northwest (Fig. 4a). Coefficient of rainfall variation in August ranges from 50% in Jeju Island to 70% in the southeast and northwest (Fig. 4b).

Probabilistic below-normal rainfall in 1 year out of 4 years in August varies from less than 140 mm in the southeast to more than 180 mm in the west and north and in Jeju Island (Fig. 4c). Probabilistic above-normal rainfall in 1 year out of 4 years varies from 300 mm in the extreme

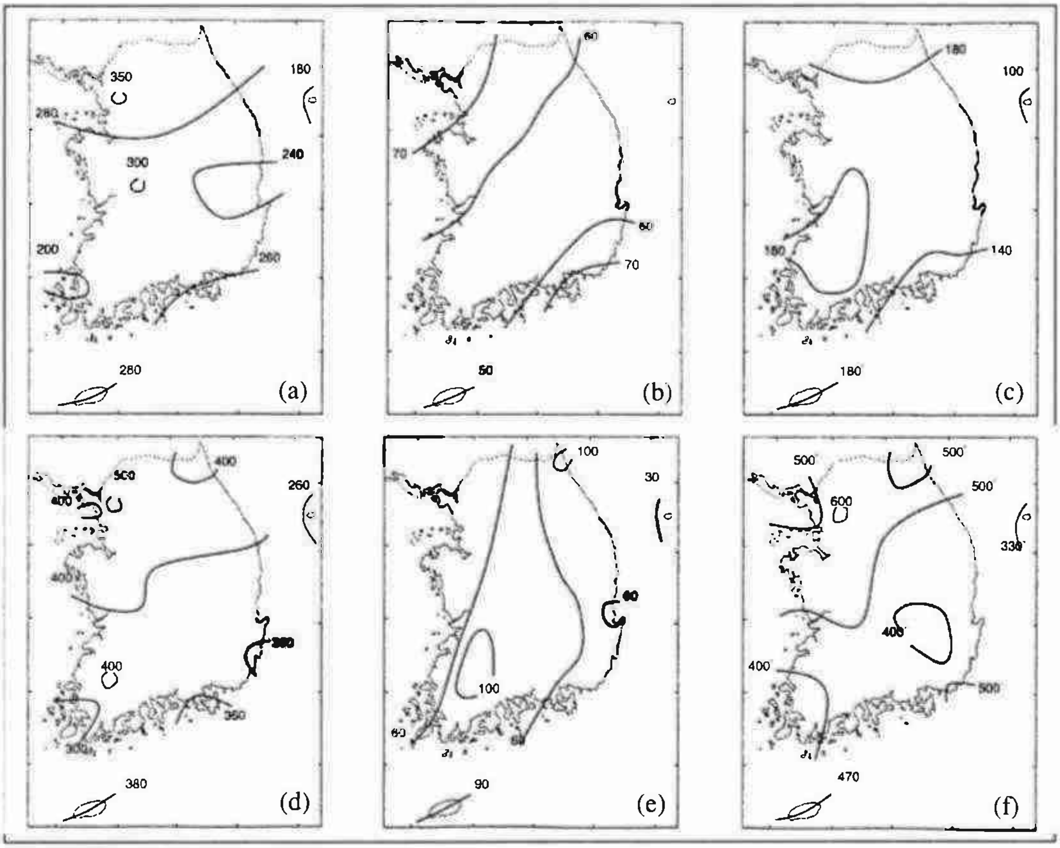


Fig. 4: Rainfall in August: (a) Mean rainfall (mm), (b) coefficient of rainfall variation (%), (c) probabilistic below-normal rainfall in 1 year out of 4 years (mm), (d) probabilistic above-normal rainfall in 1 year out of 4 years (mm), (e) probabilistic below-normal rainfall in 1 year out of 10 years (mm), and (f) probabilistic above-normal rainfall in 1 year out of 10 years (mm).

southwest to 360 mm in the southeast, 380 mm in Jeju Island, and 400-500 mm in the northern half of the country (Fig. 4d).

Probabilistic below-normal rainfall in 1 year out of 10 years in August varies from 60 mm in the west and east to 100 mm in the Samjin Valley in the southwest and in the extreme northeast corner of the country (Fig. 4e). Probabilistic above-normal rainfall in 1 year out of 10 years varies from 330 mm in Ulleungdo Island off the northeast coast to 400 mm in the southeast and southwest, to 500 mm in the northern half of the country (Fig. 4f).

6(D) Rainfall in September

Mean rainfall in September and its variability (CV) are shown in Figure 5a and 5b, respectively. Mean rainfall in September varies from less than 140 mm in the west to 160 mm in the southeast, 180 mm in Jeju Island, and 200 - 230 mm in the northeast

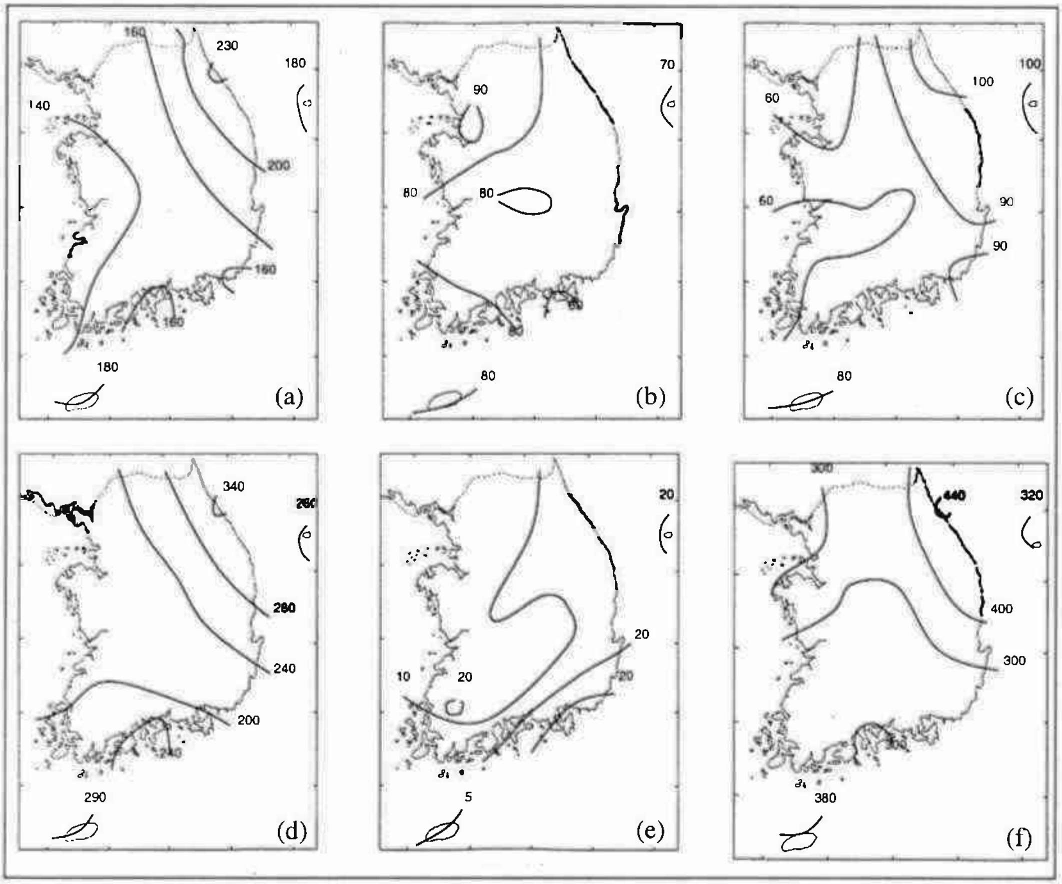


Fig. 5: Rainfall in September: (a) Mean rainfall (mm), (b) coefficient of rainfall variation (%), (c) probabilistic below-normal rainfall in 1 year out of 4 years (mm), (d) probabilistic above-normal rainfall in 1 year out of 4 years (mm), (e) probabilistic below-normal rainfall in 1 year out of 10 years (mm), and (f) probabilistic above-normal rainfall in 1 year out of 10 years (mm).

(Fig. 5a). Coefficient of variation of rainfall in September is highly variable, which ranges from 60% in the extreme southeast corner of the country (around Tonyeong) to 80% in Juju Island, southwestern and northwestern parts of the country, and 90% in the extreme northwestern corer of the country (Fig. 5b).

Probabilistic below-normal rainfall in 1 year out of 4 years in September varies from less than 60 mm in the southwest and northwest to 80 mm in Jeju Island, 100 mm in the northeast (Fig. 5c). Probabilistic above-normal rainfall in 1 year out of 4 years in September varies from 200-240 mm in the vast western part of the country to 290 mm in Jeju Island and 340 mm in the extreme northeast (Fig. 5d).

Probabilistic below-normal rainfall in 1 year out of 10 years in September varies

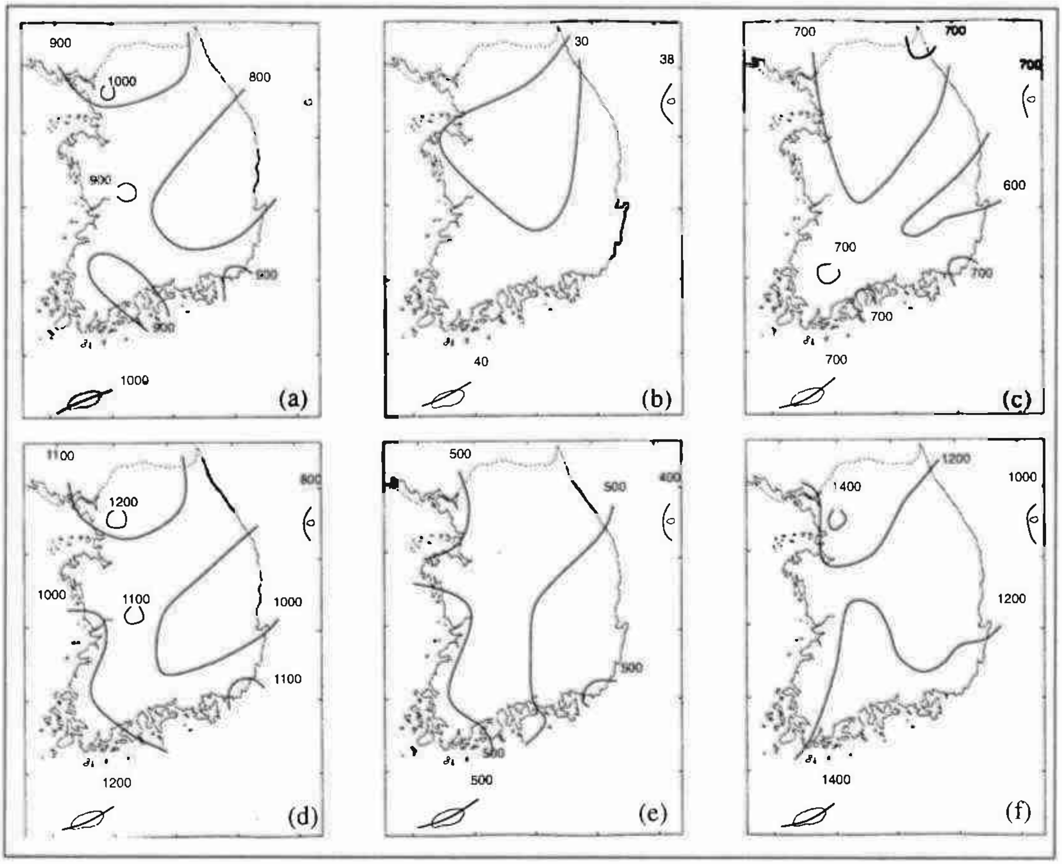


Fig. 6: Rainfall in the summer season (June-September): (a) Mean rainfall (mm), (b) coefficient of rainfall variation (%), (c) probabilistic below-normal rainfall in 1 year out of 4 years (mm), (d) probabilistic above-normal rainfall in 1 year out of 4 years (mm), (e) probabilistic below-normal rainfall in 1 year out of 10 years (mm), and (f) probabilistic above-normal rainfall in 1 year out of 10 years (mm).

from 5 mm in Jeju Island to10 mm in the western half of the country, and 20 mm in the southeast (Fig. 5e). Probabilistic above-normal rainfall amount in 1 year out of 10 years in September varies from 300 mm in the southern half of the country and northwest to 380 mm in Jeju Island and 400 mm in the northeast (Fig. 5f).

6(E) Summer Season Rainfall (June-September)

Mean rainfall in summer and its variability (CV) are shown in Figure 6a and 6b, respectively. Mean rainfall in the summer season increases from less than 800 mm in the northeast to more than 900 mm in the northwest and south, and 1000 mm in Jeju Island (Fig. 6a). However, the coefficient of variation of the summer season rainfall is far less than any monthly values, which ranges from less than 30% in the northeast to 40% west and south (Fig. 6b).

Probabilistic below-normal summer rainfall in 1 year out of 4 years varies from less than 600 mm in the east-central part to 700 mm in the rest of the country (Fig. 6c). Probabilistic above-normal summer rainfall in 1 year out of 4 years varies from 800 mm near Ulleungdo Island in the east to 1000 – 1100 mm in rest of mainland, and 1200 mm in Jeju Island (Fig. 6d).

Probabilistic below-normal summer rainfall in 1 year out of 10 years varies from 400 mm near Ulleungdo Island to 500 mm over most of the country (Fig. 6e). Probabilistic above-normal summer rainfall in 1 year out of 10 years varies from 1000 mm near Ulleungdo Island to 1200 – 1400 mm in the north and south, and 1400 mm in Jeju Island (Fig. 6f)

7. Conclusions

This study describes the geographic distribution of monthly and seasonal rainfall, their variability (coefficient of variation, CV), probabilistic rainfall amounts in South Korea for each month of the summer season (June through September) and for the summer season as a whole. Based on the discussion in the preceding section, the following conclusions can be made:

(a) Among the four summer months, June has the lowest mean rainfall, with mean rainfall ranging from 130 mm in the north to more than 300 mm in the northwestern part of the country. July is the rainiest month, when mean rainfall varies from 200 mm in the extreme east to 360 mm in the northwest. Rainfall gradually decreases after July, with mean rainfall in August ranging from 200 mm in the extreme southwest to 350 mm in the northwest. Mean rainfall in September ranges between less than 140 mm in the west to 230 mm in the east. Mean rainfall in the summer season ranges from less than 800 mm in the northeast to more than 900 mm in the northwest and south, and 1000 mm in Jeju Island.

(b) Variability of rainfall is relatively high on a monthly basis, but is relatively low for the season as a whole. On a monthly basis, rainfall variability ranges from 50% to 70% in June, 50% to 60% in July, 60% to 70% in August and 80%-90% in September. However, seasonal variability ranges from less than 30% to 40%.

(c) Maps of probabilistic rainfall amounts illustrate how much rainfall can be expected as a relatively more frequent event (in 1 year out of 4 years) and as a relatively extreme event (in 1 year out of 10 years), for both below-normal and above-normal amounts, on a monthly and seasonal basis. Below-normal probabilistic rainfall amounts in 1 year out of 4 years cause small rainfall deficit all over the country, both on a monthly and seasonal basis. Above-normal probabilistic rainfall amounts in 1 year out of 4 years cause slightly excessive rainfall all over the country, both on a monthly and seasonal basis. However, below-normal probabilistic rainfall in 1 year out of 10 years, both on a monthly and seasonal basis, causes large rainfall deficit over most of the country. This is very likely to cause serious water shortages for agriculture, urban and domestic uses, and for industrial uses. On the other hand, above-normal probabilistic rainfall in 1 year out of 10 years, both on a monthly and seasonal basis, causes excessive rainfall over most of the country. This is very likely to contribute to increased flood events and landslides in the country.

The findings from this study will serve as an inventory of rainwater resources in South Korea during the summer season, both on a monthly and seasonal basis. These will be useful to the agricultural planners, irrigation engineers, hydrologists, transportation engineers and local and regional planners for the proper utilization and management of the water resources and hazard potential during the summer season.

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Il-Kon Kim
Silla University
Busan 617- 736
Republic of Korea

Rafique Ahmed
University of Wisconsin
– La Crosse La Crosse.
Wisconsin 54601. USA