Spatial variations of summer precipitation trends in South Korea, 1973–2005

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Abstract
We have investigated the spatial patterns of trends in summer precipitation amount, intensity, and heavy precipitation for South Korea between 1973 and 2005. All stations show increasing trends in precipitation amount during the summer months, with the highest percentage of significant increase in June precipitation for the northern and central western part of South Korea. There is a significant increase in August precipitation for stations in the southeastern part of South Korea. Only a few stations exhibited significant upward trends in September precipitation. There is a weak to moderate spatial autocorrelation with the highest Moran’s I value in June precipitation amount and August precipitation intensity. The number of days with daily precipitation exceeding 50 and 30 mm during the summer has increased at all stations. Observed trends are likely to be associated with changes in large-scale atmospheric circulation, sea surface temperature anomalies, and orography, but detailed causes of these trends need further investigation.

Keywords: summer precipitation, trend, spatial autocorrelation, Korea

1. Introduction
Precipitation is the major source of freshwater in East Asia. East Asia receives approximately two thirds of its annual precipitation during the summer monsoon season. Summer precipitation is a major source of moisture for agriculture, industry, and municipal water use. Changes in the timing and amount of precipitation could lead to agriculture failure or flood hazards. Thus, there has been much attention paid to identifying any cyclical or long-term trends of summer precipitation (Su et al 2006) and reliable prediction of summer monsoon precipitation (Lim and Kim 2006). As human-induced global climate change accelerates the water cycle (Gong and Wang 2000, Huntington 2006, Oki and Kanae 2006), there is a growing concern in the scientific community (IPCC 2007) over whether there are significant changes in precipitation amount and intensity and heavy precipitation events (Nicholls and Alexander 2007).

Previous studies have shown different trend results depending on the region of interest or detection methods or time periods employed in each individual study. Groisman et al (2004), for example, showed increasing trends in heavy (above the 95th percentile) and very heavy (above the 99th percentile) precipitation in the northeastern United States during the last three decades. In a similar vein, Robinson (2006) identified decreasing trends in summer precipitation amount in North Carolina in the 20th century. In Europe, Pal et al (2004) detected a drying trend in summer precipitation amount in recent decades. In East Asia, Gong and Ho (2003) examined the relationship between the Arctic Oscillation and the East Asian summer monsoon in the 20th century, suggesting that changing Oscillation is associated with the dryness or wetness of the region. In China, summer precipitation increased in east China between 1961 and 2000 (Wang and Zhou 2005) and in the Yangtze River basin between 1950 and 1999 (Becker et al 2006). The extreme precipitation events in summer dramatically increased by 10–20% every ten years in the Yangtze River basin (Wang and Zhou 2005).

There are several studies investigating summer precipitation characteristics in Korea. Ha et al (2005) examined
the interannual variability of the summer monsoon in Korea, while Ho et al. (2003) investigated changes in summer rainfall regimes between 1954 and 2001. Lee and Kwon (2004) investigated summer rainfall characteristics for 13 stations and identified the relationship between the variation of rainfall amount and Pacific sea surface temperature. Previous studies, however, either examined one station for a long time (Wang et al. 2006) or merged individual station information into a region (Lee and Kwon 2004, Baek and Kwon 2005). When precipitation totals are averaged across more than two stations, no statistically significant trend could be observed. Thus, it is currently unknown whether or not trends are spatially homogeneous. As the first nationwide assessment using the most comprehensive data set, our study will uncover the spatial patterns of summer precipitation trends and explore potential causes of these trends. In addition, it will provide baseline climate information for basin-wide water resource planning under climate change.

2. Data and methods

2.1. Data

The Korea Meteorological Administration (KMA) and the Korean Ministry of Construction and Transportation have provided daily precipitation measurements over 200 stations since 1973, when the nationwide comprehensive measurements began. The stations are generally well distributed across the country and five major river basins, although there are relatively few stations in the southern region (figure 1). Stations that are located in remote islands or have missing precipitation data are excluded from the analysis. We examined homogeneity for each station based on the Worsley likelihood ratio, the cumulative deviations, and the Bayesian procedures in AnClim (Stepanek 2007). Only a few stations exhibit homogeneity with significance slightly less than the 95% confidence level by one or two criteria. The Korea Water Resources Corporation has done extensive quality control for available weather station data maintained by the Korea Meteorological Administration and Korea Ministry of Construction and Transportation. Accordingly, 187 stations that have full records of precipitation data are used for the current study. This is advantageous because a consistent and comprehensive data set is important for studying the frequency and intensity of precipitation. We used these stations to identify trends in precipitation amount and intensity and heavy precipitation.

2.2. Precipitation trends

We used three indices for detecting summer precipitation trends. First, we used the total summer precipitation amount (figure 1). The second index calculates the precipitation intensity during the summer season from June to September. Summer precipitation intensity is determined by dividing the total summer precipitation amount by the total number of precipitation days during the same period. Monthly precipitation intensity is calculated in the same manner. Finally, we examined the trend in heavy precipitation events.
Heavy precipitation events are defined as those with daily precipitation amounts greater than 30 and 50 mm. A daily threshold of 30 mm (Ho et al 2003) and 50 mm (Su et al 2006) has been used in other studies in East Asia. As shown in figure 2, 50 mm (30 mm) is approximately the 90th (80th) percentile of summer daily precipitation totals for the majority of stations. We counted the number of summer days with daily precipitation exceeding these thresholds and investigated whether the numbers have significantly increased over the study period. All trend analysis was based on the non-parametric Kendall’s $\tau$ test. Kendall’s $\tau$ test was applied to each station to detect positive or negative trends in precipitation amount, intensity and extreme events. Kendall’s $\tau$ test has been used in previous studies (e.g., Chang 2007, George 2007).

### 3. Results

#### 3.1. Precipitation amount

The results of the Kendall’s $\tau$ test show increasing summer precipitation amount (Kendall’s $\tau$ values are all positive) for all stations in South Korea (figure 3). Trends are significant for 37 stations at the 99% confidence level and for 103 stations at the 95% confidence level (approximately 55% of the total number of stations). These stations are widely spread over four major river basins except in the Sumjin and Youngsan River basins. No stations in the Youngsan and Sumjin River basins show significant trends in the June precipitation amount. Ten stations in the Han River basin and three stations in the Nakdong River basin show a significant trend. Trends in individual monthly precipitation amount show different patterns. The June precipitation amount increased for 35 stations (95% confidence level), while the July, August, and September precipitation amounts increased for only 12, 25, 2 stations, respectively (figure 4). No stations in the Youngsan and Sumjin River basins show significant trends in the June precipitation amount. Ten stations in the Han River basin and three stations in the Nakdong River basin
Figure 3. Trends in summer precipitation amount and intensity for 187 weather stations in Korea, 1973–2005. Closed triangles exhibit significant trends at the 95% (small triangle) and at the 99% (large triangle) confidence levels, respectively.

Table 1. Moran’s \( I \) values for summer precipitation amount and intensity.

| Month       | June | July | August | September | Summer |
|-------------|------|------|--------|-----------|--------|
| Precipitation amount | 0.35 | 0.27 | 0.35 | 0.20 | 0.32 |
| Precipitation intensity | 0.27 | 0.15 | 0.29 | 0.15 | 0.14 |

show significantly increasing trends in the July precipitation amount. The August precipitation trends show a dissimilar spatial pattern. Only a few stations in the Han and Gum River basins show significantly increasing trends. Fifteen stations in the Nakdong River basin exhibit significantly increasing trends in the August precipitation amount. The September precipitation amount shows either increasing or decreasing trends. Only two stations show significantly increasing trends in the September precipitation amount. Global measures of spatial dependence indicate that there is a weak to moderate positive spatial autocorrelation in the trends of individual monthly precipitation amount. The June precipitation trend shows the highest autocorrelation (Moran’s \( I = 0.35 \)), while the September precipitation trend shows the lowest autocorrelation (Moran’s \( I = 0.20 \)) (see table 1).

3.2. Precipitation intensity

The trends of summer precipitation intensity are similar to those of summer precipitation amount, but to a lesser extent.

Fifty nine stations (approximately 30% of the total number of stations) show significant increasing trends in summer precipitation intensity at the 95% confidence level. However, even though not statistically significant at the 95% confidence level, 24 stations (13% of the total) show negative trends, indicating the increasing number of rain days in summer (figure 5). Several stations that do not exhibit significant trends in precipitation amount show significant trends in precipitation intensity. About half of the stations in the Han River and Gum River basins show significant upward trends in precipitation intensity. Forty one stations exhibit significant increasing trends in the June precipitation at the 95% confidence level. Only a few stations show significant upward trends in the July, August, and September precipitation intensity (figure 5). Fifty three stations exhibit downward trends in the August precipitation intensity. As indicated by smaller Moran’s \( I \) values (0.15–0.29), there is a weaker spatial autocorrelation in precipitation intensity than in precipitation amount. The trends in entire summer precipitation intensity show the lowest spatial autocorrelation (Moran’s \( I = 0.14 \)), suggesting that regional variability in precipitation intensity is masked when data are averaged over a longer time period. In addition, with very complex terrain in the Korean peninsula, some nearby stations show very different precipitation trends.

3.3. Heavy precipitation

Trend analysis indicates that the number of days with daily precipitation exceeding 30 and 50 mm during the summer have
increased at all stations (figure 6). However, only less than half of the stations (77 stations and 80 stations for 30 mm and 50 mm, respectively) exhibit a significant positive trend at the 95% confidence level. These stations are located in either the northern part of South Korea (mainly in the Han River basin) or the southeastern part (Nakdong River basin). Several
coastal locations (mainly at the east coast and southeast coast) also exhibit a significant upward trend in heavy precipitation. Some of these stations are located in major urban areas, making residents vulnerable to potential flooding. There is no spatial autocorrelation (the Moran’s $I$ values are 0.02 for precipitation $\geq 30$ mm day$^{-1}$ and $-0.05$ for precipitation $\geq 50$ mm day$^{-1}$).
in the trends of heavy precipitation events. While heavy precipitation events are often associated with typhoons in late summer, it is unlikely that the frequency of typhoons increased over the study period because not all coastal locations show increasing trends.

4. Discussion

What are the causes of the spatial variations of the observed trends in summer precipitation? One possible cause of the different magnitude of trends in each month is the temporal redistribution of summer rainfall. Chung et al (2004) showed changes in the nature of the Changma front (called Mei-yu in Chinese), a quasi-stationary front that brings monsoon precipitation in Korea. The Changma front used to bring the majority of summer precipitation in a relatively short period between mid June and late July. Since the 1990s, however, the front has tended to be weakened over the Korea peninsula, resulting in relatively more precipitation toward late summer. In a similar vein, Lee and Kwon (2004), in a comparative study of climate between the two periods (1941–1970 versus 1971–2000), showed a decrease in July precipitation by 20% and an increase in August precipitation by 54% in the east and southeast part of Korea. Ko et al (2005), in the analysis of 5-day precipitation between 1998 and 2003, showed a marked increase in late July precipitation in the western part of the Han River basin, including the Seoul metropolitan area. Our findings are consistent with the aforementioned studies.

A related possible explanation for this increasing trend in summer precipitation is the sudden increase in the domain-mean geopotential height at 700 hPa ($\Phi_{700}$) over mid-latitude Asia for summer in the mid 1970s (Ho et al 2003). The increased $\Phi_{700}$ brings a stronger northerly wind, producing a moisture convergence and eventually producing heavy rainfall over Korea. Similarly, Becker et al (2006), in the analysis of precipitation trends in the Yangtze River basin of China, showed that increasing summer precipitation trends are associated with a change in the southwesterly flow and Mei-yu characteristics. Zhou and Wang (2006) explained the summer precipitation variability in the Yangtze River valley as a function of boreal spring Hadley circulation and the following summer east Asian atmospheric circulations. They found a significant positive correlation between the Hadley circulation and the summer rainfall amount. Sea surface temperature (SST) anomalies in the Indian Ocean and South China Sea, which cause anomalies in the east Asian summer monsoon, are likely to be caused by spring Hadley circulation.

Changes in the SST are also believed to be associated with observed precipitation trends in South Korea. Lee and Kwon (2004) found different relationships between SST anomalies and summer precipitation, depending on the timing of the summer and the region investigated. While there was a positive relationship between spring Pacific Decadal Oscillation and
mid July precipitation in the central western region of South Korea, there was a negative relationship between the Southern Oscillation Index (SOI) and mid August precipitation in the eastern and southeastern part of South Korea. In a similar vein, Jin et al (2005) detected significant correlations between the SOI and the transformed precipitation for five stations in South Korea. In southern coastal lowlands, monthly precipitation is influenced by a La Nina event with a lag time of four months. In middle to high regions of South Korea a lag time of five months is detected. A detailed examination on the onset and the length of the Changma season with the summer wind patterns and changes in sea surface temperature in the Pacific Ocean could prove some of the link between these factors and summer precipitation trends.

The results of spatial autocorrelation indicate the spatial and temporal variations of precipitation trends. June, the first month of the rainy season, is the month with the highest spatial autocorrelation in precipitation amount and the second highest in precipitation intensity. This is likely the result of the gradual movement of the Changma front from south to north. The weaker autocorrelation in subsequent months suggests that localized convective or orographically induced precipitation becomes important as the Changma front disappears. Accordingly, in a complex mountainous terrain, adjacent weather stations could exhibit different trends in precipitation amount and intensity.

Coastal areas in the southeastern and eastern parts of Korea are vulnerable to the landfalls of typhoons in late summer (from late August to September). The weakest spatial autocorrelation in September precipitation suggests that the sources of moisture are mixed in September. Namely, both frontal systems and typhoons bring rainfall in September. The localized impact of typhoons could have contributed to weak spatial autocorrelation. However, it is difficult to separate one from the other as they often tend to occur concurrently. While some studies suggest the frequency of typhoons decreased in the North Pacific Ocean during the past decades (Webster et al 2005), it is also possible that the intensity of typhoons could increase as the ocean water temperature will rise under global warming. These intense typhoons typically accompany very localized heavy precipitation events, resulting in devastating flood damage, particularly in coastal urban areas when inland freshwater and storm surges occur at the same time (Kim et al 2006, Chang et al 2007).

While it is currently uncertain whether these observed trends will continue in the future, a long-term analysis of precipitation provides some insights. If the study period is extended to a longer one, we might observe a cyclical pattern as well. Wang et al (2006) identified a significant increasing trend in the summer precipitation in Seoul between 1778 and 2004. When the study period was confined to the pre-1950 period, however, there was no significant trend in this region. The increasing trends since the 1950s are likely to be caused by large-scale changes in the circulation of the East Asian summer monsoon system. Recent regional climate modeling studies in the study region provide additional insights into the possible future paths of precipitation trends. A regional downscaling model, based on the RegCM3 high-resolution one-way double-nested system (the mother domain = 60 km, the nested domain = 20 km), projects increasing summer precipitation for the 30-year period 2021–2050 with respect to the reference period (1971–2000) under the IPCC SERS B2 emission scenario, particularly in the northern part of Korea (Im et al 2007). Similarly, Boo et al (2006), based on the IPCC SRES A2 scenario, showed an increase in the number of the days of heavy precipitation as well as the corresponding amount by the end of the 21st century (2071–2100) compared to the reference period (1971–2000). Their simulation was based on the MM5 downscaling at 27 km horizontal resolution using the ECMWF Hamburg Atmosphere Model Version 4 coupled with the Hamburg Ocean Primitive Equation-Global (ECHAM4/HOPE-G) model of the Max Planck Institute for Meteorology.

5. Conclusions

Using the nationwide comprehensive daily precipitation data in South Korea, we found generally increasing trends in summer precipitation amount and intensity. However, there are substantial within-summer variations and spatial variations of these trends. The June precipitation amount and intensity significantly increased in the northern and western central parts of South Korea, while the August precipitation amount significantly increased in the southeastern part of South Korea. These variations are associated with changes in large circulation patterns, sea surface temperature anomalies, and orography. Changes in the timing and magnitude of summer precipitation will have significant effects on regional water balance. Water resource managers should consider changes in the frequency, timing, and magnitude of potential flooding or droughts if the observed trends were to continue in the future under a warming world.

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