Polarizing rain types linked to June drought in the Korean peninsula over last 20 years

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Abstract
We observe a notable decreasing trend of June rainfall over the Korean peninsula in recent 20 years. This drought condition is found to be linked to the polarizing trend of rainfall intensity; more non-rain and drizzle-like rain, less moderate-intensity rain, and more heavy rain events. Overall, the June drought over the Korean peninsula is found to be associated with less occurring moderate-intensity rain. This feature is interpreted as that the dominant warm-type heavy rain systems with a medium storm height tends to be less frequent while cold-type heavy rains characterized by taller storm become more frequent during last 20 years. The north-westward expansion of the North Pacific high in June appears to weaken the continuous moisture supply to the Korean peninsula, which is a main element of forming the warm-type heavy rain there.

KEYWORDS
cold-type, drought, GPM, Korea, rain, TRMM, warm-type

1 | INTRODUCTION

Climatologically the Asian summer monsoon establishes a quasi-stationary front in South China in May, and then propagates to central China by mid-June. By that time, the rainfall zone disappears abruptly and a new rainfall zone develops from mid-June to late July over North China, Japan, and Korea (Park et al., 1988; Lee et al., 2017). The latter part of the Asian monsoon is called East Asian summer monsoon (EASM) and is regionally known as Mei-Yu in China, Baiu in Japan, and Changma in Korea (Wang and LinHo, 2002; Yihui and Chan, 2005). A northward advance of the North Pacific high is also observed during this period. Although this abrupt advance occurs regularly on an annual basis, the EASM experiences significant interannual as well as intraseasonal variations of the regional circulation in both space and time (Sohn and Han, 1995; Sohn et al., 2001; Chu et al., 2012; Ha et al., 2012). Followed, in response to the varying monsoon circulations, are significant fluctuations in the rainfall. Furthermore, the climate change associated with ongoing man-made global warming may influence this phase-locked northward advance of the monsoon system.

In line with such notion, the circulation and rainfall related to the EASM have undergone a significant change around the mid to late 1990s (Kwon et al., 2007; Yim et al., 2014; Lee et al., 2017). For example, the rainfall in the northern part of the EASM area (including eastern China, Korea, and Japan) has been substantially decreased, in contrast to the increased rainfall in the southern part of the EASM area (i.e., southeastern China, Taiwan, and East China Sea, and adjacent northwestern Pacific Ocean). In fact, the decreasing rainfall over the northern part is apparently linked to the wide-spread drought over northeast Asia.
in recent years (Han et al., 2015; Xu et al., 2015; Zhang and Zhou, 2015; Piao et al., 2017).

In association with the change in the EASM system, it is of interest to observe how the regional monsoon phenomena such as Changma in Korea have been changed. This is because frontal activities over the Changma area are largely modulated with moisture transport from the southwest along the northwestern boundary of the North Pacific high. Thus, any change in the large-scale circulation and its variations should influence the meteorological conditions and then rainfall over the regionally known monsoon area. Exploring how the recent change in EASM system, if there is any, might influence the rain distribution over the Korean peninsula, we analyse the trend of surface observations and satellite measurements of rainfall. In fact, the Korean peninsula has been experiencing a noticeable decrease in June rainfall during the recent 20 years (see Figure 1a of this study).

It is well conceived that the rain system over the Korean peninsula is best depicted by the combination of two heavy rain types (i.e., warm type vs. cold type) (Sohn et al., 2013; Song and Sohn, 2015; Song et al., 2017). The warm-type heavy rain is characterized by comparatively lower storm height with cloud-liquid-water rich clouds under rather convectively near neutral conditions, while the cold-type heavy rain by high storm height with abundant ice water content in the deep convective clouds. These two types of heavy rain are similar concept with extreme rainfall and extreme convective events defined using maximum near-surface rain rate and 40 dBZ echo-top height from Hamada et al. (2015) over the tropics and Hamada and Takayabu (2018) around Japan. Since the humid environment prerequisite for the warm-type heavy precipitation is established by large-scale water vapour transport from the southwest and its convergence onto the monsoon frontal area where the rain forms (Sohn et al., 2013), the monsoon circulation change, particularly associated with the development and evolution of the North Pacific high, should result in change in the rain type in Korea. It is thought that the rain type change in Korea may be linked to the local drought noted in last 20 years. With this postulate in mind, we will examine whether the recent Korean drought is related to rain type changes, which are probably caused by changes in the large-scale monsoon circulation.

2 | USED DATA

For the rainfall trend analysis, we use the Automated Synoptic Observing System (ASOS) rainfall data collected at the Korea Meteorological Administration (KMA)'s 60 weather stations in South Korea for three summer months (June–August) over a 45-year period (1973–2017). The ASOS data represent rainfall over the middle and southern parts over the Korean peninsula. To examine rainfall change features over East Asia we focus on most recent 20 three summer months (1998–2017) using Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA,
Huffman et al. (2007)) monthly rainfall data (version 7). Although satellite-based rain products show a severe under-estimate over the Korean peninsula, TMPA rainfall appears to be relatively close to the gauge measurements because of a scaling procedure against surface rain gauge observations (Huffman et al., 2007; Sohn et al., 2010). The ERA-Interim reanalysis monthly data (Dee et al., 2011) are also used to analyse vertically integrated moisture flux convergence, and geopotential height and moisture flux at the 850-hPa level over East Asia. The TMPA and ERA-Interim data are re-gridded in the same format of the horizontal resolution (1° × 1°) using their respective resolutions (0.25° × 0.25° and 0.75° × 0.75°).

In order to investigate microphysical properties of precipitating clouds, near-surface radar reflectivity and storm height (or echo-top height) from the TRMM Precipitation Radar (PR) products (2A25 version 8) are collected for the summer of 1998–2014. By adding 3 years (2015–2017) of Global Precipitation Measurement (GPM) Dual-frequency Precipitation Radar (DPR) Ku-band only products (version 6), total 1,266,632 rain cloud data are considered during the 20-year period (1998–2017). The PR V8 and DPR V6 data were developed with the same algorithm and adjusted for long-term climate study. Two active sensors (PR vs. DPR) have similar characteristics in radar frequency (13.8 GHz vs. 13.6 GHz) and resolution (horizontal: 5 km; vertical: 0.25 km), except for the spatial coverage (about ±36° vs. ±65° latitude) and the visit frequency (twice vs. once a day over Korea). Also noted is the different horizontal resolution of the PR sensor (4.3 km) before the TRMM orbit boost (August 7, 2001). Because this study mainly uses the vertical distribution of precipitation parameters at each target (4.3 km vs. 5 km), the effect of orbit boost may not be meaningful.

3 | RESULTS

Although the summertime rainfall over the Korean peninsula exhibits strong inter-annual variability, June rainfall has been gradually decreasing since 1978 (−23.72 mm decade$^{-1}$ at 96.8% confidence level) as shown in Figure 1a. Although the decreasing trend of June rainfall is strongest since 1996 (−75.63 mm decade$^{-1}$ with 99.9% confidence level), we focus on the recent 20-year period (1998–2017) because of PR and DPR data availability. It is noted that the decreasing trend of −70.55 mm decade$^{-1}$ for June rainfall over the 20-year period is statistically significant at a 99.2% confidence level. The year of 2011 appears to be anomalous, and it is thought to be associated with Typhoon MEARI which heavily influenced the analysis area for 24–26 June 2011 (especially June 24, 2011, which recorded the heaviest rainfall as a result of the combination of monsoon front and typhoon’s indirect effects). If June 2011 is excluded, then the decreasing trend of −80.05 mm decade$^{-1}$ for 1998–2017 is statistically significant at a 99.98% confidence level. The decreased rainfall in June is especially interesting because the period is in between dry and wet seasons in South Korea. The rainy season in the Korea peninsula, called Changma, starts from the southern part of the peninsula late June, and it lasts until September (Wang and LinHo, 2002). Therefore, the prolonged drought in June may suggest a longer dry season with shorter rainy wet season, or late start of the rainy season.

It is also of note that the rainfall trend in July over the 20-year period is not clear, whereas the rainfall in August exhibits a decreasing trend with a relatively weak statistical significance (i.e., 94.6% confidence level) compared to that in June (Figure 1b,c). Overall, summertime rainfall over the 20-year period shows an evident decreasing trend (i.e., −185.82 mm decade$^{-1}$) at a 99% confidence level. Henceforth, the Korean peninsula has been experiencing a severe summer drought in recent years. Kwon et al. (2016) also reported that the recent drought for the period of 2013–2015 over the Korean peninsula is quite extreme for last 50 years from a statistical point of view.

In order to identify the large-scale variability of rainfall linked to the prevailing June drought over the Korean peninsula, we analyse the June mean and trend of TMPA rainfall for the 1998–2017 period over the East Asian monsoon region (Figure 2a,c). The spatial distribution of June rainfall appears to be organized as a form of rain band, located at around 30°N (Figure 2a). The rainfall area over the Korean peninsula shown in Figure 2a is mainly shaped by the rainfall occurred in the later part of June (not shown). The TMPA rainfall also shows a dominant decreasing trend in the southern part of the Korean peninsula (Figure 2c). The decreasing rainfall trend (at a 95% of the statistical confidence) is clear over the Korean peninsula. Here, the outlined area (34°–36.25°N, 123°–132°E) over the Korean peninsula is selected for further analysis; the northern limit of the domain is confined within 36.25°N because of the TRMM PR coverage. The mean trend of June rainfall over the Korean peninsula is −81.58 mm decade$^{-1}$, slightly larger than from the ASOS 60 rain gauge stations (−70.55 mm decade$^{-1}$), but it looks similar to the trend after excluding June 2011 (−80.05 mm decade$^{-1}$). No such decreasing trend is found in July over Korea (Figure 2c). In August, again, a decreasing rainfall trend is mainly found in the middle part of the Korean peninsula while the decreasing rainfall trend over the southern part of the peninsula is relatively weak (Figure 3d). Thus, main analysis is done for June again because of the limited TRMM PR coverage.

As intuitively connected, the June rainfall should be closely related to the large-scale moisture flux convergence around the 30°N latitude, located in the northwestern periphery of the North Pacific high (Figure 2b). From these
analyses, it can be conjectured that June rainfall in Korea is strongly influenced by the evolution of the North Pacific high. In fact, the further northwestward intrusion of the North Pacific high may cause more rainfall over the Korean peninsula or vice versa in June. In accordance with such notion, 850-hPa geopotential height has been decreased over the most of study domain. The highly decreasing area centred at the southeast of Japan extends west and then northwest, toward the northeast China, causing the weakened North Pacific high over the Korean peninsula and surrounding areas. Ha and Lee (2007) also noted that the weak EASM was strongly affected by weakening of the Western North Pacific Subtropical High (WNPSH) around Bonin Islands, which transports water vapour into the EASM region via southwesterly wind on its western periphery (Sampe and Xie, 2010). Since the NNPSH is expected to weaken and move eastward under global warming scenarios (He et al., 2015), June drought on the Korean peninsula can be even worse in the future.

In line with weaker North Pacific high in June, southwesterly moisture flux at the 850-hPa level is also weakened over the periphery of the North Pacific high (see arrows in the opposite direction in Figure 2d), compared to the mean moisture flux. As a result, the moisture flux convergence (given in colour scale in Figure 2d) over the Korean peninsula is reduced, suggesting that decreasing rainfall over the Korean peninsula is synoptically forced. By contrast, no significant change is made in thermodynamic variables (such as total precipitable water and convective available potential energy) over the Korean peninsula for June, 1998–2017 (not

**FIGURE 2** Climatological June mean (a) TMPA rainfall (mm) and (b) ERA-Interim moisture flux convergence ($10^{-3}$ g m$^{-2}$ s$^{-1}$, colour) with 850-hPa geopotential height (gpm, solid line). June trend during 1998–2017; (c) precipitation (mm decade$^{-1}$) and (d) moisture flux convergence ($10^{-3}$ g m$^{-2}$ s$^{-1}$ decade$^{-1}$, colour) and geopotential height (gpm-decade$^{-1}$, solid line). Arrows in (b) and (d) represent June moisture flux (m s$^{-1}$) and its trend (m s$^{-1}$ decade$^{-1}$) at the 850-hPa level. In (c) the sign “×” indicates that the trend at the given grid is not significant at the 95% confidence level. The rectangular box (34–36.25°N, 123–132°E) outlined with grey lines in (c) and (d) is the area where TRMM PR/GPM DPR observations are analysed.
shown), again implying that the rainfall decrease in June is induced dynamically rather than thermodynamically. It is certainly interesting and important to examine what caused the weakened North Pacific high in the beginning; however, it is beyond the scope of this study because our main focus is the rain type change associated with the recent summer drought over the Korean peninsula.

From now on, we examine how physical characteristics of precipitation have been changed in the course of 20-year period and how those changes can be linked to the recent drought over Korea in June. In doing so, we first analyse the frequency change of ASOS hourly accumulated rainfall intensity in South Korea. Figure 4a–c shows the climatological mean for the probability density function (PDF) distributions of the ASOS rainfall intensity. The mean occurrence frequencies of non-rain events, which are represented in the first column of Figure 4, are 91.6% in June, 87.5 in July, and 88.5% in August. Here, the rainfall intensity of 0.1 mm hr$^{-1}$ was used as the threshold value to distinguish between non-rain and rain cases. Since the beginning of June is generally before the rainy season (i.e., Changma period), the occurrence frequency of non-rain events in June is higher than those in July and August. In addition, the frequency of heavy rain cases (>10 mm hr$^{-1}$) in June (3.94%) is about half of those in July (7.72%) and August (7.60%).

The change in the PDF distribution of rainfall intensity for the recent 20-year period is quite interesting (Figure 4d–f). Here the PDF trends are calculated separately for the non-rain, drizzle to light rain (0.1–10 mm hr$^{-1}$), and heavy rain (>10 mm hr$^{-1}$) cases. The grey bar in Figure 4d–f denote statistically significant rain rate trend for the given rain rate in the 90% confidence level. For the PDF trend in June (Figure 4d), it is of importance to note that non-rain and drizzle-like rain cases (0.1–1 mm hr$^{-1}$) obviously become much more frequent while moderate-intensity rain cases (1–11 mm hr$^{-1}$) showing decrease in frequency. Considering that the moderate-intensity rainfall cases occupy 67% of the total rainfall in June, the significant decrease in moderate-intensity rainfall intensities should be a main cause
of the June drought of 1998–2017, along with the direct increase of non-rain events. The decreasing rainfall frequency is also found in 11–16 mm hr⁻¹ range (except for 13–14 mm hr⁻¹), while the magnitude and statistical significance of trends are relatively low. By contrast, extreme heavy rain cases greater than 16 mm hr⁻¹ tend to become more frequent. Overall, non-rain, drizzle, and extreme heavy rain events are found to be more frequent while light and moderate-intensity rains in between become less frequent in June over the last 20-year period. Although an increase of drizzle-like rain and a decrease of moderate-intensity rain are also found in July and August (Figure 4e,f), the magnitude of linear trend is relatively small compared to June.

It is certainly interesting to observe increasing extreme heavy rain in spite of decreasing total June rainfall over Korea. Concerning the summer rainfall trend over the Korean peninsula, Jung et al. (2011) reported that both intensity and frequency of heavy rainfall have been increased during the summer seasons over the 1973–2005 periods, contributing to the increasing annual precipitation. However, the decreasing rainfall mainly associated with reduced rain cases showing moderate intensities in this study is different from previous results, suggesting that the contribution of decreasing moderate-intensity rains to the drought is a more recent phenomenon. In addition, the separation of the whole summer analysis into individual month’s analysis may uncover disguised signals. Such trend changes are obvious in Figure 1.

The results found so far in this study suggest that there may be organized changes in the type of precipitating clouds, which then cause the rain intensity changes. Here, from such point of view, we examine TRMM/GPM-observed precipitation structures. In doing so, we use near-surface radar reflectivity and storm height of precipitating clouds. Here, storm height used in this study is from the TRMM/GPM products, not from the user-defined reflectivity threshold (e.g., 18 dBZ). Figure 5a–c shows the mean frequency distributions of the storm height corresponding

FIGURE 4 Climatological mean and linear trend for the probability density function (PDF) distribution of ASOS hourly accumulated rainfall intensities in South Korea for June, July, and August of 1998–2017. The occurrence frequency of non-rain cases is represented in the first column of figure, and statistics of rain cases are given after the second column. Different Y-axis scales are used for drizzle-light rain (0.1–10 mm hr⁻¹) and heavy rain (>10 mm hr⁻¹) cases. The grey bars in (d–f) denote statistically significant points in the 90% confidence level.
to near-surface radar reflectivity, but normalized at each reflectivity bin. Since the minimum detectable reflectivity for near-surface rain rate is different between PR (18 dBZ) and DPR (12 dBZ) measurements (Hamada and Takayabu, 2016), results are expressed for reflectivities greater than 18 dBZ. The reflectivity of 18 dBZ and 12 dBZ correspond roughly to rain rates of 0.7 \text{ mm hr}^{-1} and 0.2 \text{ mm hr}^{-1}, respectively. Figure 5a–c clearly exhibits that near-surface radar reflectivity and storm height have a positive linear relationship, indicating that heavier rain is associated with more vertically developed rain cloud. The storm heights averaged for all reflectivity ranges are 6.3 km in June, 6.9 km in July, and 7.3 km in August. These mean storm heights represent that stratiform and warm-type heavy rain clouds are dominant in the Korea peninsula. This type of rain structure and related cloud microphysics responsible for such rain formations are given in detail in Sohn et al. (2013), Song and Sohn (2015), Song et al. (2017), and Song and Sohn (2018). Overall, the results strongly suggest that the rainfall in June occurs mainly in association with either stratiform or warm-type heavy rain. However, taller storms occur relatively frequently in August over the Korean peninsula. Seo and Kim (2017) also noted that the mean storm height of rain clouds during the post Changma period (later July to August) is higher than that during the Changma period (late June to mid-late July).

Figure 5d exhibits a decrease in low storm height and an increase in high storm height (i.e., more elevated storm height) in June during the last 20 years. For the reflectivity range less than 40 dBZ, the storm heights of 4–7 km have been decreased, whereas the storm heights of 7–10 km have been increased. These are associated with the changes of light and moderate-intensity rains. Also noted is an increase in frequency for the storm height of 2–3 km and radar reflectivity less than 20 dBZ. This appears to be associated with the increased drizzle-like rain shown in Figure 4d. For reflectivity above 40 dBZ, the decreasing and increasing storm-height areas are further lifted up to 9 km and 15 km, respectively. Since heavy rain cases with rain rate greater than 10 mm hr$^{-1}$ approximately corresponds to the radar reflectivities above 35 dBZ, the results in Figure 5d are interpreted as that the dominant warm-type heavy rain system over the Korean peninsula in June evolves into more cold-type heavy rains with taller clouds. It also implies an increase of locally-organized rain systems with
stronger rain intensity because the cold-type heavy rain is generally developed with a relatively narrow area and stronger rain intensity compared to the warm-type heavy rain (Song and Sohn, 2015). Although we admit that there may be some contamination with the use of different sensors between last 17 years (PR) and recent 3 years (DPR), the increased of cold-type heavy rain in June was also found in results for a 17-yr study period (1998–2014) from PR V7 product (Figure 5e), enhancing the confidence of the results.

In June, it is concluded that light rain is getting lighter and heavy rain is getting heavier with taller cloud tops, and at the same time, the warm-type rains are getting suppressed. And this polarizing rain type change appears to be closely linked to the continuous decrease in rainfall over the Korean peninsula. In addition, rain type changes in August are linked with the increased drought by decreasing moderate-intensity rainfall (Figure 4f). Overall, rain type changes occurred during June and August must have contributed to the overall summertime drought over the Korean peninsula over last 20 years.

4 CONCLUSIONS

This study examined changes of rainfall over the Korean peninsula during June and how those changes are linked to continuous drought in the past 20 years (1998–2017). Surface rain gauge observations reveal a notable decreasing trend of June rainfall (70.55 mm decade⁻¹) over the recent 20-year period. We also examined July and August periods, and found that August shows a decreasing trend whereas no meaningful trend is noted in July. Overall, the summer time in Korea seems to have experienced the drought condition over the last 20 years.

Satellite-based TRMM and GPM rain estimates indicate that such decreasing trend in June is attributed to the more frequent non-rain events and drizzle-like rain (＜1 mm hr⁻¹), decreasing tendency of moderate-intensity rains (1–11 mm hr⁻¹), and an increasing tendency of extreme heavy rainfall (＞16 mm hr⁻¹). The different tendencies dependent upon the rain intensity strongly suggest a polarizing feature of the rain events; light rain gets lighter while heavy rain gets heavier, losing the moderate-intensity rain. Thus, overall June drought over the Korean peninsula should be related to less occurring moderate-intensity rains as well as more non-rain events.

Polarizing rain types are also linked to the shift of convection type; dominant warm-type heavy rain tends to be weakened by increasing cold-type heavy rains which are well characterized by taller storm. This shift is consistent with results of losing the moderate-intensity rain. This fact also concludes that the moderate-intensity rains are mostly warm-type rain related. Less warm type over the Korean peninsula area implies less water vapour convergence onto the region through the large-scale water vapour transport. Since the northwestward expansion of North Pacific high is prerequisite for supplying water vapour into the Korean Changma area, following anti-cyclonic flow along the northwestern edge of the high, the reduced warm-type rainfall strongly suggest that the evolution of the North Pacific high and associated circulations has been changed. We confirmed this notion from the mean and trend analysis of 850 hPa-level geopotential height and moisture flux; the 850-hPa geopotential showed a decreasing trend over the most of Korea and Japan and East China sea area, resulting in decreasing water vapour flux convergence over the area extending from East China to Japanese main island, through the Korean peninsula.

Overall, we conclude that the June drought over the Korean peninsula experienced in last 20 years appears to be related to the northwestward expansion of the North Pacific high, which consequently hinders moisture supply to the Korean peninsula area. Less of moisture convergence there may result in a decreasing tendency of warm-type rainfall, which is largely dependent upon the continuous large-scale moisture supply, bringing in the polarized rain distribution.

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