Jour. Korean Earth Science Society, v. 28, no. 5, p. 585–597, September 2007

The Recent Increase in the Heavy Rainfall Events in August over the Korean Peninsula

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Abstract: The characteristics of the rainfall events on the Korean peninsula have been investigated by means of regional and global observational data collected from 1954 to 2004 with an emphasis on extreme cases 80 mm day^{-1}. According to our analysis, long-term annual rainfall anomalies show an increasing trend. This trend is pronounced in the month of August, when both the amount of monthly rainfall and the frequency of extreme events increase significantly. Composite maps on August during the 8 wet years reveal warm SST anomalies over the eastern Philippine Sea which are associated with enhanced convection and vertical motion and intensified positive SLP over central Eurasia during August. The rainfall pattern suggests that the most significant increase in moisture supply over the southern parts of China and Korea in August is associated with positive SLP changes over Eurasia and negative SLP changes over the subtropical western Pacific off the east coast of south China. The frequent generation of typhoons over the warm eastern Philippine Sea and their tracks appear to influence the extreme rainfall events in Korea during the month of August. The typhoons in August mainly passed the western coast of Korea, resulting in the frequent occurrence of extreme rainfall events in this region. Furthermore, anomalous cyclonic circulations over the eastern Philippine Sea also promoted the generation of tropical cyclones. The position of pressure systems - positive SLP over Eurasia and negative SLP over the subtropical Pacific - in turn provided a pathway for typhoons. The moisture is then effectively transported further north toward Korea and east toward the southern parts of China during the extreme rainfall period.

Keywords: typhoon, heavy rainfall, August

Introduction

The bulk of annual rainfall occurs during the Northern Hemisphere (NH) summer (June-July-August; hereafter, JJA) when the stationary fronts are most active and gradually move toward East Asia. The stationary fronts, called *Changma* in Korea, are regarded as a regional phenomenon related to the East Asian monsoon system. They are also called *Meiyu* in China or *Baiu* in Japan. Summer rainfall is mainly due to these fronts, which contribute to more than half of the annual precipitation in these regions. The availability of water resources in these regions strongly depends on the summer rainfall. Thus, its onset, evolution, and termination over the East Asian countries are of prime importance in the forecast community.

From the mid-1990s through the beginning of 2000s, in particular, we experienced extreme rainfall events and severe flash flooding during the month of August, when the *Changma* had already been terminated (KMA, 1998, 1999, 2000, 2002b, 2003, 2004). A number of rainfall experienced record-breaking events with the loss of life and substantial property damage by widespread flooding in a short span of time. Such wet conditions over Korea were extended further to the southern parts of China and some parts of Japan to cause extensive damage (JMA, 1998, 2000, 2002, 2003, 2004; Fujibe et al., 2005).

Extreme rainfall events and flooding have received a great deal of attention, because changes in their variability, intensity, and frequency may significantly influence human resources and socioeconomic activities

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(e.g., Bernard, 1993; Mearns et al., 1997). To date, several studies on extreme rainfall events occurring in various regions have been conducted. Over the last 50 years, the total area affected by the top 10% of the heaviest rainfalls has significantly increased; however, there has been a slight decrease in annual rainfall over certain areas (China: e.g., Zhai et al., 1999). Zhai et al. (1999) reported a significant increase in rainfall over the middle and lower reaches of the Yangtze River and west China during the latter part of the twentieth century. Recently Ho et al. (2005) examined that the interdecadal change in the rainfall exceeding 30 mm day^{-1} accounted for a significant part of the total rainfall variability in China. Also Ho et al. (2003) pointed out that the Korean summer rainfall also showed an abrupt increase in the late 1970s. In Japan, the frequency of extremely heavy daily rainfall clearly showed a long-term increase over the last hundred years (Iwashima and Yamamoto, 1993).

Dai et al. (1998) examined global variations in droughts and wet spells from 1900 to 1995. According to their results, since the late 1970s, there has been some increase in the combined percentage areas that experienced severe drought and moisture surplus, resulting from an increase in either the drought area (e.g., the Sahel, eastern Asia, and southern Africa) or both the drought and wet areas (e.g., the U.S. and Europe). The recent changes are closely related to the shift in the El Niño and Southern Oscillation (ENSO) toward more warm events and coincide with record-high global mean temperatures. An examination of the relationships between ENSO and extreme rainfall in Korea (Cha et al., 1999) suggests that the extreme rainfall events tend to occur more frequently during El Niño years, albeit with small statistically significance.

Global climate models (GCMs) (Houghton et al., 1996; Gregory et al., 1997) indicate that due to global warming, droughts may last longer and become more severe in current drought-prone regions because of enhanced evaporation. Moreover, the increase in atmospheric moisture may intensify precipitation events and consequently lead to further flooding. Furthermore, in Houghton et al. (2001) and references therein, it is reported that unusual precipitation behavior is more frequent nowadays. They observed long-term variations in the frequency and intensity of extreme rainfall events across the world. Kimoto et al. (2005) examined changes in precipitation around Japan using a coupled atmosphere-ocean climate model. Their model results show increases not only in mean precipitation, but also in heavy rainfall days.

On the basis of above mentioned observational and model results, the objective of this study is to investigate the characteristics of rainfall and to suggest the possible causes of recent extreme rainfall events that occurred over Korea in the month of August from 1954 to 2004. Section 2 describes the datasets. Section 3 presents the characteristics of rainfall and its extremes. Section 4 examines the large-scale circulations associated with variations in rainfall. Section 5 presents the summary and concluding remarks.

DATA

In this study, daily rainfall data are obtained by averaging data obtained from 11 operational weather stations of the Korea Meteorological Administration (KMA) across South Korea from 1954 to 2004 (KMA, 1995b). These stations are homogeneously distributed (80-100 km apart) in order to represent an area mean, which is suitable for analyzing synoptic scale disturbances. Figure 1 shows the geographic distribution of the operational weather stations.

We used monthly global data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis from 1954 to 2004 (Kalnay et al., 1996). We also used global sea surface temperature (SST) data provided by the UK Met Office (Parker et al., 1995), referred to as HadISST, from January 1954 to December 2004. The global rainfall distributions are examined using gridded monthly rainfall data from the University of East Anglia (UEA) (New et al., 2000). Supplementary rainfall datasets analyzed in this study include those from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1996).

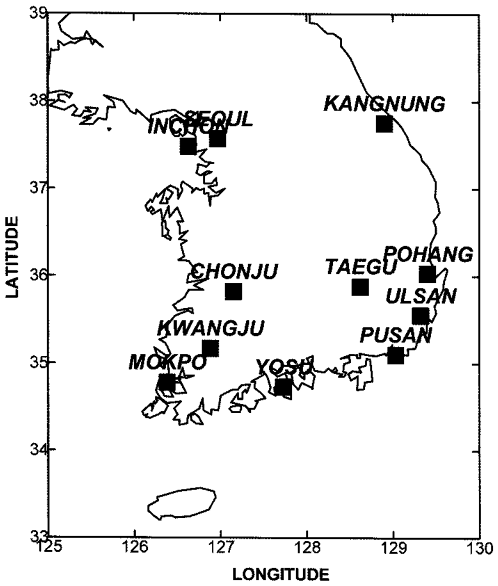

Fig. 1. Locations of 11 operational weather stations in Korea.

Estimates of tropical precipitation anomalies are derived from remote sensing data using polar orbiting satellite measurements of outgoing long-wave radiation (OLR). This data is available from 1974 to the present. OLR data are missing for the period from March to December 1978 (Liebmann and Smith, 1996). The climatology of OLR is computed from 1979 to 2004.

Currently, SST index data of NIÑO WEST (Equator-14°N, 130°E-150°E), NIÑO 4 (4°N-4°S, 160°E-160°W), and NIÑO 3 (4°N-4°S, 150°W-90°W) are available since 1949 and these data can be obtained from the JMA website (http://www.data.kishou.go.jp/climate/diag/index.html). The Joint Typhoon Warning Center (JTWC)'s best-track data of the western North Pacific tropical cyclone are used. The climatology is computed from 1954 to 2004 (51 years), averaged over all the datasets, expect for OLR datasets.

Characteristics of Heavy Rainfall Events

Climatology

The distribution of climatological monthly rainfall and the number of accumulated extreme rainfall days

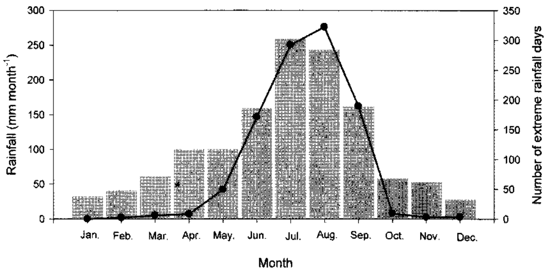

Fig. 2. Annual distribution of the climatological monthly rainfall (in mm; bar). The climatologies are obtained over 51 years (1954-2004) averaged over 11 stations. The number of accumulated extreme rainfall days (80 mm day^{-1}) are also indicated (solid line).

can be examined via histograms using data obtained from 11 stations over 51 years (1954-2004; Fig. 2). The definition of extreme rainfall events used in this study follows that of KMA (1995), i.e., extreme rainfall occurs if the daily rainfall exceeds the fixed threshold value of 80 mm day^{-1}. This is issued as a heavy rainfall warning by KMA to the public.

The total amount of annual rainfall from the 11 station mean is about 1300 mm. It is apparent that the amount of summer rainfall comprises more than half of the total annual rainfall in most regions of Korea. July experiences rainfall (~258 mm month^{-1}), followed by August (~243 mm month^{-1}). The 51 year climatological results reveal that there are more frequent extreme rainfall events in August (322 events) than in July (292 events). In other words, the extreme rainfall events contribute more to the total amount of rainfall in August.

In order to examine the characteristics of temporal distribution of rainfall over the Korean peninsula, we used daily rainfall data obtained during the same period. Figure 3 shows the daily and 20 day running mean of rainfall over Korea, computed from observations. The 20 day running mean of daily rainfall is performed in order to smoothen the possible intraseasonal and synoptic-scale variations in the midlatitude region. For simplifying the computation, daily rainfall data for February 29 every 4 years is not considered. The straight line in Fig. 3 indicates the annual mean daily rainfall of 4.3 mm day^{-1}.

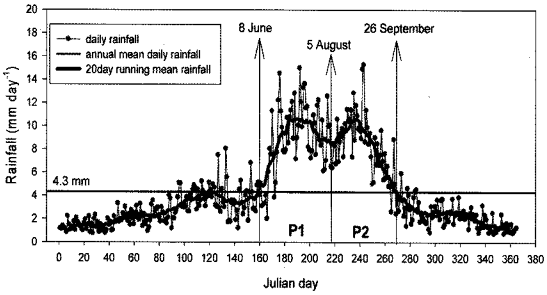

Fig. 3. Annual distribution of the climatological daily rainfall (in mm) averaged over 11 stations for the 51 years. The thin solid line with circles indicates the daily rainfall; thick solid line represents 20 day running mean daily rainfall; straight line means annual mean daily rainfall (4.3 mm day^{-1}). The first (second) rainy season is denoted by P1 (P2).

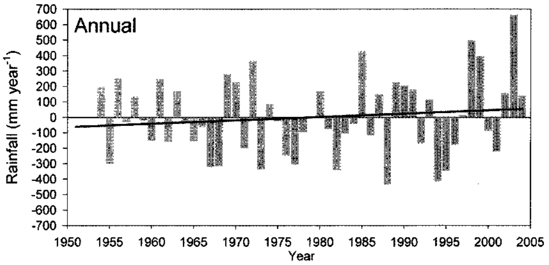

Fig. 4. Time series of the annual rainfall anomalies (in mm; bar) over Korea. Regression trend is also represented (solid line).

The time series of the 20 day running mean daily rainfall reveals a bimodal pattern. Based on the annual mean daily rainfall, we can define 2 rainy seasons. These 2 seasons were identified with respect to the 4.3 mm day^{-1} threshold: the first (P1) occurs from June 8 to August 5 and the second (P2) occurs from August 6 to September 26.

The rainfall in P1 is mainly attributed to the stationary fronts (*Changma* in Korea, *Meiyu* in China, and *Baiu* in Japan), which are the regional components of the East Asian summer monsoon whose front is fully developed. They then move northward and southward over the whole country in July. On the other hand, the large amounts of rainfall in P2 are caused by typhoons (including their direct and indirect impacts) on the nation-wide scale (KMA, 1995a; Wang and LinHo, 2002), cyclones and instability in the boundary of the North Pacific High on the regional scale (KMA, 1995a).

Trends

We first examine the long-term variability of the annual and seasonal rainfall anomalies over Korea in order to investigate their characteristics. Figure 4 shows the time series of the annual rainfall anomalies. The estimated linear regression trend for the annual rainfall indicates a gradual increase with time. Seasonal mean rainfall anomalies in spring (March-April-May, MAM), summer (JJA), autumn (September-October-November, SON), and winter (December-January-February, DJF) are calculated in the same way. The rainfall anomalies during MAM, SON, and DJF exhibit no dominant trend (figure not shown). However, summer rainfall anomalies exhibit a strong long-term increasing trend.

Figure 5 compares the monthly and JJA seasonal rainfall anomaly trends and the 7 year running mean of the Palmer Drought Severity Index (PDSI) over Korea. Pink bars represent rainfall anomaly values less than −1 S.D. (dry years) and blue bars represent those greater than +1 S.D. (wet years). The PDSI is introduced in order to investigate the intensity of the droughts and floods. For its computation, we used the algorithm from KMA (2002), which was derived from Palmer (1965) and Alley (1984). The PDSI generally ranges from −7.0 (dry) to +7.0 (wet) (Dai et al., 1998).

The long-term trends of monthly rainfall anomaly in June (Fig. 5a) show a relatively small increase. It is no dominant trend both in July (Fig. 5b) and both in September (Fig. 5d). The monthly rainfall anomalies in August shown in Fig. 5c are of considerable interest. The largest anomalies have occurred in recent years, while the lowest values are observed in the mid-1970s. At the same time, rainfall trends show rapid increases since the late 1970s, and the past 10 years hold the record for being the wettest years. The distributions of the JJA mean (Fig. 5e) are consistent with those of August. Figure 5c also shows the time series of the 7 year running average PDSI. Extreme

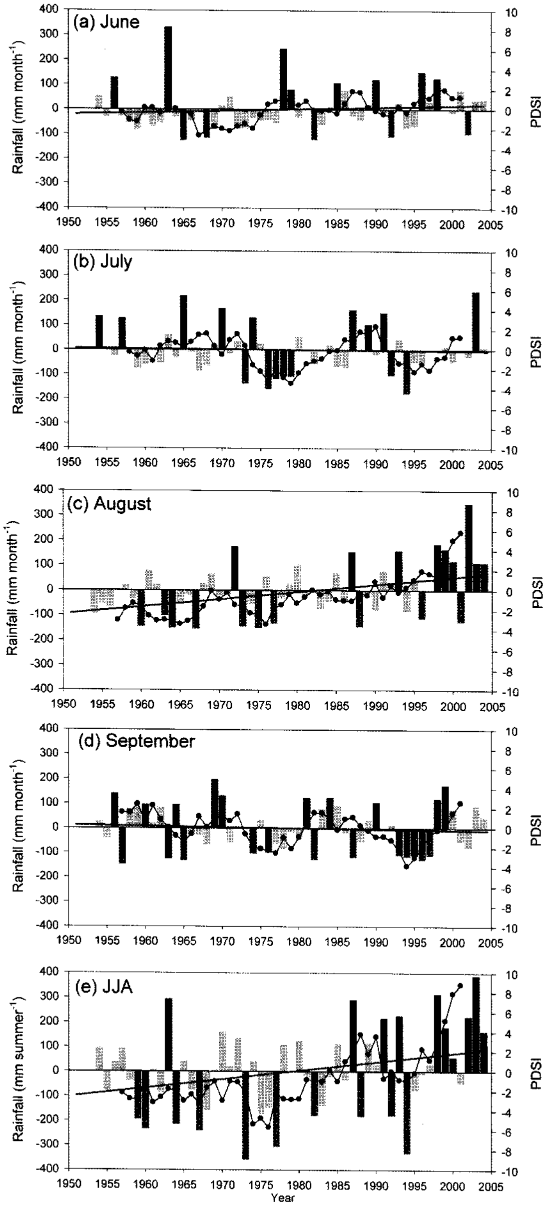

Fig. 5. Same as in Fig. 4 except for (a) June, (b) July, (c) August, (d) September, and (e) JJA. 7 year running mean PDSI data are indicated by a solid line with circles. The light color bars represent rainfall anomaly values less than −1 S.D. (dry years) and dark color bars represent those greater than +1 S.D. (wet years). Regression trend is also represented by straight solid line.

drought occurred in the mid-1970s, except in 1972. Drought was also a frequent occurrence from 1954 to the late 1970s and during the first half of the 1990s. No extreme droughts occurred after the latter half of the 1990s. Most of the increase in the amount of rainfall occurred after 1979. With the exception of the mid-1990s, the wet spells lasted until 2004, and the magnitude of the PDSI during the last five years reached ~6, which corresponds to extremely wet conditions. The distinct occurrence of drought conditions in Korea before the 1980s coincides with the abrupt increase in the number of droughts in eastern Asia around 1979 (Dai et al., 1998). On the whole, the 7 year running mean PDSI exhibits a gradual increase with time due to more frequent occurrences of heavy rainfall in recent years.

In order to examine the cause of the recent wet condition in Korea, we analyze the number of extreme rainfall days. Figure 6 shows the total number of days that experienced rainfall exceeding the fixed threshold value of 80 mm day^{-1} in June, July, August, September, and summer. An examination of the number of extreme rainfall days in August suggests an increasing trend (Fig. 6c).

The increasing trend observed in the month of August can mainly be attributed to the most extreme rainfall events on historical record in the summers of recent years (1987, 1993, 1998, 1999, 2000, 2002, 2003, and 2004; hereafter, the 8 wet years). In the 8 wet years, the *Changma* front did not exhibit normal behavior nor did it develop fully. Further, a delay in its onset and termination was observed along with relatively less rainfall (KMA, 1998, 1999, 2000, 2002b, 2003, 2004). However, heavy rainfalls after retreat of the *Changma* ware reported by most stations across Korea in those wet years. Recent characteristics of the summer rainy season rainfall - show a significant deviation from the climatological features, which is most prominent in August. We therefore focus on extreme rainfall events in August during the 8 wet years.

On the basis of the abovementioned results obtained from the KMA data, we analyze the large-scale circulations during the northern summer and how they are related to the regional changes in rainfall. The Kendall analysis is used to examine the significance for the long-term trend of rainfalls. We adopted the same

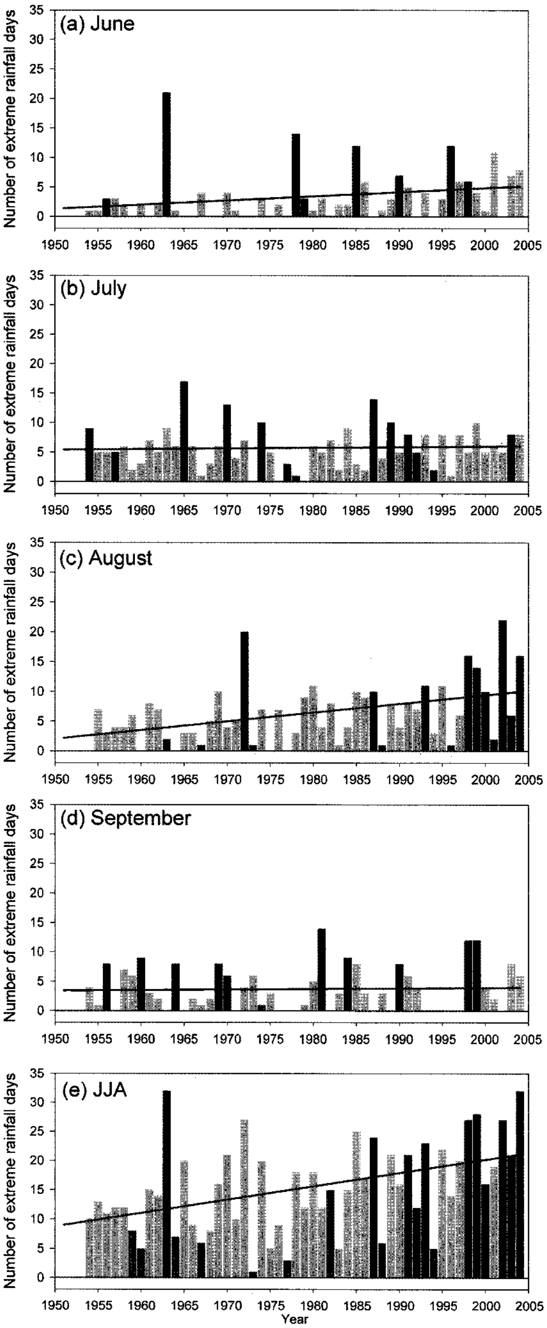

Fig. 6. Same as in Fig. 5 except for the number of accumulated extreme rainfall days (≥80 mm day^{-1}; data obtained from 11 stations).

significant method conducted by Webster et al. (2005). The Kendall test results show that the trend of August (Fig. 5c), summer rainfall (Fig. 5e), and P2 (Fig. 7b) are significantly different at the 95% confidence level.

Large Scale Circulation Associated with Recent Increasing Heavy Rainfall Trend

In this section, in order to find the possible causes of increased rainfall and extreme rainfall events in August of the recent years, the composite maps of large-scale circulation patterns associated with the 8 recent extreme rainfall years for August is presented. We also highlight the accompanying SST fields, the selected components of hydrological circulation, and the influences of typhoons during extreme rainfall periods. We also performed a Student's *t*-test to obtain the significance for composite differences.

Role of the western Pacific SST

In Fig. 7a, the warm SST anomalies are located in the region of the ocean near Indochina Peninsula, South China Sea, and the tropical western Pacific. The other warm SST anomalies are located at 50°N-60°N. However, negative SST anomalies are found in certain parts of the North Pacific. Figure 8b shows that the vertical motion in terms of OLR (shading), velocity potential at 200 hPa (contour), and divergent wind (vector) anomalies are accompanied by SST anomaly distributions. The enhanced convection areas are closely related to the warm SST anomalies from the Indochina Peninsula to the Philippine Sea. The other active zonal convections are located in the midlatitudes. The anomalously inactive convection zone in the western Pacific exhibits a horseshoe pattern.

The large-scale features of the anomalous convective activity are consistent with the 200 hPa velocity potential (Fig. 8b). The latter is characterized by a dipole pattern with a divergence center in the eastern Philippine Sea and a convergence center above Sumatra. These characteristics are coincident with enhanced convection in those regions (Fig. 8b). The strongest anomalous divergent winds concentrate over the eastern Philippine Sea, where warm SST anomalies coincide well with anomalous upward motions.

In order to reveal the pattern of the SSTs around the eastern Philippine Sea, we present a time series of

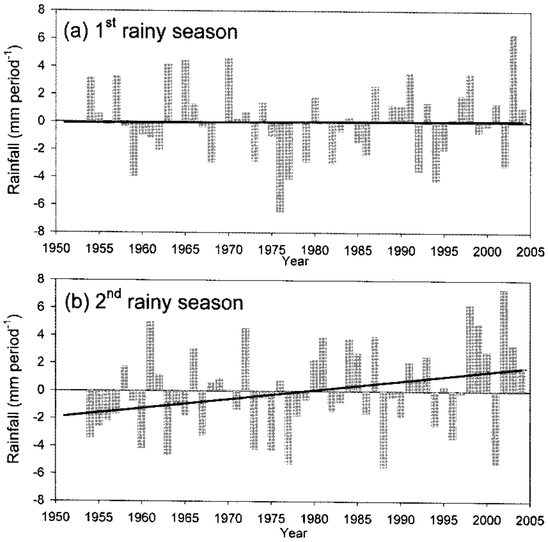

Fig. 7. Same as in Fig. 5 except for (a) P1 and (b) P2.

JJA SSTs in NIÑO WEST obtained from the JMA (Fig. 8c). Also, the Kendall significance test of the change in NINO WEST SST shown in Fig. 8c is statistically significant at the 95% level.

The SST distributions over the tropical eastern Philippine Sea in recent summers were very warm, suggesting that the heat in this region probably plays a major role in generating the anomalous convection and vertical motion. Other possibility of recent warm SSTs near the Philippine Sea has influenced the tropical cyclone in the Western Pacific Ocean. A relationship between tropical cyclone activity and SST has addressed by many researchers. Webster et al. (2005) and Emanuel (2005) reported the significant increasing trend both in occurrence and in intensity in the Western Pacific Ocean. The anomalously warm SST that region may contribute this increase. Trenberth (2005) also stressed the warm SST contributed to the increasing hurricane frequency and intensity in terms of an acceleration of the hydrological cycle arising from the relation between saturated vapor pressure and temperature. These studies support that warm SSTs in recent summers near the Philippine Sea may play a role for formation of typhoons. Figure 8c also shows the time series of SSTs for the equatorial central Pacific (NIÑO 4) and

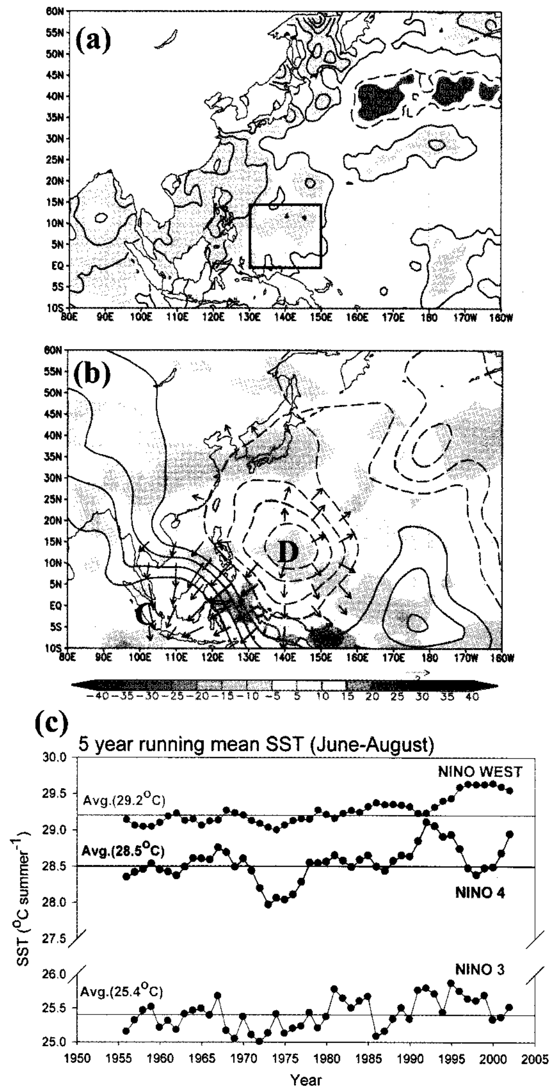

Fig. 8. (a) Composite maps of August SST anomalies of 8 wet years. Dark and light shading represent negative and positive values at a significance level of 95%, respectively. Contour interval is 0.3°C. Zero contours are not shown. Dotted lines represent the negative values. The areas of NIÑO WEST are indicated by a red box. (b) Same as in Fig. 8(a) except for OLR (shading, Wm^{-2}), 200 hPa velocity potential (contour, 10^{-6} m^{-2} s^{-1}), and divergent wind (vector). The divergent winds are calculated from the velocity potential. Only the vectors with significance are shown. The wind scale is given at the lower right corner. (c) Time series of the NIÑO WEST (red line), NINO 4 (black line), and NINO 3 (blue line) SSTs for JJA. Red line indicates the 5 year running mean of SSTs in NINO WEST; black line represents the 5 year running mean of SSTs in NINO 4; blue straight line means the 5 year running mean of SSTs in NINO 3.

eastern Pacific (NIÑO 3). The threshold SST for tropical cyclone formation under the current climate is warmer than 26°C (Gray, 1968). Therefore, SST in NIÑO 3 whose average is 25.4°C can not give an impact of generation of tropical cyclone. The recent trend of SSTs in NIÑO 4 drops under their average. August SSTs in the above three regions exhibit the similar pattern shown in Fig. 8c (not shown).

The warm surface temperature anomalies (Fig. 9a) are located from the Indochina Peninsula to the Philippine Sea. These anomaly patterns are closely similar to those of SST anomalies shown in Fig. 8a. However, in the Eurasian continent, the temperature structures are characterized by positive values of +2°C over central Eurasia (45°-60°N, 80°-120°E) and negative values of up to −2°C over northwestern China-Korea-Japan.

We examined the monthly (Fig. 9b) Sea Level Pressure (SLP) composite over the past 51 years. The positive SLP anomalies (Fig. 9b) are most pronounced in the Eurasian continent. The center of the positive SLP is located around Mongolia, reaching up to 4 hPa. The negative SLP anomaly patterns are dominated on 30 August over the East Asian sectors. Recent study by Ha et al. (2005) pointed that the positive SLP anomaly were observed over northeastern China during strong (wet) Changma years in Korea. Our monthly and pentad SLP distributions are consistent with their results.

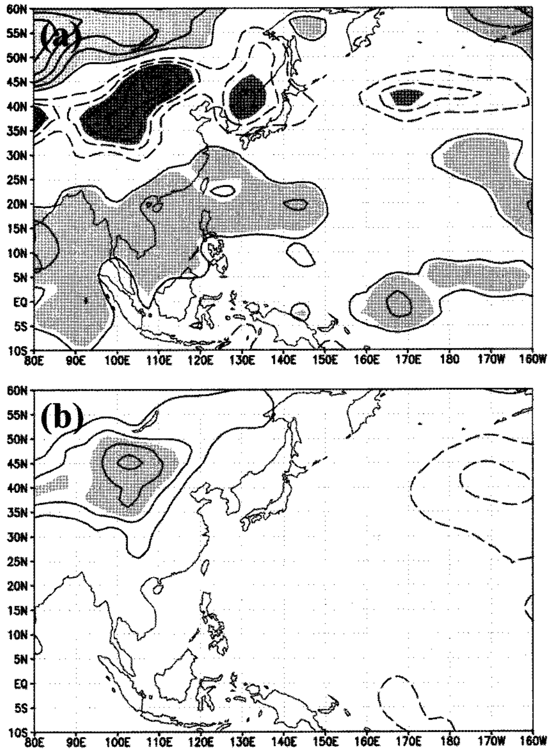

Fig. 9. Same as in Fig. 8a except for (a) surface temperature and (b) SLP. Contour intervals are 0.3°C in (a) and 1 hPa in (b).

Influence of Typhoon on recent extreme rainfall events

Figure 10a shows the vertically integrated moisture flux and precipitable water during the 8 wet years. Further, it shows the primary moisture source for August over the eastern Philippine Sea (lighter shading). A reduction in moisture is observed over northern China. The positive SLP over East Asia during this period introduces a stronger northerly wind, which transports cool and dry surface air from the high SLP region toward the tropical western Pacific. It superimposes the warm and moist surfaces provided by the prevailing southerly wind at low levels, and it also possibly produces enhanced convective activity and consequently heavy rainfall over the region. The strong moisture convergence in the eastern Philippine Sea is partially responsible for the frequent formation of tropical cyclones at around 20°N (Fig. 10c). This is consistent with the anomalous cyclonic circulation and enhanced moisture convergence shown in Fig. 10a (lighter shading).

The spatial patterns of composite surface temperature (Fig. 9a) and SLP (Fig. 9b) anomalies are compared to the regression map of surface temperature (shading) and SLP (contour) for the monthly NIÑO WEST SST anomalies (Fig. 10b). Figures 9a, 9b, and 10b share a common feature of cool and strong positive SLP over the Eurasian continent and warm and weak negative SLP near the Philippine Sea.

Monthly UEA rainfall data are adopted to obtain the spatial distribution of recent extreme floods over East Asia associated with the 8 wet years in Korea. In

Fig. 10c (rainfall), wet conditions (positive shading) associated with enhanced moisture supply are found over the Philippines and over large regions in the midlatitudes extending from the southern parts of China to Korea and the southern and northern parts of Japan, while dry conditions (negative shading) are found over the northern parts of China and eastern Siberia. These rainfall distributions are consistent with moisture patterns shown in Fig. 10a. The rainfall patterns from the UEA rainfall data are relatively consistent with the KMA rainfall patterns as well. Particularly, the substantially enhanced rainfall over the southern parts of central China and Korea are well represented.

The rainfall pattern in Fig. 10c suggests that the most significant increase in moisture supply (lighter shading in Fig. 10a) over the southern parts of China and Korea in August is associated with positive SLP changes over Eurasia and negative SLP changes over the subtropical western Pacific off the east coast of south China (Fig. 9b). The reduction in rainfall over the northern parts of China and Manchuria at around 50°N-60°N in August is consistent with the decreased moisture shown in Fig. 10a (darker shading). The typhoons that influence the extreme rainfall events over Korea in the 8 wet years are listed in Table 1, and their trajectories are shown in Fig. 10c. The first point of each trajectory is defined as the point that a tropical depression strengthens to a tropical storm. While the last point of track is defined as the point that a tropical storm weakens to a cyclone.

There exists evidence for a correlation between extreme rainfall in the 8 wet years (except in 1998) and typhoons. We note that more than half the extreme rainfall events in August appear to be strongly affected by major typhoons, especially in 1987, 1999, 2000, and 2002. A series of typhoons generated in the western Pacific, centered at 20°N, greatly contributed to the outbreak of heavy rainfall in 1999. In August 2000, two typhoons occurred consecutively and contributed to the excessive rainfall. The BILIS hit first the central part of China and provided huge amount of water vapor to the Korean Peninsula. The intense period of rainfall induced

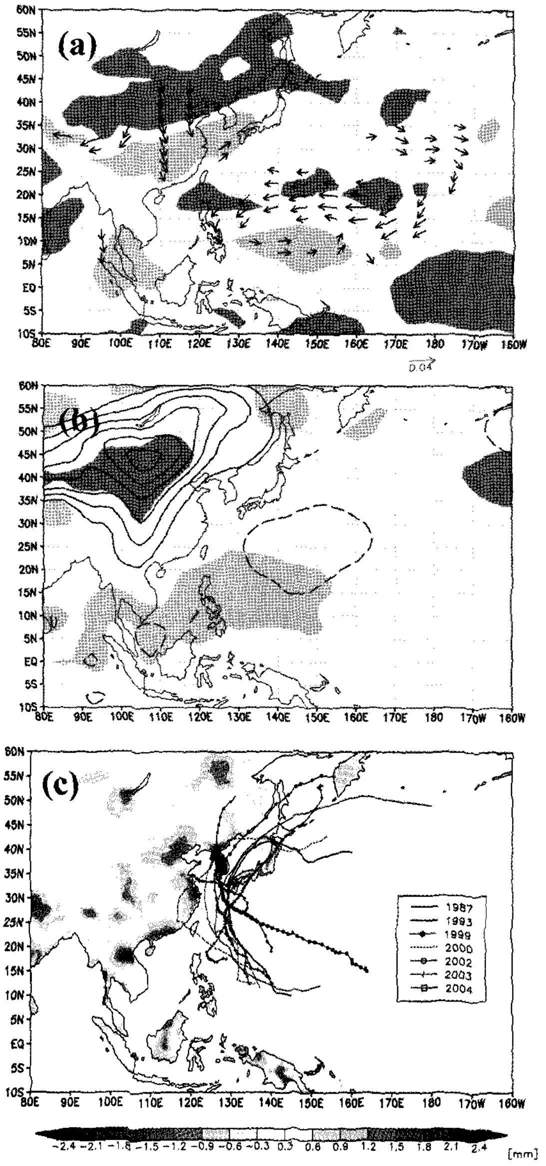

Fig. 10. (a) Composite maps of August on 8 wet years vertically integrated moisture flux (vectors; in kg^{-1} m s^{-1}, arbitrary size) and specific humidity (shading). Light and dark shading denote positive and negative vertically integrated specific humidities, respectively. Only the vectors with significance are shown. (b) Same as in Fig. 9 (a) except for surface temperature (shading) and SLP (contour) anomalies that regress with the monthly NIÑO WEST SST anomalies. The regression results of only the surface temperature and SLP with significance are displayed. Light and dark shading denote positive and negative regressed surface temperatures, respectively. Solid and dotted lines represent positive and negative regressed SLPs, respectively. Contour interval is 0.1. (c) Same as in Fig. 9 (a) except for UEA rainfall (shading) anomalies and typhoon tracks that impacted during the extreme rainfall period over Korea in August during the 8 recent wet years (listed in Table 1). The UAE rainfall anomalies are shown as contours in mm month^{-1}.

Table 1. Major typhoons that influenced the extreme rainfall events in the 8 recent wet years. The mark (*) indicates indirect impact of typhoon on the Korean Peninsula

Year	Date of impact	Name
1987	Aug. 30-31	DINAH
1993	Aug. 8-11	ROBIN
1998	No Typhoon	
1999	Aug. 2-4	OLGA
	Aug. 4-5	PAUL
2000	Aug. 24-28	BILIS*
	Aug. 31-Sep. 1	PRAPIROON
2002	Aug. 30-Sep. 1	RUSA
2003	Aug. 6-8	ETAU*
2004	Aug. 17-19	MEGI

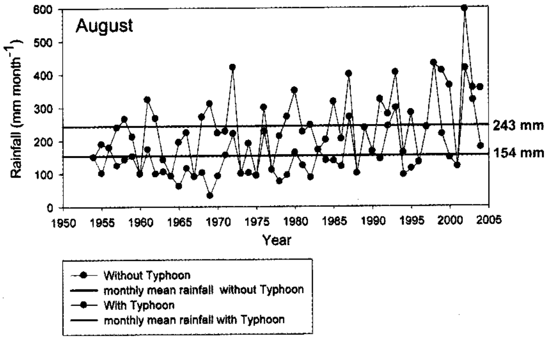

Fig. 11. Time series of the rainfall amounts for August. Red line indicates the total rainfall values; removed rainfall amounts during the typhoon impact period over the Korean Peninsula are denoted by blue line.

by a typhoon named RUSA was reported by most stations in the eastern and southern parts of Korea in August 2002. The typhoons mainly passed the western coast of Korea (Fig. 10c), resulting in the frequent occurrence of extreme rainfall events in this region (figure not shown). Although the Typhoon ETAU in August 2003 that passed Japan Islands far from the Korean Peninsula, it gave indirect effect on Korean area. The enhanced moisture supply by ETAU toward the Korean peninsula was closely tied to the intensification of the trough which was located over the northern part of Korea during 6-8 August 2003. The combined effect of the Typhoon ETAU and the trough was found to be responsible for heavy rainfalls in August 2003 (KMA, 2003).

Furthermore, anomalous cyclonic circulations over the eastern Philippine Sea also promote the generation of tropical cyclones. Strong moisture convergence in the western North Pacific is partially responsible for the frequent formation of typhoons at around 10°N-20°N. The position of pressure systems - positive SLP over Eurasia and negative SLP over the subtropical Pacific - in turn provide a pathway for typhoons. The moisture is then effectively transported further north toward Korea and east toward the southern parts of China during the extreme rainfall period. The rainfall patterns shown in Fig. 10c show that wet conditions exist across much of the interior circles of the typhoon tracks. However, the condition of the dry areas of the northern parts of China and Manchuria - located on the exterior circles of the typhoon tracks - is worsening.

In order to confirm the contribution of typhoons to the August rainfall, we remove the rainfall amounts during the impact period of typhoons that occurred over the Korean Peninsula in August (Fig. 11) in all years. A comparison between the rainfall events including (blue line in Fig. 11) and excluding (red line in Fig. 11) the typhoon effect reveals an apparent difference. While the monthly mean rainfall with typhoon effect is 243 mm, the August mean rainfall without rainfalls during typhoon impact period over the Korean area is 154 mm. Therefore, it can be thought that the typhoon contribute about 37% to the total rainfalls on August.

Summary and Concluding Remarks

In this study, we investigated long-term changes in rainfall over Korea, focusing on rainfall events that occurred in summer during the period from 1954 to 2004. We particularly focused on the recent unusual wet conditions over Korea. This study also documents and analyzes the anomalous circulation during summer associated with floods in Korea.

The long-term annual rainfall anomalies exhibit an increasing trend. This can mainly be attributed to the increasing occurrence of extreme rainfall events in summer - especially August - during recent years. Notable increasing trends of both monthly rainfall and frequency of extreme events (80 mm day^{-1}) are also observed in August. This trend is mainly observed in the 8 wet years (1987, 1993, 1998, 1999, 2000, 2002, 2003, and 2004). Based on the amount of rainfall and the number of extreme rainfall days, this increasing trend appears to be prevailing since the mid-1980s.

Composite maps of large-scale circulation patterns show that the warm SST anomalies over the eastern Philippine Sea, which are associated with enhanced convection and vertical motion, are responsible for the occurrence of the extreme rainfall events over Korea during August. Low temperature and high SLP are substantially intensified over central Eurasia during the eight wet years, while cyclonic circulation is found over the eastern Philippine Sea.

The enhanced moisture supply is closely related to the intensification of moisture over the warm eastern Philippine Sea prior to the outbreak of heavy rainfall events in Korea. The rainfall patterns suggest that the most significant increase in moisture supply over the southern parts of China and Korea in August is associated with positive SLP changes over Eurasia and negative SLP changes over the subtropical western Pacific off the east coast of south China. The reduction in rainfall over the northern parts of China and Manchuria at around 50°N-60°N in August is consistent with the decreased moisture.

The frequent generation of strong typhoons over the warm eastern Philippine Sea and their tracks appear to influence the extreme rainfall events in Korea during the month of August. Even though the strongest typhoon, it is difficult to influence to the Korean area if it can not reach closely this area. We have also included the annual frequency of typhoons (Fig. 12a) and landfall (Fig. 12b) in the Korean Peninsula. Annual mean of total frequency of typhoons which are occurred in the Western Pacific is 26.9 and while annual landfall in the Korean area is 3.2, respectively. According to this figure, there are no dominant changes both in frequency of annual typhoon and in landfall during wet years. Recently, Webster et al. (2005) examined the number of tropical cyclones and cyclone days as well as tropical cyclone intensity from 1970 to 2004, in the various ocean basins. They found that a large increase was seen both in the number and in intensity. The largest increase occurred in the Western Pacific Ocean (120°E-180, 5-20°N, their definition) under an increasing condition of SST.

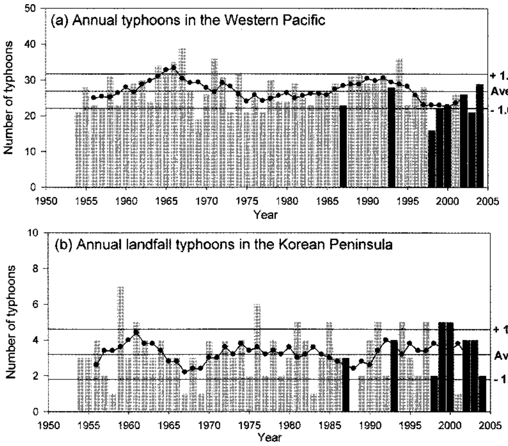

Fig. 12. Time series of the annual (a) frequency of typhoon and (b) landfall over the Korean Peninsula. Regression trend is also represented (solid line). The lower line represents typhoon occurrence values less than −1 S.D. and upper line indicates that greater than +1 S.D.

A series of typhoons generated in the western Pacific, centered at 20°N, greatly contribute to the outbreak of heavy rainfall events during the wet years (except in 1998). The typhoons mainly passed the western coast of Korea, resulting in the frequent occurrence of extreme rainfall events in this region. Furthermore, anomalous cyclonic circulations over the eastern Philippine Sea also promote the generation of tropical cyclones. Strong moisture convergence in the western North Pacific is partially responsible for the frequent formation of typhoons at around 10°N-20°N. The position of pressure systems - positive SLP over Eurasia and negative SLP over the subtropical Pacific - in turn provide a pathway for typhoons. The moisture is then effectively transported further north toward Korea and east toward the southern parts of China during the extreme rainfall period. The rainfall patterns show that wet conditions exist across much of the interior circles of the typhoon tracks. However, the condition of the dry areas of northern parts of China and Manchuria - located on the exterior circles of the typhoon tracks - is worsening.

The recent increasing heavy rainfalls can be attributed to the combined effect of (1) unusually strong moisture primarily from the warm SST in the eastern Philippine Sea, (2) frequent formation of strong typhoons and their track, (3) positive SLP over northern China that serves as a barrier to the typhoon tracks.

However, a number of issues remain to be clarified, for example, the causes of negative surface temperature (Fig. 9a) and positive SLP (Fig. 9b) in the lower troposphere over the Eurasian continent are unclear. Several studies (Wang and Li, 1990; Xue, 1996) have pointed out the pronounced cooling trend of surface temperature in Mongolia. According to their analyses, this trend can be attributed to deforestation and the expansion of arid areas, which may be associated with climate change. Furthermore, deforestation increases the reflection of shortwave radiation and leads to a decrease in surface temperature over arid regions as well as an increase in surface albedo. Deforestation may also cause an increase in the frequency of dust events, leading to an increase in the Earth's albedo, which is caused an increase in backscattered shortwave radiation. Sinking motions are thus expected to develop over Eurasia to compensate for the surface cooling.

In addition, the shift in the SST change over the eastern Philippine Sea, approximately represented by the NIÑO WEST area, toward warmer phases after about 1993 is very unusual considering the trend observed during the last 50 years (Figs. 8a and c). It is unclear whether this shift is related to changes in the evolution of ENSO or independent changes across the Pacific basin.

Further, in this study, we have not considered the orography of Korea. The orography also contributes to the regional characteristics of mountain rainfall on a short time-scale. The Korean Peninsula has complex mountainous terrains and is surrounded by seas. In order to conduct climate research on a regional scale in Korea, thorough knowledge on the orography is necessary.

Acknowledgments

This work was funded by the Korea Meteorological Administration Research and Development Program under Grant CATER 2006-4205.

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Manuscript received: 14 May 2007
Revised manuscript received: 7 July 2007
Manuscript accepted: 13 August 2007