Precipitation trends over the Korean peninsula: typhoon-induced changes and a typology for characterizing climate-related risk

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Abstract
Typhoons originating in the west Pacific are major contributors to climate-related risk over the Korean peninsula. The current perspective regarding improved characterization of climatic risk and the projected increases in the intensity, frequency, duration, and power dissipation of typhoons during the 21st century in the western North Pacific region motivated a reappraisal of historical trends in precipitation. In this study, trends in the magnitude and frequency of seasonal precipitation in the five major river basins in Korea are analyzed on the basis of a separation analysis, with recognition of moisture sources (typhoon and non-typhoon). Over the 1966–2007 period, typhoons accounted for 21–26% of seasonal precipitation, with the largest values in the Nakdong River Basin. Typhoon-related precipitation events have increased significantly over portions of Han, Nakdong, and Geum River Basins. Alongside broad patterns toward increases in the magnitude and frequency of precipitation, distinct patterns of trends in the upper and lower quartiles (corresponding to changes in extreme events) are evident. A trend typology—spatially resolved characterization of the combination of shifts in the upper and lower tails of the precipitation distribution—shows that a number of sub-basins have undergone significant changes in one or both of the tails of the precipitation distribution. This broader characterization of trends illuminates the relative role of causal climatic factors and an identification of ‘hot spots’ likely to experience high exposure to typhoon-related climatic extremes in the future.

Keywords: summer precipitation, Korean peninsula, trend typology, quantile regression, climate risk

1. Introduction
Recent studies have reported trends toward increases in the frequency of heavy precipitation over the Korean peninsula during the summer season, as well as significant increases in the seasonal precipitation totals (Jung et al 2002, Chang and Kwon 2007, Bae et al 2008, Jung et al 2011). Extreme precipitation events are critically important not only for their episodic impacts, such as floods, but also for their significant contribution to seasonal freshwater supplies that maintain the integrity of human and natural systems. In Korea’s five major
river basins, precipitation during the summer season (June–September) contributes nearly 70% of regional freshwater supplies. Over the past four decades, the human population in Korea has increased by 67% to an estimated 48.5 million (TWB 2011). As a result, expanding cities and urbanized areas, which depend on complex life support systems, are increasingly vulnerable to these climatic extremes (Chang et al 2009). A majority of heavy precipitation events are concentrated in the summer season, in part due to the coincident typhoon season in the western North Pacific (for example, Kim et al 2010). During the 1995–2004 period, typhoons caused 69% of the total property damage over the Korean peninsula (NAK 2011). In 2002, Typhoon Rusa caused US$5 billion in property damages and a loss of two hundred and sixty six human lives (Lee 2007). Furthermore, current multi-model projections for the late twenty-first century indicate increases (as a per cent change from a late twentieth century baseline) in key attributes of typhoons in the western North Pacific region (Emanuel et al 2008, Knuston et al 2010): intensity (+10.8%), frequency (+5.5%), duration (+2.7%) and power dissipation (+19.1%).

The need for improved characterization of climatic risk and the projected increases in the typhoon events motivates a reappraisal of historical trends in precipitation over the Korean peninsula. Climate risk assessment hinges upon probabilistic estimates of the likelihood of precipitation deficits and excesses, and trends therein. To this end, understanding the spatial patterns of typhoon and non-typhoon precipitation, as well as an assessment of the trends across key precipitation thresholds is necessary to advance the understanding of causal climatic factors and an identification of ‘hot spots’ likely to experience high exposure to climatic extremes in the future.

Diagnosis, interpretation, and separability (contingent upon moisture sources) of episodic-to-seasonal and long-term changes in precipitation are critical steps in understanding the nature and causes of historical precipitation trends. In the following sections, we consider three questions. (1) What is the relative contribution of typhoon and non-typhoon moisture sources to the observed trends in the magnitude and frequency of warm season precipitation? (2) What are the spatial characteristics of trends parsed by principal moisture sources? (3) What are the temporal shifts in the empirical probability distribution of seasonal precipitation, and the nature of trend typology in seasonal precipitation extremes?

2. Data and methods

Analysis of the warm season precipitation (June–September) characteristics pursued in this study is based on a spatially averaged daily precipitation dataset produced by the Korean water resources management information system (WAMIS 2011; http://www.wamis.go.kr). Sub-basins are used as the areal units for daily precipitation estimates for the 1966–2007 period. As a result, spatial coverage includes the five major river basins and coastal watersheds over the Korean peninsula. Daily precipitation for sub-basins is estimated based on a Thiessen polygon approach. An advantage of assessing precipitation trends on subwatershed scale is their direct relevance to hydrologic hazards, such as floods and droughts. However, spatial averaging often tends to induce estimation errors, especially in cases with sparse network of stations. The network of rainfall stations (Han River Basin: 43, Nakdong River Basin: 45, Geum River Basin: 28, Sunmijin River Basin: 17, and Yeongsan River Basin: 7) applied to this study is generally well distributed across South Korea.

In the western North Pacific region, episodic typhoons contribute significantly to the spatio-temporal characteristics of seasonal rainfall. In this study, prior to the analysis of trends, a particular focus is that of ascertaining the relative contribution of typhoon-induced precipitation to the warm season totals. A methodology to identify time windows wherein precipitation stems predominantly from typhoons or its remnants was developed recently by the authors (Kim et al 2010). Historical typhoon records for the western North Pacific basin are obtained from the Typhoon Research Center (TRC 2011) and the Japan Meteorological Agency (JMA 2011). A total of 208 tropical cyclones have been recorded in the domain (120°E–138°E, 32°N–40°N) used by the Korea Meteorological Administration (KMA) to identify impacts of typhoons over the Korean peninsula (KMA 1996, Kim et al 2010). Based on the historical data (1966–2007), 98% of the typhoon events show up to four-day residence time within the spatial domain (120°E–138°E, 32°N–40°N).

As noted in Kim et al (2010), this time window provides a conservative estimate of the precipitation stemming from episodic typhoon events. This event-based approach indicates that approximately 23.7% of the seasonal precipitation is linked to episodic typhoon events throughout Korea. In the supplementary section (available at stacks.iop.org/ERL/6/034033/mmedia), we provide a summary of precipitation variability coincident with typhoon events using boxplots. Kim et al (2010) also provide a detailed explanation of this approach.

The analysis presented in this letter focuses on the relative effects of trends in seasonal precipitation across key quantiles (median, upper quartile, and lower quartile). This analysis is especially relevant for climate risk assessment efforts because it not only quantifies changes in the conditional median precipitation, but also the upper and lower tails (signifying extreme events). Quantile regression (QR) methodology (Koenker 2005) was used to estimate trends at subwatershed scale. Barbosa (2008) has applied the QR methodology to assess trends in sea level data. Koenker (2005) provides a detailed overview of the QR methodology and advantages over other approaches, such as linear regression. Results from quantile regression provide a relatively complete picture of the distributional changes, including changing tail probabilities and asymmetry in trends for various quantiles. A bootstrap approach was used to compute confidence intervals for QR estimates. Trends are computed for total precipitation and its typhoon-induced counterparts. Results from this approach are used to develop a trend typology for each of the 113 sub-basins in Korea (see section 3.2.3 for details).

We also conducted long-term trend analysis of the number of rain days with heavy precipitation (>30 and >50 mm/day). A Poisson regression is a widely used methodology for
count data. We used a generalized linear modeling (GLM; McCullagh and Nelder 1989) approach for the Poisson regression. The GLM analyses also considered number of rain days (above 30 and 50 mm/day) for typhoon-induced precipitation and non-typhoon precipitation.

3. Analysis and results

3.1. Characteristic of typhoon and non-typhoon precipitation

Over the Korean peninsula, nearly two-thirds of the annual precipitation and freshwater supplies occur during the June–September season. The spatial pattern of seasonal precipitation over this region (figure 1(a)) indicates two regions of high precipitation during the June–September season—Sumjin River Basin (934 mm) and the Han River Basin (873 mm). Seasonal precipitation in the other three major river basins is somewhat lower (see figure 1 caption). Interannual variability in precipitation is highest in the Yeongsan River Basin, where the coefficient of variation (CV; the ratio of standard deviation to mean) is nearly 0.3, while CV in other river basins ranges between 0.22 and 0.27 for the Geum and Nakdong River Basins respectively. Of particular interest from the standpoint on understanding the relative import of typhoon-induced precipitation (and the potential for flood hazards) is the spatial pattern of typhoon-induced precipitation. The distribution of the fraction of seasonal precipitation induced by typhoons is as follows (figure 1(b)): Nakdong River (26.1%), Sumjin River (24.9%) and Yeongsan River (23.9%), Han River (21.8%), and Geum River (21.4%). High year-to-year variability in typhoon-induced precipitation is evident from the CV estimates: Yeongsan River (0.69), Sumjin River (0.66), Nakdong River (0.59), Han River (0.55), and Geum River (0.51). The spatial distribution of typhoon-induced precipitation is influenced by topography, resulting in a smaller contribution of typhoon precipitation to the seasonal total of the interior and western river basins (especially the Geum River Basin, 21.4%). The empirical probability distributions derived from typhoon precipitation show asymmetry in the distribution shape; on average, the distance between upper quartile and the median is 54% higher than that for the median and lower quartile. Non-typhoon precipitation shows an asymmetry
toward upper tail only for the Geum River Basin; all other basins show asymmetry with an opposite sign. This asymmetry in the variability about the median further reinforces the need for a systematic and separate analysis in upper and lower tails of the precipitation distribution.

The important role of individual typhoons events and their seasonal contributions to freshwater supplies are evident from analyses presented in figures 1(b) and (c). Furthermore, high interannual variability (CV values noted in table 1) indicates that an important first step in understanding precipitation variability and trends is a characterization of the empirical probability distribution wherein: (a) upper and lower tail probabilities (signifying extreme events) can be quantified, and (b) a separation of precipitation by moisture sources (typhoon, non-typhoon) facilitates an assessment of the individual and joint contributions from typhoon and non-typhoon precipitation to extreme precipitation trends. Implicit in this line of inquiry is the recognition of the asymmetric changes in precipitation probability distribution over time, most often manifest as trends in select quantiles, while others remain relatively unchanged. Figure 1(c) provides a summary of the empirical probability distribution for the five major river basins. It is important to note that the typhoon contributes significantly to the seasonal precipitation over the Korean peninsula. Thus, in section 3.2, we discuss the results from the long-term trend analysis in the magnitude and frequency of typhoon and non-typhoon precipitation events.

3.2. Precipitation trend and its typological characteristics

3.2.1. Frequency of heavy precipitation. Chang and Kwon (2007) reported a widespread increase in the number of days with daily precipitation (>30 and >50 mm) over the past three decades. We revisit this issue to clarify the trends seen in typhoon and non-typhoon precipitation. As a starting point, figure 2 shows the long-term trends in the number of days that daily precipitation exceeds 30 and 50 mm. This analysis is similar to the one presented in Chang and Kwon (2007). However, Chang and Kwon (2007) employed the Mann–Kendall method for trend assessment, while we use a Poisson regression approach. Our results reaffirm the trends in the frequency of daily precipitation over a large fraction of the Korean peninsula except for the northern part of the Han River Basin.

The frequency of heavy precipitation coincident with typhoon events shows an increase over the watersheds in the eastern coastal region, as well as southern portions of the Han River Basin and several sub-basins of the Yeongsan and Geum Rivers. Non-typhoon precipitation shows widespread trends, consistent with the trends in seasonal precipitation frequency (figure 2). A particular utility of the analysis approach presented here is that the relative role of typhoon and non-typhoon precipitation can be analyzed to understand the spatial patterns and the causal factors contributing to the observed trends in the frequency of heavy precipitation. The frequency of rain days with heavy daily precipitation (>30 and >50 mm) is highly correlated with seasonal precipitation total (median value over the 112 sub-basins is 0.88 (>30 mm/day) and 0.81 (>50 mm/day), figure is not shown). In the supplementary section (available at stacks.iop.org/ERL/6/034033/mmedia), spatial variability of correlation between the typhoon-related rainy days (>30 and >50 mm) and seasonal precipitation total (supplementary figure 2 available at stacks.iop.org/ERL/6/034033/mmedia) are presented. The eastern and southern portions of the Korean peninsula show relatively high correlation coefficients. Based on the results presented in figure 2, trends in non-typhoon precipitation appear to mirror those seen in the daily precipitation frequency for the entire regions.

3.2.2. Seasonal precipitation quantiles. Previous studies (Chang and Kwon 2007, Bae et al 2008, Jung et al 2011) have used the Mann–Kendall (MK) statistical test (Mann 1945, Kendall 1975) to determine trends in precipitation and streamflow. While this method has been widely used and is resistant to outliers, it provides a single summary statistic for

| River basin       | Seasonal precipitation (June–September) | Mean  | Standard deviation | Coefficient of variation | Quantiles |
|-------------------|-----------------------------------------|-------|--------------------|--------------------------|-----------|
| Han River         | Total precipitation                      | 873   | 212                | 0.24                     | 599 737 859 999 1129 |
|                   | Non-typhoon precipitation               | 683   | 208                | 0.30                     | 421 572 663 747 985  |
|                   | Typhoon-induced precipitation            | 190   | 104                | 0.55                     | 67 121 170 250 302  |
| Nakdong River     | Total precipitation                      | 821   | 224                | 0.27                     | 538 674 824 974 1132 |
|                   | Non-typhoon precipitation               | 606   | 177                | 0.29                     | 394 477 630 725 784  |
|                   | Typhoon-induced precipitation            | 215   | 126                | 0.59                     | 64 140 185 264 362  |
| Geum River        | Total precipitation                      | 836   | 185                | 0.22                     | 567 755 869 927 1084 |
|                   | Non-typhoon precipitation               | 657   | 182                | 0.28                     | 449 546 645 754 909  |
|                   | Typhoon-induced precipitation            | 179   | 91                 | 0.51                     | 86 117 164 225 269  |
| Sumjin River      | Total precipitation                      | 934   | 254                | 0.27                     | 611 749 941 1126 1244|
|                   | Non-typhoon precipitation               | 701   | 218                | 0.31                     | 447 549 720 801 942  |
|                   | Typhoon-induced precipitation            | 234   | 154                | 0.66                     | 89 130 192 295 397  |
| Yeongsan River    | Total precipitation                      | 828   | 251                | 0.30                     | 444 636 870 988 1151 |
|                   | Non-typhoon precipitation               | 630   | 223                | 0.35                     | 352 455 637 776 858  |
|                   | Typhoon-induced precipitation            | 198   | 137                | 0.69                     | 73 105 164 245 361  |
Figure 2. Trend analysis based on GLM fitted to the Poisson regression for the number of days with heavy precipitations (>30 and >50 mm/day). The solid polygon in blue shows statistically significant increasing trends. The hatched polygons represent upward trends in non-typhoon precipitation (green) and typhoon-induced precipitation (red). For each case, trends with $p < 0.10$ were considered as statistically significant.

Figure 3. Trends based on a median quantile regression of seasonal precipitation (June–September) during the 1966–2007 time period. The solid polygon shows statistically significant upward trends for seasonal precipitation, non-typhoon precipitation, and typhoon-induced precipitation. Trends in precipitation are highlighted based on a 90% confidence level.

trends. In this study, we focused on identifying the nature and extent of changes using a quantile-regression-based trend approach that allows a well-defined assessment across various conditional quantiles (upper quartile, median, lower quartile) for seasonal precipitation (June–September). The analysis provides improved characterization of shifts in the location and scale empirical probability distribution of precipitation.

Figure 3 shows trends using median-based quantile regression of seasonal precipitation, non-typhoon and typhoon-induced precipitation for the five major river basins during the 1966–2007 time period. Increasing trends in total precipitation are widespread over the five river basins except in the Sumjin and Yeongsan River Basin (figure 3(a)). For the Han River Basin, 9 out of 29 (34.4% of the total area) sub-basins show significant trends in total precipitation. Among these 9 sub-basins, 4 sub-basins shows increasing trends in non-typhoon precipitation (18.8% of the total area). However, no sub-basins in the Han River Basin show significant trend in typhoon-induced precipitation during June to September season. The most significant changes in total precipitation are found in the Nakdong River Basin (57.3% of the total area). Trends in non-typhoon precipitation are significant for 13 out of 33 sub-basins (40.7% of the total area). Along the east and a part of the south coast, a positive trend shows for typhoon-induced precipitation (30.6% of the total area). In the Nakdong River Basin, the observed trend in total precipitation has occurred alongside corresponding trends in both the typhoon and non-typhoon precipitation.

An improved understanding of the atmospheric and oceanic controls on non-typhoon precipitation provides useful insights regarding the mechanisms that underpin warm season hydroclimatology and the future trends over the Korean
peninsula. For example, over the Han River region, Kim et al (2010) note that non-typhoon precipitation show significant correlations with the East Atlantic–West Russia teleconnection pattern. An extension of the analysis presented in Kim et al (2010) to the five major river basins confirms the joint variability of the EA–WR teleconnection pattern and non-typhoon seasonal precipitation (Pearson correlation for a 1966–2005 record: Han (−0.39), Nakdong (−0.41), Geum (−0.45), Sumjin (−0.49), and Yeongsan (−0.51)). Future variability and changes in the identified teleconnection patterns and the western North Pacific typhoons are important factors influencing hydroclimatic trends over the Korean peninsula. A recent study considers these factors for developing conditional streamflow distributions based on teleconnection pattern information for the Han River Basin (Kim et al 2011).

3.2.3. Typology of trends. The analyses approach developed in previous sections provide a spatially explicit view of the recent trends in typhoon and non-typhoon precipitation. On the one hand, these analyses clarify the relative role and import of large-scale climatic drivers (such as, typhoons), the other thrust of this results work is an improved characterization of extreme events frequencies—an important concern for climate risk assessment. Based on results from quantile regression, we find that the upward trends in the median of the seasonal precipitation distribution are concentrated in the Nakdong and Han River Basins (figure 3). Trends in the median, however, offer an incomplete view of the precipitation changes, especially the extremes. To redress this issue, we pursued trend analyses for the upper and lower quartile of the seasonal precipitation distribution. Furthermore, to catalog the array of shifts in the upper and lower tails of the precipitation distribution over the Korean peninsula, we present trends as a typology with nine categories (figure 4), representing all the combinations of upper and lower quartile trends (upward, down, and no trend).

The upper quartile regression analysis shows increasing trends in total precipitation (June–September) in south-eastern part of the Han River Basin, a region spanning 29.6% (7 out of 29 sub-basins) of the total area of the Han River Basin. In addition, 19.8% of the Han River Basin shows an increasing trend in both total precipitation (figure 4) and non-typhoon precipitation (shown in supplementary figure 3 available at stacks.iop.org/ERL/6/034033/mmedia). For total precipitation, 10 out of 33 (42.9% of the total area) sub-basins belonging to the Nakdong River Basin show upward trends. An estimated 8.3% of the Nakdong River Basin shows an increasing trend in both total precipitation (figure 4) and non-typhoon precipitation. In the Geum River Basin, 45.8% of sub-basins show increases in total precipitation. Increases in non-typhoon precipitation is also seen in 36.3% of the Geum River Basin. The results of upper-quartile-based trend analysis show no trends toward significant increases in the typhoon-related precipitation amounts excluding one sub-basin (Daejongchun) in the Nakdong River Basin. The results of the lower-quartile-based regression analysis shows that the increasing trends in typhoon-induced precipitation are widespread over the portions of the major river basins: Nakdong (33.2%), Geum (37.2%), Yeongsan (36.7%), and Sumjin (38.2%) River Basin. However, there is no significant trend in typhoon-related precipitation for the Han River Basin.

While the Nakdong River Basin shows upward shift in the median (figure 3), only a few sub-basins show statistically significant increases in the lower and upper quartiles. In the Han River Basin, out of a total of 29 sub-basins, upward trends of various flavors are seen in 15 sub-basins. These include increases in both lower and upper quartiles (2), upper quartile only (5), and lower quartile only (8). When viewed jointly with the trends in the median (figure 3), other contrasts appear. For example, in the Geum River Basin, while no significant shifts in the median precipitation are seen, six sub-basins show increases in upper quartile precipitation, and six other sub-basins show increases in the lower quartile precipitation. It is important to note that the richness in the nature of changes and trends needs to be tempered with limits imposed by sample size (n = 42). The other factor that may potentially confound analysis results is that of the use of a four-day time window coincident with typhoons for the separation of seasonal precipitation. To clarify this issue, we repeated the entire analysis for two other candidate time windows (three-day and five-day). Results from these analyses indicate that the identified spatial trend patterns and typology are largely robust with respect to window width used for separation of typhoon-induced precipitation (supplementary figure 4 available at stacks.iop.org/ERL/6/034033/mmedia).

Nonetheless, the observed trends noted in the trend typology have important bearing the vulnerability of human and natural systems. Furthermore, it is also worth noting that linear regression and other measures of changes in the central tendency are not equipped to quantify changes in the full empirical distributions, especially in cases where only the upper or lower tails undergo changes, while remainder of the distribution shows no statistically significant shifts.
4. Summary and conclusions

A careful characterization of precipitation variability and trends is an important starting point for adaptation and decision making involving environmental and human contexts, such as: water resources, hazard response, engineering design, agriculture, and ecosystem services. In this study, we used an empirical approach to identify the relative contribution of typhoon and non-typhoon precipitation to changes in the magnitude and frequency of seasonal precipitation in the five major river basins in Korea. In addition, we developed a trend typology to characterize the combination of shifts in the upper and lower tails of the precipitation distribution that manifest as trends in extreme events. Geum River Basin exemplifies these changes—no significant shifts in the median precipitation are seen, the upper (6 sub-basins) and lower (6 other sub-basins) tails undergo statistically significant shifts. Observed nature of trend typology over the Korean peninsula illuminates the diversity of changes in high and low precipitation extremes, occurring simultaneously alongside broad increases in median precipitation and not evident from analyses such as linear regression.

The characterization of precipitation trends, associated climatic factors, and the changing envelope of year-to-year precipitation variability confirms the changing nature of climate over the Korean peninsula; the methodology developed here is geared toward a better understanding of the causes and facilitate an improved interpretation of trends for risk and impacts assessment.

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