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Short Communication

Warm season streamflow variability in the Korean Han River Basin: Links with atmospheric teleconnections

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ABSTRACT: Warm season (June–September) hydroclimatology is a key determinant of freshwater supplies in the Korean Peninsula. In the Han River Basin, nearly three-fourths of annual discharge occurs during the warm season. Given the increased reliance on water supplies for numerous human and ecosystem functions, an integrated view of water supplies within the context of the regional hydroclimate will aid efforts to achieve water resources sustainability. To that end, this diagnostic study investigates several key aspects of the Han River hydrologic regime: (i) the warm season hydroclimatology; (ii) understanding the relative contribution of typhoon and non-typhoon precipitation events to warm season streamflow; and (iii) relationships with large-scale atmospheric teleconnections patterns and the implied seasonal predictability. Statistical analysis of modelled unimpaired streamflow indicates that the East Atlantic-Western Russia (EA–WR) teleconnection pattern modulates the Han River streamflow during the warm season. Furthermore, a linear modelling approach using the EA–WR and East Atlantic (EA) teleconnection indices offers a useful empirical framework for understanding the systematic shifts in streamflow probability distributions. Based on these results, potential use of this information for multi-objective water resources management, environmental flow prescriptions, proactive use of seasonal forecasts, and some open questions are briefly discussed.

Additional Supporting information may be found in the online version of this article.

KEY WORDS hydroclimatic variability; teleconnection patterns; water resources management

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1. Introduction

Freshwater supplies are increasingly relied upon to support socioeconomic development and ecosystem function. The Han River Basin is a representative case: given the pace of development in the Korean Peninsula, management of freshwater resources is viewed as a critical consideration for a sustainable future (WWAP, 2009). Several research studies have explored the long-term trends in rainfall and extreme events over the Korean Peninsula (Jung *et al.*, 2002; Chung *et al.*, 2004; Chang and Kwon, 2007; Bae *et al.*, 2008; Jung *et al.*, 2010). While increases in seasonal precipitation and streamflow have been noted, these changes are not statistically significant (Bae *et al.*, 2008). However, Chang and Kwon (2007) documented significant upward trend in heavy precipitation (>50 mm/day) for several sub-watersheds in the Han River Basin.

Seasonal atmospheric teleconnection patterns play an important role in modulating the frequency and magnitude of precipitation (Glantz *et al.*, 1991), as a result determining the inter-annual and longer-term hydrologic variability in the major river basins, such as the Han River Basin. This diagnostic study investigates several key aspects of the Han River hydrologic regime: (i) the warm season hydroclimatology and associated variability; (ii) understanding the relative contribution of typhoon and non-typhoon events to season streamflow; and (iii) relationships with large-scale atmospheric teleconnection patterns and potential seasonal predictability.

2. Data

The analysis presented here is based on serially complete daily runoff data provided by the Korean Water Resources Management Information System (WAMIS; http://wamis.go.kr/) for the 1966–2005 period. The long-term runoff data provided by WAMIS is the result of a national watershed research project in Korea. As little applicable and reliable long-term runoff data for Korea

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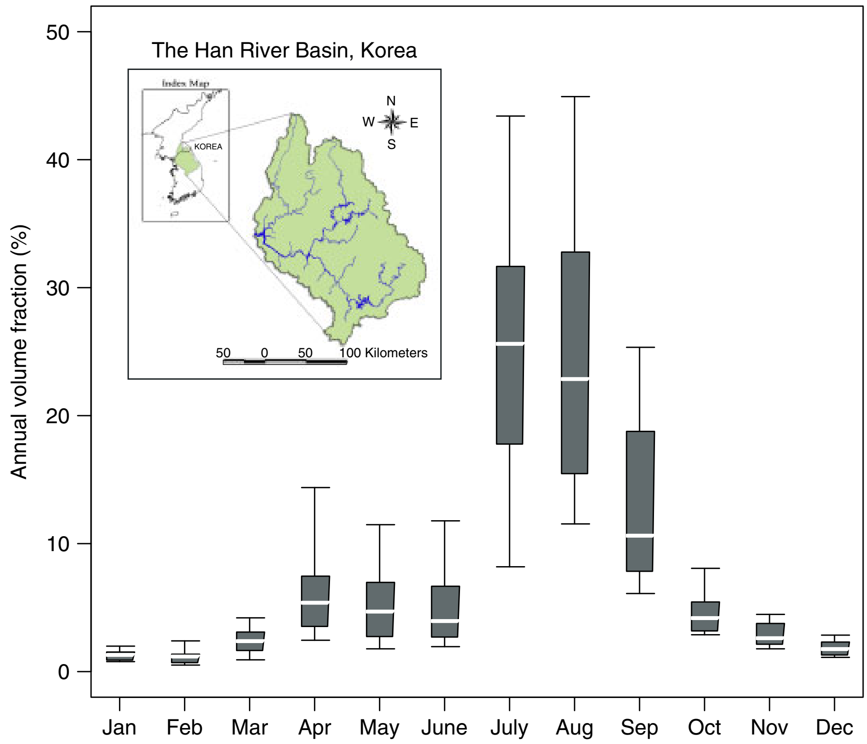

Figure 1. Annual volume fraction in Han River basin for the period 1966–2005. For each month, the variability is summarized using a boxplot (0.1, 0.25, 0.5, 0.75, 0.9 quantile levels are shown). (Inset) Map of the Korean Peninsula showing the location of the Han River Basin. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

river basins is available, we used streamflow data calculated by the Precipitation Runoff Modelling System (PRMS) to identify the relationship between atmospheric teleconnections and streamflow variability at regional scales. The PRMS model, developed by the US Geological Survey (USGS), has been used to evaluate the effects of various combinations of climatic and hydrologic variables on streamflow (Leavesley *et al*., 1983; Dressler *et al*., 2006; Bae *et al*., 2008). Evaluated as the runoff model for watershed studies, the PRMS can be reliably used to model Korea's river basin hydrology including the complexity due to topographic conditions (Chang and Jung, 2010). Bae *et al*. (2008) provide extensive details regarding a systematic calibration and regionalization of modelled hydrologic responses throughout the Korean Peninsula. Streamflow estimates that are free from flow regulation effects are especially suitable for studying the relationship between large-scale climatic variables and streamflow.

To understand the empirical relationship between large-scale climate precursors and basin-scale hydrologic variables, standardized Northern Hemisphere teleconnection indices were used from the NOAA Climate Prediction Center (ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh). We calculated seasonal indices (June–September) for teleconnections and streamflow for the common period of record (1966–2005); these seasonal indices were used for correlation and linear modelling analyses. The area-averaged rainfall, obtained from WAMIS, was used for additional confirmation regarding the empirical relationships between teleconnections and hydroclimatic variables for the Han River Basin.

In the western North Pacific basin, episodic typhoons exert a strong influence on hydrologic variability in the Korean region. We examined statistics of variations for typhoon-induced streamflow and non-typhoon flow during the warm season. Based on the historical record (1966–2005), 198 typhoon storm tracks have been recorded within the restricted domain (120 °E–138 °E, 32°N–40°N), which is used by the Korea Meteorological Administration (http://web.kma.go.kr/eng/index.jsp) to identify impacts of typhoons throughout Korea (KMA, 1996; Oh and Moon, 2008). Daily streamflow variations coincident with the typhoon events were analysed to quantify their fractional contribution to seasonal streamflow (Section 3.2 for details).

3. Analysis and Results

3.1. Seasonal cycle of streamflow

The Han River Basin is located in the center of the Korean Peninsula, at 36°30′–38°55′ north latitude, and 126°24′–129°02′ east longitude (inset, Figure 1). The watershed area spanning 26 356 km^2 accounts for approximately 23% of the South Korea territory. The seasonal cycle of streamflow reveals that warm season (June–September) hydroclimatology is a key determinant of freshwater supplies (Figure 1). Year-to-year variability is similarly high during the JJAS season. Based on the 1966–2005 period daily streamflow, nearly three-fourths

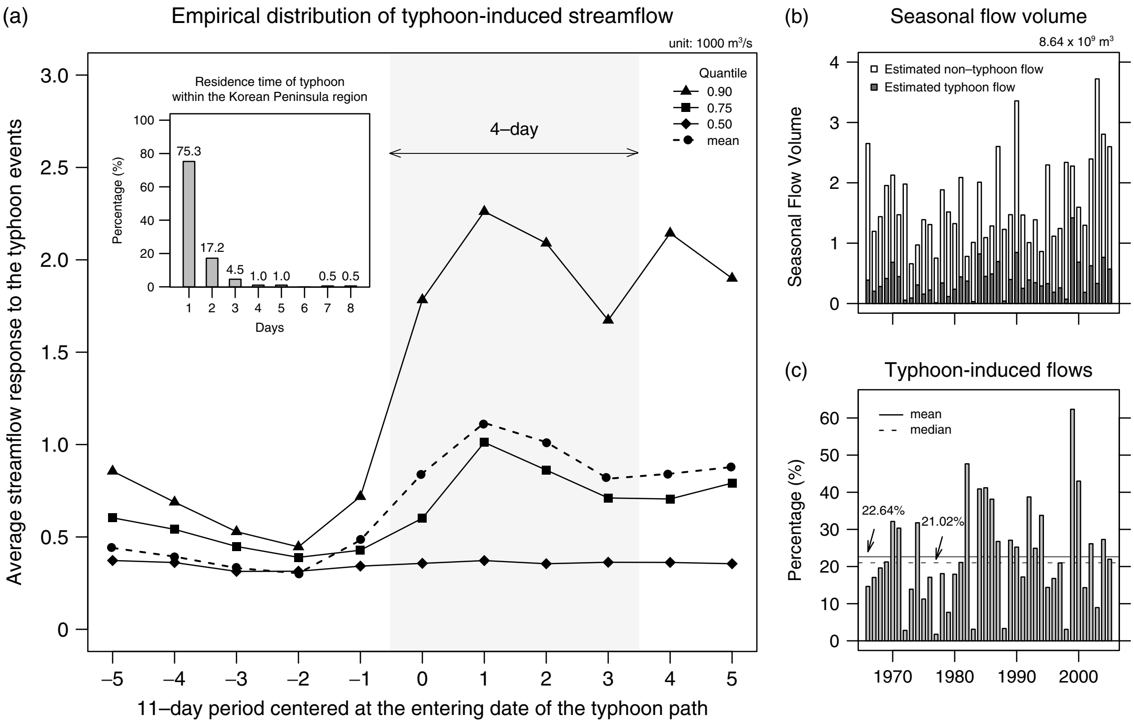

Figure 2. Empirical estimates of typhoon-induced streamflow. a, Empirical distribution of typhoon-induced streamflow. Streamflow variations are shown for an 11-day period centered at the entering date of the typhoon path within the restricted domain (noted at time = 0). At each of the 11 days ($t = -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5$), quantiles (0.90, 0.75, 0.50, and mean) are computed to ascertain the empirical distribution of streamflow response to the typhoon events. (Inset) Distribution of the residence time (number of days) of the typhoon track within the restricted domain. b, Interannual variability in the June–September seasonal flow volume for the Han River. Flow volumes contributions estimated to be typhoon-induced are shown as black bars (based on the typhoon track information). The remainder of the season flow volume (white stacked bar) corresponds to other moisture sources. Baseflow contributions are included in both typhoon and non-typhoon flow volume estimates. c, Estimated typhoon-induced flow volumes as a fraction of the total seasonal flow volume (expressed as percent).

of the annual flow occurs during the JJAS season (mean = 70.0%, standard deviation = 15.3%).

Climatologically, tropical moisture sources, North Pacific typhoons, and summer monsoonal precipitation are key drivers of hydrologic variability in the Korean Peninsula. To understand the role of large-scale atmospheric circulation in modulating seasonal streamflow volumes, we first develop an empirical approach to separate the typhoon-induced streamflow volumes and examine the non-typhoon streamflow volume for links with seasonal teleconnection patterns.

3.2. Empirical estimates of typhoon-induced streamflow

Using the daily record of streamflow and the long archive of typhoons events, a subjective empirical analysis of streamflow variations shows high flows coincident with periods when typhoons are in the Korean Peninsula region (Figure 2). To estimate the relative contribution of large-scale moisture sources associated with episodic typhoons events, a composite analysis of flow events coincident with the typhoons was pursued (Figure 2a); the streamflow quantiles highlight the impact of typhoon on streamflow. Based on a visual inspection of the mean streamflow response distribution and the quantiles, it is evident that in a majority of cases, streamflow response occurs within three days from the time when the typhoon track first intersects with our chosen domain; consequently, a four-day time period (day 0, 1, 2, and 3 in Figure 2a) constitutes the primary window associated with high-flow response. As shown in Figure 2a (inset), 97% of the historical typhoon events with intercepts in the Korean region have up to a three-day residence time. We believe that this choice of time window provides a conservative estimate of the typhoon-induced streamflow for the Han River Basin. At the same time, the choice of the spatial domain encompassing the Korean peninsula – consistent with that used by the Korea Meteorological Administration (120 °E–138 °E, 32°N–40°N) – impacts the time-window identified for typhoon-streamflow analysis. Analysis allowed a baseline estimate of the fraction of JJAS streamflow stemming from episodic typhoons. It is noteworthy that, on average, nearly 22.6% of the JJAS streamflow is associated with typhoon events (Figure 2c). Consequently, 77.4% of the seasonal flow volume is associated with frontal systems and tropical moisture sources, with likely links to the teleconnection patterns. While persistent atmospheric patterns are also known to influence tropical cyclones through steering effects, this study does not investigate those factors.

Interannual variations in the streamflow and the typhoon-induced streamflow are shown in Figure 2b and c – an understanding of the variability and change in

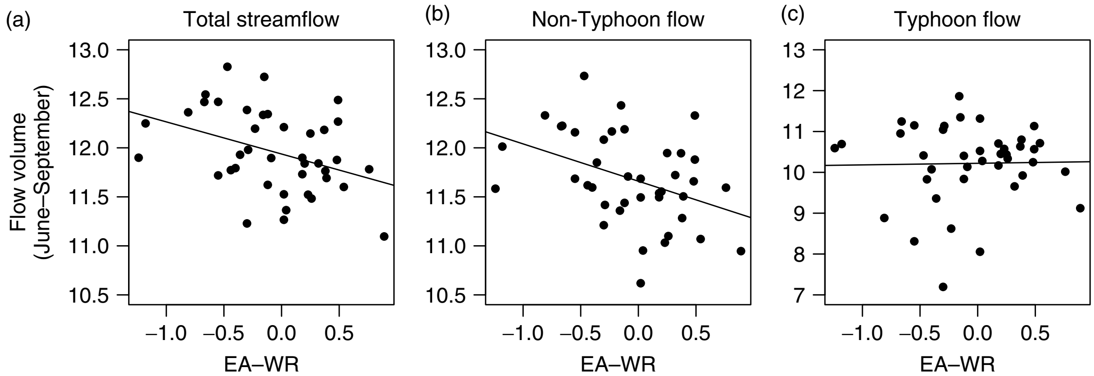

Figure 3. Linear dependence between log-transformed streamflow volume and EA−WR pattern. a, June−September seasonal flow volume versus EA−WR. b, Non-typhoon flow volume versus EA−WR. c, Estimated typhoon-induced flow volume versus EA−WR. A four-day time window starting with the day that the typhoon path enters the restricted domain (120E−138E, 32N−40N) was used to calculate the contribution of typhoon to seasonal streamflow. For each case, the solid line represents the best linear fit.

the two dominant moisture sources is critically important for seasonal and longer-term management of water resources in the region. We also conducted a simple analysis to estimate the relative role of baseflow using the Eckhardt method (Eckhardt, 2005). Results from this analysis suggest that the warm season baseflow variability is significantly smaller than one for the total streamflow (Supplementary Information Section for details). Detailed analyses of separate baseflow will be important for future studies on this topic, especially ones focused on low-flow variability. Next, we examine the warm-season relationships between large-scale atmospheric circulation patterns and streamflow variability.

3.3. Regional and global teleconnections

As noted in the previous section, the warm season streamflow variability in the Han River region stems from the seasonal evolution of the synoptic weather systems related to monsoon (also referred to as Changma front), episodic typhoons, and from moisture supplied by remnants of typhoons events. A key consideration for the seasonal predictability of streamflow is the nature and impact of persistent atmospheric circulation patterns in the north hemispheric extratropical regions. These patterns exhibit systematic year-to-year variability, influencing the magnitude, direction, and timing of the regional moisture fluxes. Atmospheric teleconnection patterns have associated surface expression regional footprints of precipitation and temperature that result from systematic shifts in the strength and location of storm tracks (IPCC, 2007). Barnston and Livezey (1987) provide a detailed analysis methodology to isolate teleconnection patterns based on an empirical orthogonal function approach. The United States National Oceanic and Atmospheric Administration (NOAA) Web resources provide a detailed summary of the Northern Hemisphere teleconnection patterns, season-by-season temperature and precipitation impacts, and index values for these data that are updated regularly (URL: http://www.cpc.noaa.gov/data/teledoc/teleintro.shtml).

A correlation analysis between the Han River streamflow and major teleconnection patterns during the JJAS season provides a useful starting point for understanding the linear signal of large-scale climatic variability. A Spearman correlation analysis shows the following estimates: North Atlantic Oscillation (NAO): – 0.07, East Atlantic Pattern (EA): 0.04, West Pacific Pattern (WP): 0.05, East Pacific/North Pacific Pattern (EP−NP): −0.09, Pacific/North American Pattern (PNA): 0.18, East Atlantic/West Russia Pattern (EA−WR): −0.40, Scandinavia Pattern (SCA): −0.24, Polar/Eurasia Pattern (POL): −0.02. A Pearson correlation analysis shows similar results. For example, the EA−WR teleconnection index is negatively correlated with the Han River seasonal volume (correlation coefficient = −0.37; p-value = 0.01). The linear dependence between the EA−WR pattern and the seasonal streamflow volumes is shown in Figure 3. To confirm the relationship between the EA−WR pattern and precipitation, we pursued an ancillary correlation analysis based on the precipitation dataset from the Global Precipitation Climatology Project (Adler *et al*., 2003). This result is presented in the Supplementary Information Section. Other teleconnection patterns show modest correlations (measuring linear dependence), yet may serve as useful climate precursors for understanding hydrologic variability.

In the following section, we discuss the results from an analysis of relationships between the streamflow and teleconnections patterns using a Generalized Linear Modeling approach (GLM; McCullagh and Nelder, 1989).

3.4. Linear modelling

Atmospheric circulation patterns can exert a strong regional influence on weather. A number of studies have linked streamflow with regional teleconnection patterns and highlighted the prospect for improved understanding of hydrologic variability and use of seasonal forecasts for water resources management (Kingston *et al*., 2007; Chiew and McMahon, 2002). While atmospheric teleconnection patterns represent distinct regional expressions of the atmospheric circulation, their spatial footprints

Table I. GLM analysis using teleconnection patterns.

	Total streamflow		Non-typhoon flow	
	Estimate	p-value	Estimate	p-value
Intercept	−0.45	0.98	11.02	0.48
Year	0.01	0.41	0.01	0.97
NAO	−0.03	0.83	−0.06	0.68
EA	−0.16	0.18	**−0.28**	0.05
WP	−0.02	0.86	−0.08	0.58
EP–NP	−0.05	0.79	−0.19	0.30
PNA	0.12	0.35	0.15	0.26
EA–WR	**−0.29**	0.09	**−0.43**	0.02
SCA	−0.11	0.47	−0.09	0.56
POL	−0.09	0.47	−0.19	0.12

(impacts on precipitation, temperature, and streamflow, etc.) overlap, complicating diagnosis of large-scale climatic influences on hydrologic variability. Furthermore, understanding the linear dependence between streamflow and teleconnection indices offers potentially useful conditional information for water resources management and decision making. Consequently, to understand the systematic shifts in regional hydrological variability associated with atmospheric circulation patterns, we consider a GLM approach.

The GLM analyses considered all eight teleconnection indices described in Section 3.3. Two separate models were constructed – one based on the streamflow volume for the JJAS period, the other based on the non-typhoon streamflow volume using the subjective typhoon-related streamflow separation approach described in Section 3.2. In both cases, we use a log-transformation on streamflow data. For the total seasonal volume analysis, the linear model shows a significant relationship between EA–WR teleconnection index (p-value = 0.09) and the streamflow volume. Given the year-to-year variability in typhoon-induced streamflow contributions, it is likely that large-scale teleconnection relationships related to other patterns may be obscured in the first GLM analysis. Hence, we repeated the GLM analysis for the non-typhoon streamflow volume. The results confirm the strong relationship between streamflow volume and EA–WR pattern (p-value = 0.02) and also illuminate a significant relationship with EA pattern (p-value = 0.05). Details regarding the GLM analyses are presented in Tables I and II. Regional precipitation correlations with EA–WR and EA pattern for the month of July are available at NOAA CPC website (http://www.cpc.noaa.gov/data/teledoc/telecontents.shtml). These patterns confirm the hydroclimatic relationships over the Korean peninsula. Furthermore, we repeated the linear modelling analysis with river basin-averaged precipitation. The results from this analysis further confirm the empirical relationships between the select teleconnection patterns (EA–WR and EA) and hydroclimatic variables (streamflow and precipitation) in the Han River Basin. With a view to better understand the nature of relationship between select teleconnection patterns (EA–WR and EA) and the streamflow, we examined the outliers in the linear model. Three years (1966, 1983, and 2003) show large residuals, and highlight the role of other dominant factors not captured by the linear model. Secondary effects from typhoons, antecedent moisture conditions, as well as modulation of tropical moisture sources and Changma fronts are some of the candidate factors that merit careful analyses to further improve the prospects of seasonal streamflow prediction. The focus of this study was limited to determining the key large-scale atmospheric circulation-based predictors for the Han River Basin.

Table II. GLM analysis using EA and EA–WR patterns.

	Total streamflow		Non-typhoon flow	
	Estimate	p-value	Estimate	p-value
Intercept	11.94	2×10^{-16}	11.67	2×10^{-16}
EA	−0.07	0.49	−0.15	0.19
EA–WR	**−0.37**	0.01	**−0.47**	0.01

4. Summary and Conclusions

This study is motivated by the recognition that emerging development and increasing pressures on water resources in the Han River Basin can benefit from seasonal-lead streamflow forecasts. Based on a 40-year-long hydroclimatic dataset for the Han River Basin and the atmospheric teleconnection information, diagnostic analysis and linear modelling was pursued to explicate the relationship between the large-scale atmospheric circulation patterns and the June–September streamflow volume. The results presented in this study can be summarised as:

1. To understand the interannual co-variability between the streamflow and teleconnection patterns, we developed an empirical approach to identify time windows related to typhoon-induced precipitation, thus allowing seasonal estimates of typhoon and non-typhoon

induced streamflow volume. In comparison to the total seasonal streamflow volume, it is shown that the teleconnection patterns exhibit a higher correlation with the non-typhoon streamflow volume.

2. Two teleconnection patterns (EA–WR and EA) show a statistically significant relationship with the Han River streamflow volume. The regional precipitation patterns associated with EA–WR and EA teleconnection patterns further affirm this relationship.
3. The diagnostic and linear modelling approach highlight the potential for predicting seasonal streamflow for the Han River Basin. Important considerations related to hydropower, water supplies, and ecosystem health can benefit from proactive planning and management approach based on climate information.

The results presented here indicate that analyses based on an empirical separation of typhoon and non-typhoon induced streamflow volume give useful new information regarding the regional hydrologic impacts of large-scale climate teleconnections. Furthermore, improved characterization of the impact of episodic typhoons and their interannual variability is also afforded by the new estimates of streamflow volumes.

Future studies in this area are needed to develop well-tested, linear, and non-linear predictive models for streamflow variability, studies that clarify the mechanisms that control the regional climate-hydrology linkages, as well as understanding the seasonal and longer-term predictability of teleconnection patterns and trends therein. Adaptive management of water resources to meet human needs and at the same time ensuring the integrity of freshwater ecosystems continues to be the biggest challenge facing river basin management – Han River is a compelling example in this regard. Climate information has the potential to inform current and future adaptive management efforts in this river basin. Our current work addresses these issues.

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