이학석사학위논문

Typhoon track and extra-tropical transition as the decisive factors for the risk distribution in South Korea

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Abstract

Typhoon track and extra-tropical transition as the decisive factors for the risk distribution in South Korea

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The present thesis aims to probe the priority structure in the tropical cyclone (TC) risk realization process in South Korea. So far, most TC risk research and real-time forecasts have been focusing on TC wind intensity. However, our results show that TC track and extra-tropical transition information is more important than TC intensity, to decide whether the TC risk to be activated as a catastrophe or to stay in the potential status. First, weak TCs (WTCs, maximum wind speed <17 m s^{-1}), which is even ignored in the TC warning system of Korean Meteorological Agency for its weak intensity, appeared more damaging than strong TCs (STCs, >17 m s^{-1})

for western provinces. WTCs have significantly different tracks and landfall locations compared to STCs, so that western provinces of South Korea suffers more from WTCs than from STCs. Secondly, decision tree analysis revealed that track patterns and extra-tropical transition experiences are the most efficient attributes to predict damage occurrences among all the risk elements including maximum wind speed. In other words, the most distinctive differences that divide damaged and non-damaged TCs were 1) for STCs, if the STC is west-approaching or east-approaching to South Korea, and 2) for WTCs, whether the WTC experiences extra-tropical transition around the Korean Peninsula or not. In sum, our findings highlight the discrepancy between dormant hazards of a TC (e.g. central wind intensity) and local effective hazards (e.g. rainfall) that residents in different areas actually experience. Based on these findings, we suggest that TC warnings should more focus on its local impacts than its central wind intensity, and this requires an accurate TC track forecast and extra-tropical transition prediction most of all.

Keywords : tropical cyclone, typhoon, risk, hazard, South Korea, track, extra-tropical transition

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1. Introduction

Tropical cyclone (TC) is among the biggest concerns for disaster management since TC is the most costly natural disaster as a single natural hazard worldwide (http://emdat.be). Many researchers have tried to understand and predict TC activity and associated risk. In TC risk studies, the risk triangle concept, which describes risk as comprising three major elements (i.e., hazard, exposure, and vulnerability), is widely adopted (Peduzzi et al. 2012, Mendelsohn et al. 2012). To estimate the risk quantitatively, actual damage is used as a response variable in an empirical statistical model (Pielke et al. 2008, Park et al. 2015), although damage is more likely a materialization of risk in the strictest sense (Cardona et al. 2012). The three risk elements are often used as explanatory variables. Exposure and vulnerability are usually expressed by the number of residents and regional gross domestic product (GDP) in the area of interest, respectively (Pielke et al. 2008). Hazard is typically represented by a TC-based hazard parameter, such as central pressure, maximum wind speed, or TC size (Pielke et al. 2008, Nordhaus 2010, Hsiang and Narita 2012, Czajkowski and Done 2014, Zhai and Jiang 2014).

Using TC-based hazard parameters, however, is insufficient for estimating TC damage since TC-based hazards are more like potential hazards rather than effective hazards. Several different modes of hazards are recognized. Most hazards are ‘dormant’ or ‘potential,’ simply posing a level of threat to life, property, and/or environment, but once a hazard turns ‘active,’ it becomes an incident/emergency

(MacCollum 2007). With this classification, TC-based hazards, which indicate the intensity of a TC regardless of the possibility of actual impact occurrence, are labeled as ‘dormant’ or ‘potential’ mode if the TC is in a position of approaching a settlement. Meanwhile, ‘active’ hazards that are driven by a TC can be listed as rainfall, wind gusts, wind waves, and storm surges, all of which are localized and directly affect residents. Following their definitions, active hazards should be more closely correlated with damage than potential hazards. In addition, using active hazards for risk estimation is advantageous in that active hazards, like the damage caused, are localized. In comparison, TC-based hazards indicate only representative intensity of a TC, found in a limited area near its center. Donat et al. (2011) showed that the consideration of locality for storm winds could yield much higher accuracy in risk models.

The realization of potential hazards of a TC into active hazards seems to be largely dependent on the TC track. In other words, track has a key role in determining 1) whether the potential hazard of a TC will become active for a given settlement and 2) in how intense the activated hazard would be. Record-breaking rainfall in Gangneung city, South Korea was recorded, because the track of Typhoon Rusa (2002) was optimal to strengthen the orographic effect on precipitation over the region (Park and Lee 2007). Also, the deadliest damage by typhoon Haiyan (2013) in the Philippines was mainly because the TC penetrated Tacloban city, which is located in a low-lying area near the ocean, such that most of the damage arose from storm surge (Ching et al. 2015). In both cases, if the TCs went through a different area, avoiding the mountains and lowland, respectively, the result could have been much less devastating.

We suggest that more attention should be put on track in TC risk analysis. One may argue that if tracks are taken into account within a risk framework, they will overlap with the concept of exposure. This rebuttal can arise from the fact that both parameters indicate the possibility of actual influence by a TC. However, exposure refers to population and wealth at a certain fixed point. Track determines active hazards, i.e., how much local wind and rainfall at a fixed point will be caused by a TC with a given track. Track, however, cannot change exposure at a given point. The present study statistically evaluates priority among track, TC-based hazards, and exposure/vulnerability with respect to the realization of TC risk for a given society.

In our TC risk analysis, not only strong TCs (STCs, maximum wind speeds of the best-track data ≥ 17 m s^{-1}), but also relatively weak TCs (WTCs, maximum wind speeds of the best-track data < 17 m s^{-1}) are included. The Korean Meteorological Administration (KMA) does not issue the Typhoon Warning for WTCs, regarding them as not damaging as STCs. However, it has never been clarified if WTCs are really less damaging than STCs. Moreover, maximum wind speeds of WTCs generally are not recorded by the best-track dataset even if they are as strong as STCs. This is because many of WTCs are transformed into extra-tropical lows which are not monitored by the best-track dataset. WTCs can re-intensify under a certain environmental condition, such as the existence of upper-level trough and high surface baroclinity (Klein 2001; Jones et al. 2003; Hart et al. 2006). About 45% of TCs undergo the extra-tropical transition often characterized by fast translational speed and rapid re-intensification (Jones et al. 2003). The re-intensified WTCs may accompany multiple severe phenomena, such as gust, downpour, storm surge, and wind wave, like STCs. For example, about 0.5 million homelessness, 4 hundred casualties, and 0.8 trillion Korean Won (KRW, 1,000 KRW ≈ 1 USD) of property losses in September 1984 were led by Typhoon June although it weakened into WTCs in advance of influencing on Korea.

Thus, prior to risk process analysis of WTCs and STCs, this thesis examined three major damage types—number of homelessness, number of casualties, and amount of property loss—resulting from WTCs and STCs in each province to directly compare the actual destructiveness of WTCs with STCs'. In addition, their wind and rainfall intensities are also compared to each other. Rest of this paper is organized as follows. The data and methods used are described in section 2. The comparison of socio-economic losses and wind/rainfall intensities by WTCs and STCs are shown in section 3. Priority structure in both of WTC and STC risk realization is analyzed in Section 4. Finally, summary and discussion are given in section 5.

2. Data and Method

2.1 Data

We conducted risk comparison analysis for the WTCs and STCs in terms of three risk components - hazards, exposures, and damages. In this study, we view risk as the product of interaction of a potentially damaging event and the vulnerable conditions of a society or element exposed in accordance with the disaster risk research community (e.g. UNISDR 2004, IPCC 2007, and Cardona et al. 2012). In pseudo-mathmatical form, risk as the probability of a loss, can be expressed as (e.g. Granger et al. 1999, Crichton, 1999):

$$Risk = Hazard \times Exposure \times Vulnerability$$

If any of the three elements, hazards, exposure and vulnerability, in risk increases/decrease, then risk increases/decreases repectively. In our study, we see TC damage as the materialization of TC risk on the basis of the notion TC risk is the possibility (in other words, latent condition before realization) of TC damage. Thus we used TC damage data for quantative assessment of the total risk. Hazard parameters are defined as meteorological properties that can indicate the potential destructiveness of the TC to the society. Exposure is represented with regional wealth, which means how much wealth in the region potentially are exposed to TC risk. For vulnerability, we have not evaluateed it independently from other instinctive factors in damage data.

Now we explain how we have estimated each risk element more specifically. Damage data are collected from the National Disaster Information Center (NDIC) of Korean government (http://www.safekorea.go.kr) dataset, and used after some processing. NDIC property loss data consist of monetary damages of industrial, public, and private facilities standardized to the value of money in 2005, taking account of inflation. The loss data is collected by local governmental offices so that most of losses can be collected regardless of insured and uninsured, yet there can be some light losses not reported to the local offices by the victims. The raw dataset includes loss data caused by all types of extreme weather such as TC, heavy rainfall, heavy snowfall, high waves. Some cases are not classified into specific damage sources, and some cases are stated as high wave damage, which is in fact due to a TC. Therefore, we matched the loss data to each Korea affecting TC comparing the period of damage in the NDIC dataset with the influence period in the White Book and the period a TC stays within 3° from the Korean coastline. If any day of NDIC damage period overlaps with a TC's RSMC or White Book influence period, a loss is attributed to the TC. Then, to confine the origin of the loss data to one TC, we have excluded the cases whose damage period exceed five days from landfall, as NDIC usually aggregates the damage amounts and periods for multiple successive extreme phenomena.

The TCs' hazard parameters are obtained from two different data sources. From the Regional Specialized Meteorological Center (RSMC) best track data, the intensity and storm size values are gathered. For intensity, we use the maximum wind speed and central pressure data. For storm size, the longest radius of 30 knot winds or greater storm radius data. The 6-hourly interval of RSMC is interpolated into a 1-hour interval to get a precise hazard values at landfall (Park et al. 2011, 2014). Best-track intensity information (both maximum wind speed and central pressure) are the values very concentrated on the center of a TC. Thus best-track data is not sufficient to signify TC inland impacts, and so we have utilized weather station observations too. From 60 weather station data over South Korea, near-surface wind speed and rainfall intensity are gained. The influence duration of each station is also calculated, applying a method of Park et al (2015), by counting the number of days whose daily accumulated rainfall or the daily maximum sustained wind speed exceeded the station's critical thresholds, which we set as each station's 90^{th} percentiles. Here the range of duration is limited by the summation of three relevant periods; 1) the period of warning indicated in NTC White Book, 2) the days that TC stayed within 3 degree distance from the Korean coastline based on RSMC dataset and 3) the period of damage in the NDIC dataset.

For exposure, we used province-level aggregated population and wealth data obtained from government statistical surveys (Korean Statistical Information Service, http://kosis.kr/). We analyze exposure dividing into two different dimensions – time and space. First, temporal variation of exposure is considered through normalization of damage data to the reference year of 2005 with wealth per capita following Park et al. (2015 and 2016). In general, wealth of South Korea has consistently increased and its population is now decreasing. However, there are significant differences in the growth rates of among provinces (See Figure 2 in Park et al (2015)), which would affect TC damage records of provinces. By normalization, this possble impact of regional differences in population/wealth trend can be eliminated. The spatial disparity of exposure at a certain time, i.e. 2005, should be addressed as well. Therefore, we have introduced the regional wealth distribution at 2005 when mapping the damage distribution.

The normalized damages in terms of homelessness, casualties, and property losses caused by the *i*-th TC are calculated by the following equations.

$$A_{i,2005,r} = A_{i,y,r} \times \left({P_{2005,r}}/{P_{y,r}} \right),$$

$$C_{i,2005,r} = C_{i,y,r} \times \left({P_{2005,r}}/{P_{y,r}} \right),$$

$$D_{i,2005,r} = D_{i,y,r} \times \left({(P_{2005,r} \times W_{2005}}/{(P_{y,r} \times W_y)} \right), \tag{1}$$

where $A_{i,2005,r}$, $C_{i,2005,r}$, and $D_{i,2005,r}$ are the normalized damages in terms of homelessness, casualties, and property losses, respectively, for province, *r*. $A_{i,y,r}$, $C_{i,y,r}$, and $D_{i,y,r}$ indicate the actual damages in province *r* and year *y*. $P_{y,r}$ and $P_{2005,r}$ are the population in province *r* and year *y* and 2005, respectively. W_y and W_{2005} represent the wealth per capita in year *y* and 2005, respectively.

2.2 Selection of TCs

The Typhoon White Book issued by the NTC (NTC 2011) is used to get the list of the TCs that have affected Korea. The Typhoon White Book, that is the official record of TC activity of KMA, defines the influencing TC as a TC whose center is located in the domain of 32°N–40°N and 120°E–138°E with high probability of occurrence of damages on the country. The TC list in the White Book is the most trustworthy compared to other statistical ways for selecting influencing TCs (e.g., Kim et al. 2006; Park et al. 2006) since the list is made by comprehensive consideration of various data available at that time (Kwon and Rhyu 2011). However, the possibility if the TC can make impact or not is determined by weathermen, so it can be subjective. Several WTCs and STCs passing in the vicinity of the country but not predicted to damage Korea at the time of their influence, might have been missed in the list. Moreover, the White Book does not offer the detailed geographical locations and the maximum wind speeds of individual TCs.

To fill these gaps, the TC dataset from the International Best Track Archive for Climate Stewardship (IBTrACS) is also utilized (Knapp et al. 2010). The IBTrACS dataset has the longest track information and is least likely to miss any TCs since it is made by combining most of available TC best-track datasets from various meteorological agencies (Knapp et al. 2010). Hence, in addition to the TC list in the White Book, several TCs entering the influential area are added from the IBTrACS dataset into our TC list for analyses. In the authors' previous study (Park et al. 2015), for the definition of influential area, the line of 5° apart from the coastline was utilized. However, the old definition can include TCs which hardly affected Korea. Therefore, the line of 3° apart from the coast of Korea is newly defined as the influential area although it can miss sizable TCs far from the coast but possibly damaging the country. The TCs missed due to the shrinking influential area defined appear to be complemented by the TC list from the White Book. Meanwhile, prior to the addition of TCs, because the TC information of the IBTrACS is provided at a 6-hour interval which is too coarse to get a precise influential period of TC over Korea, the 6-hourly interval is interpolated into an 1-hour interval (Park et al. 2011, 2014). Based on the 10-minute sustained maximum wind speed from the IBTrACS, TCs are grouped in two types, WTC and STC; a WTC (STC) is defined as a TC with the maximum wind speeds less than (greater than or equal to) 17 m s^{-1} at the time in which the TC firstly goes into the influential area on Korea. The eight TCs which did not enter the influential area but reported in the White Book are classified based on the maximum wind speeds at the time of their closest approach to the Korean coastline.

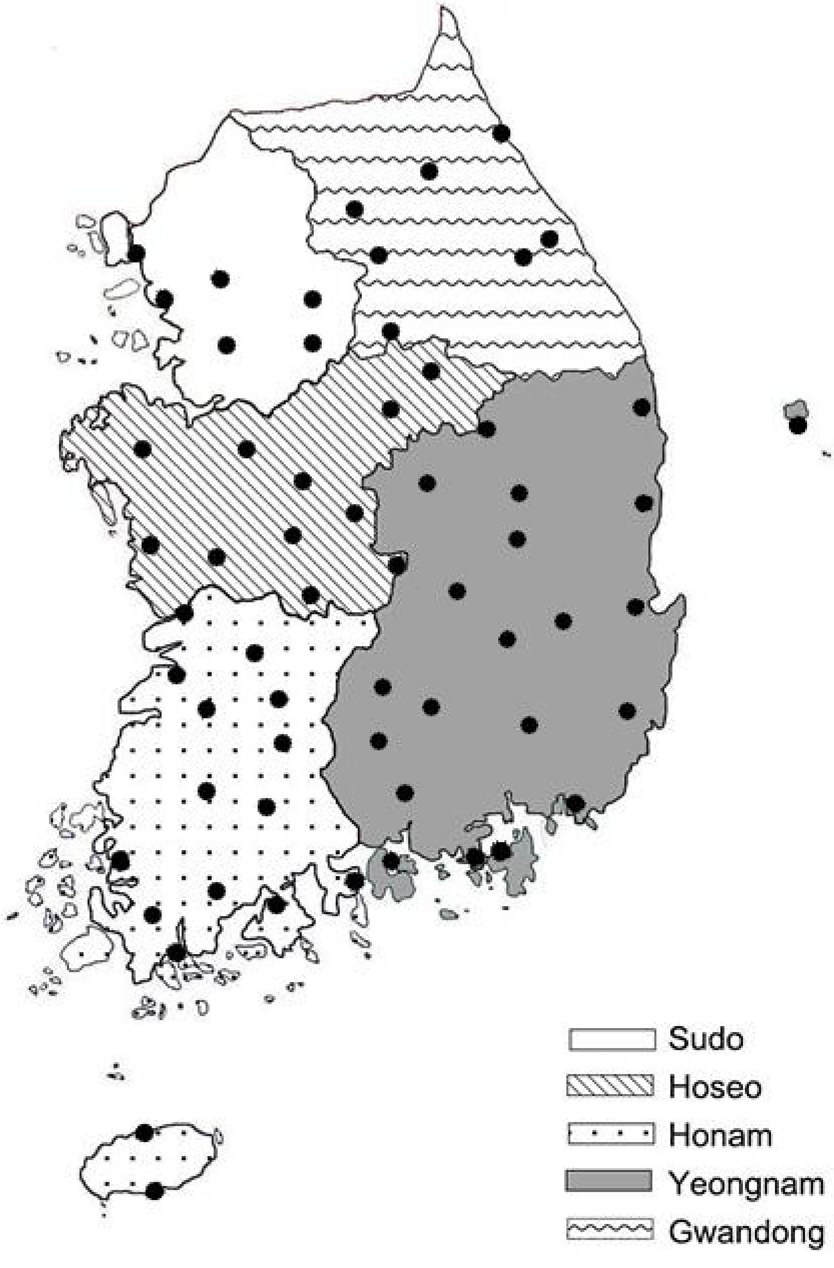

Figure 1. Five classified areas of the Republic of Korea. Dots indicate locations of 60 weather stations recording wind and rainfall.

2.3 Statistical analysis

The probability distributions of all three types of damages represent strongly skewed distributions toward zero. That is, the damage distributions do not follow the normal distribution so that typical parametric methods to examine statistical significances like the Student's t-test cannot be applied (Mankiewicz 2004). Hence, all of the significance tests are done by non-parametric ways, which do not assume any probability distributions. The Mann-Whitney U test is used to test significances of differences between two samples (Hollander and Wolfe 1999). The Mann-Whitney U test is as follows.

$$U_m = n_1 n_2 + \frac{n_m(n_m + 1)}{2} - R_m$$

$$U = \min(U_1, U_2), \quad (2)$$

where n_1 and n_2 are the sample sizes of sample 1 and 2, respectively. R_m is the rank sum of sample m (i.e. 1 or 2). U value represented by (2) is compared with a given critical value of U (U_{crit}) at a given significance level (e.g., 0.05) in the Mann-Whitney Table. If $U < U_{crit}$, the difference is significant. On the other hand, the Spearman's rank correlation analysis is utilized to get correlation coefficients between damages and intensity parameters (Daniel 1990). The Spearman's rank correlation analysis is as follows.

$$r = 1 - {6 \sum d_i^2} \Big/ {n(n^2 - 1)} \quad (3)$$

where d_i is the difference between the ranks of corresponding values of each sample. n is the sample size. The statistical significance of the Spearman's correlation can be determined by the Spearman's rank correlation table.

Kruskal-Wallis test, in other words one-way Analysis of variance (ANOVA) on ranks, is used to determine if there are statistically significant differences of a variable between track-clusters.

In total, 85 STCs are sorted out to be influential in South Korea over the period from 1979 to 2010. The 85 influential TCs are then clustered according to their track patterns by using the fuzzy c-means clustering method (FCM). The FCM is widely used for classifying the widespread data with amorphous boundaries. Some previous studies have shown this method to be effective for clustering TC track patterns (e.g. Kim et al. 2011). We have clustered the track patterns, not for the whole tracks from genesis to disappearance, but for the part of the tracks in the domain of 28°N–40°N and 120°E–138°E so that we can divide tracks focusing on the paths near South Korea, whose national TC risk distribution is examined with these clustered track patterns. The TCs are clustered into four. The optimum cluster number was decided by five validity measures - partition coefficient, partition index, separation index, Xie and Beni index and Dunn index (Kim et al. 2011), and the number of four appeared to be the optimum in our case. The indexes have still pointed at four as the optimum number of clusters even we add slight differences on TC lists such as different time window (e.g. 1979 – 2014) or different clustering domain (e.g. 5-degree area from the Korean Peninsula coastline).

We further introduced the decision tree analysis to decompose the relationships among risk elements. The decision tree method, a multi-variable technique, allowed us to explain, describe, classify, or predict a target as a result of the combined effects of multiple input variables beyond a one-cause and one-effect relationship. Compared to other multi-variable techniques, the decision tree method has its own advantage in that it is easy to use, robust with a variety of data, and most of all, intuitively interpretable. It helps decision analysts to structure the decision process in a graphical sequence.

Among several famous decision tree algorithms, this study applied See5/C5.0 as a classification method for TC risk materialization. The See5/C5.0 algorithm is an improved version of C4.5 (*34*) in terms of accuracy, speed, and computer memory consumption. Also, C4.5 algorithm is advantageous because it can accommodate all of the class, binary, and continuous variable types that we needed (See Table 1). See5/C5.0 calculates the information gain at each node based on the entropy concept in order to choose the most efficient attribute for splitting the training samples into two branches.

To prevent over-fitting, we introduced pruning and cross-validation. First, we required that branches have a sample size of at least five. The number five was determined through retrospective pruning process. Second, a ten-fold cross-validation was conducted, and we checked that the decision tree results (e.g., model accuracy, tree size, or attribute usage) are stable and consistent given the ten different cross-validation sets.

Table 1. Description of decision tree model variables – the diagnosis (target) variable and attribute (input) variables. Use column indicates the decision trees that use each variable; best-track based model (BT) and in-situ observation based model (IS) for strong TCs and rule-based classifier model (RB) for weakened TCs.

	Variables	Use	Description	Category
Diagnosis	**Damage**	BT, IS, RB	If the TC has recorded any property loss to the province	Yes or No
ributes	**Province**	BT, IS, RB	Five provinces in South Korea. Two North-western, one south-western, one north-eastern and one south-eastern provinces	Gyeong-gi, Gang-won, Chung-cheong, Jolla and Gyeong-sang
	Track cluster	BT	Track pattern clusters divided in to four through fuzzy c-means clustering method.	East-short, East-long, West-long, or West-short
	BT radius	BT	The longest radius of 30 knot winds or greater of the TC making landfall to South Korea from RSMC best-track (BT) data	Continuous
	BT maxwind	BT	Maximum sustained wind speed of the TC making landfall to South Korea from BT data	Continuous
	BT pressure	BT	Central pressure of the TC making landfall to South Korea from BT data	Continuous
	Station maxwind	IS, RB	The maximum value among daily maximum sustained wind speed (10 minutes) from all stations in the province and all daily data in the TC influence period	Continuous
	Station rainfall	IS, RB	The maximum value among daily accumulated rainfall data from all stations in the province and all daily data in the TC influence period	Continuous
	TC status	RB	The status of the TC when it is at 1-degree distance from South Korea	Extra-tropical transition, Tropical depression, Unknown, No approach unto 1-degree

3. Highlighting weak TC risk compared to strong TC risk

3.1 Damage comparison between Weak TC and Strong TC

In 1979–2010, 49 WTCs and 85 STCs have affected Korea. For each year the country almost always has wet seasons, in which steady heavy rainfall occurs (the *Changma rainy season*) from June to early August (Ho et al. 2003; Ha et al. 2005). Hence, TCs influencing Korea are often coincided with the Changma and its damages can be overestimated by combined effects of TC and Changma. 16 WTCs and 12 STCs have damage periods longer than five days, and the cases possibly accompanied with the Changma. On the other hand, two STCs' damage period is shorter than five days, but they are successive TC cases having indistinguishable damage records. Thus, total 16 WTCs and 14 STCs are screened so that 33 WTCs and 71 STCs are included in all analyses hereafter. Not surprisingly, the TC cases excluded from the analysis generally caused enormous damages; the median of each damage type by the excluded TCs is 1,935 homelessness, 25 casualties, and 0.14-trillion-KRW property losses. According to the TCs analyzed, approximately 45% of the WTCs caused damage somewhere in the country. On the other hand, approximately 70% of STCs incurred damage, indicating that there is more likelihood of damage occurrence by STCs than WTCs. All WTCs and STCs are listed in Table 2.

As discussed above, the skewed probability distributions particularly come from a lot of zeros, indicating that there are many non-damaged cases. About 55% and 30% of WTCs and STCs that have affected Korea do not have any records on losses in the NDIC dataset, respectively. It is necessary to check if the zeros are actual signals or just due to missing of the NDIC. Thus, the wind and rainfall intensities for damaged and non-damaged cases are calculated and compared to each other (Figure 2). For both WTCs and STCs, wind and rainfall intensities of the non-damaged cases are significantly weaker than those of the damaged cases. In other words, the intensities for the non-damaged cases are not strong enough to cause any damages. Meanwhile, the average wind in the damaged cases of STCs is significantly larger than that of WTCs while average rainfalls for damaged cases of STCs and WTCs are similar each other.

The discrepancy of wind intensities between WTCs and STCs is because STCs have inherently stronger wind due to their definitions (maximum wind speed of the best-track data ≥ 17 m s^{-1}). In contrast, this discrepancy in wind intensities is not found for non-damaged cases. The mean wind and rainfall intensities of non-damaged cases, about 10 m s^{-1} and 39 mm, respectively, are almost same between WTCs' and STCs', meaning that the values 10 m s^{-1} and 39 mm can be regarded as the reference values at which damages do not occur. This implies that there may be critical intensities somewhere near the reference values of the non-damaged cases, to determine if a TC including both WTC and STC is non-damaged or damaged.

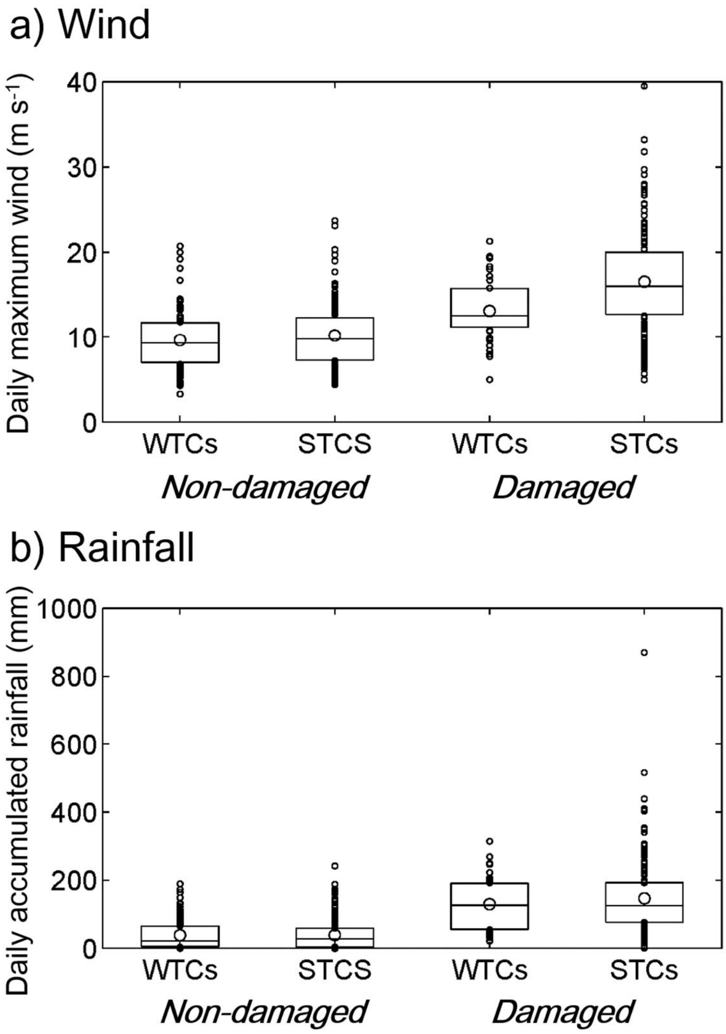

Figure 2. Boxplots of a near-surface wind and b rainfall caused by weak tropical cyclones (WTCs) and strong tropical cyclones (STCs), classified further into the damaged and non-damaged. Boxes are for quantiles. Circles on the boxes indicate average values. Dots shown outside of the boxes are all the data whose values are smaller than 1-quantile or larger than 3-quantile.

Table 2. List of weak tropical cyclones (WTCs) and strong tropical cyclones (STCs) affecting the Republic of Korea. Parentheses indicate the years of occurrence. Bold italic represent the TCs damaged longer than 5 days or affecting the country with successive TCs.

Weak TCs					Strong TCs							
Noname (1979)	***Ida (1980)***	Norris (1980)	Ike (1981)	Ogden (1981)	Irving (1979)	Judy (1979)	Orchid (1980)	June (1981)	***Agnes (1981)***	Bess (1982)	Cecil (1982)	Ellis (1982)
Clara (1981)	***Noname (1983)***	***Alex (1984)***	Gerald (1984)	Noname (1984)	Ken (1982)	Forrest (1983)	Ed (1984)	Holly (1984)	Jeff (1985)	Kit (1985)	***Lee (1985)***	***Odessa (1985)***
June (1984)	***Hal (1985)***	***Noname (1985)***	Abby (1986)	Alex (1987)	***Pat (1985)***	Brenda (1985)	Nancy (1986)	Vera (1986)	Thelma (1987)	Dinah (1987)	Ellis (1989)	Judy (1989)
Noname (1988)	Noname (1988)	Vera (1989)	***Ofelia (1990)***	***Noname (1990)***	Robyn (1990)	Zola (1990)	Flo (1990)	Caitlin (1991)	Gladys (1991)	Noname (1991)	Kinna (1991)	Mireille (1991)
Winona (1990)	Abe (1990)	Polly (1992)	Russ (1994)	Fred (1994)	Irving (1992)	Janis (1992)	Kent (1992)	Ted (1992)	Nathan (1993)	Ofelia (1993)	Percy (1993)	Robyn (1993)
Janis (1995)	***Noname (1999)***	Rachel (1999)	Noname (1999)	Sam (1999)	Yancy (1993)	Walt (1994)	Brendan (1994)	Doug (1994)	Ellie (1994)	Seth (1994)	Faye (1995)	Ryan (1995)
Wendy (1999)	***Ann (1999)***	Dan (1999)	Kai-tak (2000)	***Bilis (2000)***	Eve (1996)	Kirk (1996)	Peter (1997)	Rosie (1997)	Tina (1997)	Oliwa (1997)	Yanni (1998)	Zeb (1998)
Chebi (2001)	Noname (2001)	Nakri (2002)	***Mindulle (2004)***	***Khanun (2005)***	***Neil (1999)***	***Olga (1999)***	Paul (1999)	**Bart (1999)**	Bolaven (2000)	***Prapiroon (2000)***	Saomai (2000)	Rammasun (2002)
Chanchu (2006)	***Pabuk (2007)***	Wipha (2007)	Krosa (2007)	Kalmaegi (2008)	***Fengshen (2002)***	***Fung-wong (2002)***	Rusa (2002)	Linfa (2003)	Souldelor (2003)	***Etau (2003)***	Maemi (2003)	Namtheun (2004)
Noname (2008)	Linfa (2009)	Morakot (2009)	Meranti (2010)		Megi (2004)	Chaba (2004)	Songda (2004)	***Nabi (2005)***	***Ewiniar (2006)***	Wukong (2006)	Shanshan (2006)	Man-yi (2007)
					Usagi (2007)	***Nari (2007)***	Dianmu (2010)	Kompasu (2010)	Malou (2010)			

Spatial distributions of the damages are different between WTCs and STCs (Figure 3). WTCs generally bring more damages in the northwestern Korea, i.e. Sudo and Hoseo, than other provinces while STCs incur more damages in the southern and southeastern regions, i.e. Honam, Yeongnam and Gwandong, than other provinces. In terms of national aggregate damages, STCs are more harmful than WTCs (not shown), particularly in the Honam, the Yeongnam, and the Gwandong regions, losses by STCs are significantly larger than those by WTCs (Figure 3). However, in the Sudo and the Hoseo, the damages by STCs and WTCs are comparable and not significantly different from each other. This implies that WTC can bring extreme phenomena as damaging as STCs in the northwestern Korea despite its relatively weak maximum wind speeds recorded in the IBTrACS dataset. This comparability is important because about half of the total population and wealth of Korea are concentrated in the Sudo region in which the capital city, Seoul, is located.

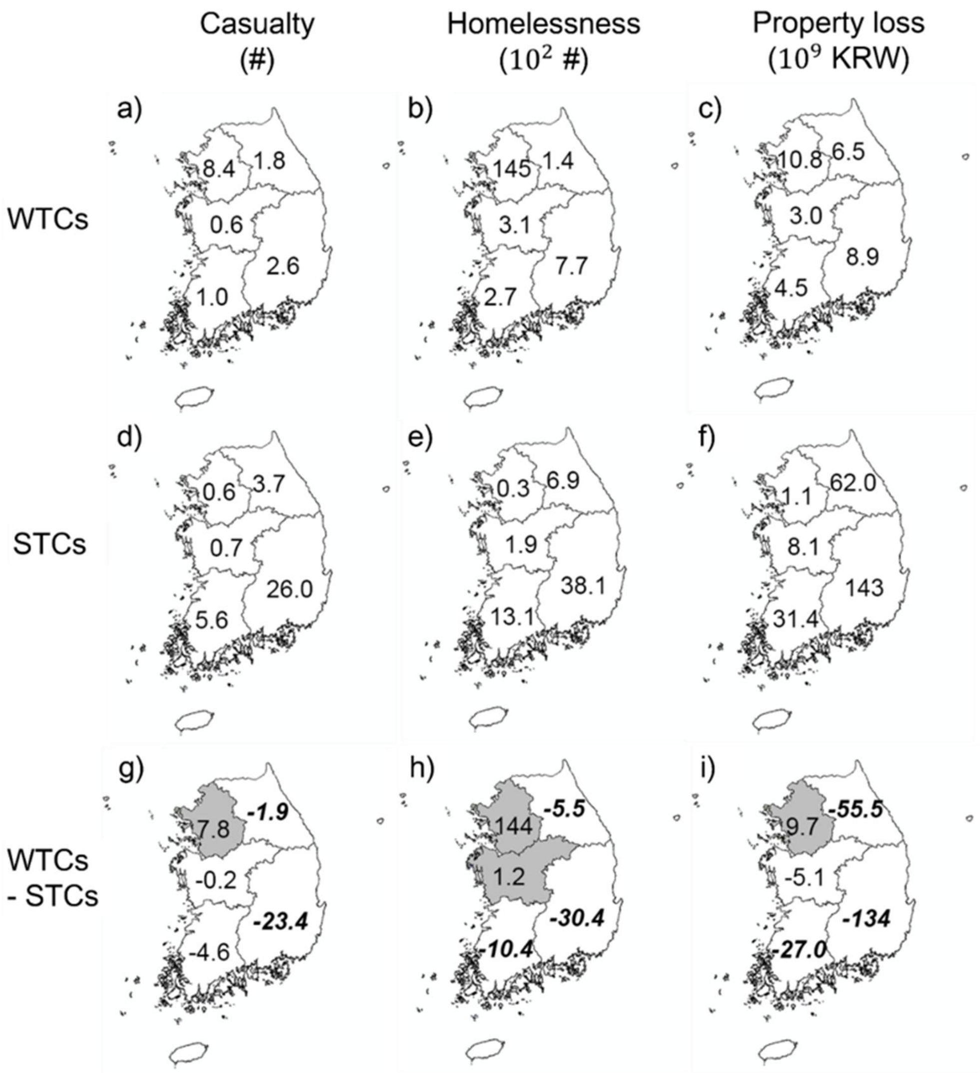

Figure 3. Averages and differences in the number of homelessness, casualties, and property loss caused by weak tropical cyclones (WTCs) and strong tropical cyclones (STCs) for the five areas. Shading indicates that the WTC-induced value is larger than the STC one. Bold italic indicates that the difference is statistically significant at the 90 % confidence level based on the Mann–Whitney U test.

3.2 Climate environment comparison between weak TC and Strong TC

The geographical variations in the socio-economic losses caused by WTCs and STCs can be well explained by that in the near-surface wind speed and rainfall by WTCs and STCs (Figures 3 and 4). WTCs can bring strong winds and torrential rainfall to the Sudo and the Hoseo provinces as vigorous as STCs, representing about 9 m s^{-1} and 50 mm. Hence, the similar amount of losses can be occurred by WTCs and STCs over the northwestern Korea. Meanwhile, compared to WTCs, more violent wind and heavy rainfall of STCs in the southeastern Korea are responsible for larger STC-induced socioeconomic losses therein. The comparability in wind and rainfall intensities between WTCs and STCs over the northwest Korea can be accounted by their different mean tracks. As shown in Figure 1, the coastlines of Sudo and Hoseo are only open to the West Sea of Korea while those of Honam, Yeongnam, and Gwandong are adjacent to the South and East Seas of Korea. Because STCs generally pass by the southeastern coast of Korea (Figure 5), it is hard for STCs to directly affect the West Sea. This is natural when considering the counter-clockwise circulation of TC; TC-induced wind may become weak after penetrating through the Korean peninsula due to surface friction of land. In other words, the western coast of Korea is located in downwind area so that decelerated wind only get there. In contrast, the southeastern coast is located in upwind area so that wind can reach there directly from the ocean surface without weakening by land friction. Thus, the northwestern Korea can be less threatened by STCs although STCs are stronger systems according to the IBTrACS dataset. Otherwise, since the centers of WTCs generally move closer to the northwestern coast than STCs (Figure 5), WTCs can affect the northwest part of the country as much as STCs despite of their weakness based on the IBTrACS dataset. For the rainfall distribution that appears to be more intense over the south-to-east coastlines particularly in case of STCs (Figure 4), the existence of high mountains along south and east coasts may be responsible related with orographic updraft (Park et al. 2006). On the other hand, the average wind and rainfall intensities for non-damaged TCs over the Sudo are about 7 m s^{-1} and 27 mm, respectively, which are smaller than those of the other provinces (not shown), implying that exposure and/or vulnerability of the Sudo to TCs may be higher than the other provinces because of the largest population and wealth in the Sudo.

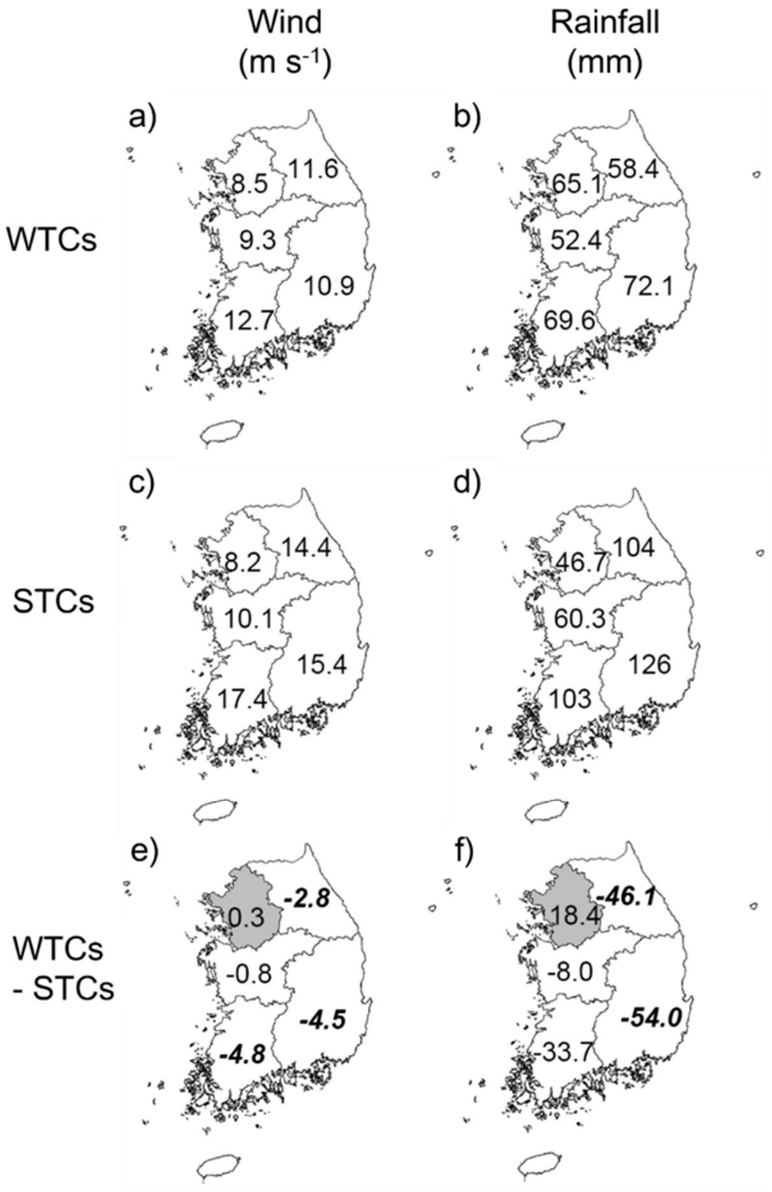

Figure 4. Averages and differences in near-surface wind and rainfall caused by weak tropical cyclones (WTCs) and strong tropical cyclones (STCs) for the five areas. Shading indicates the WTC-induced value is larger than the STC one. Bold italic indicates that the difference is statistically significant at the 90 %confidence level based on the Mann–Whitney U test

The analyses above show that WTCs are as influential as STCs at least in the western part of the country. Here, in order to confirm if both wind and rainfall are still major factors to drive damages in case of WTC, the correlation coefficients are calculated between each intensity parameter (i.e. wind and rainfall) and each damage type (i.e. homelessness, casualties, and property losses). The result suggests that both wind and rainfall of WTCs are still significant explanatory variables for all types of damages even though WTCs are weakened systems according to the IBTrACS dataset (Table 3). All of WTCs' correlation coefficients are statistically significant, just little bit smaller by 0.15 compared to STCs' (Table 3). This implies that WTCs can induce simultaneous multiple severe phenomena interrelated with wind and rainfall (e.g., gust, downpour, storm surge, and wind wave) as much as STCs. On the other hand, rainfall is more closely correlated with the damages than winds; all of the correlation coefficients of rainfall are higher by about 0.1 than those of wind (Table 3). This result is consistent with Park et al. (2015), who suggested rainfall is the most influential factor to determine TC-induced damage amount among the other intensity factors including wind and affected number of stations over Korea. However, this does not mean that wind-related damages are small; rather, both winds and rainfall cause serious damages in Korea.

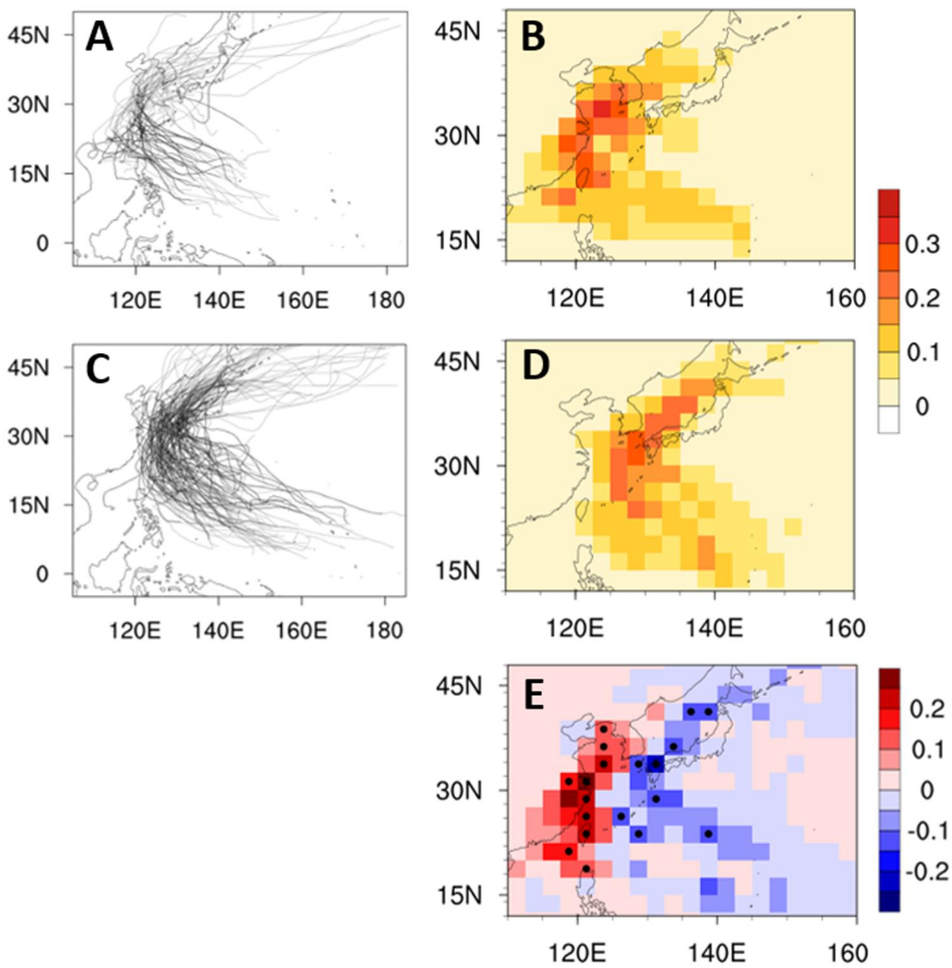

Figure 5. Track comparison between weak tropical cyclones (WTCs) and strong tropical cyclones (STCs). (A) WTC tracks, (B) average track density of one WTC, (C) STC tracks, (D) average track density of one STC, (E) track density differnces (WTC minus STC). Track density is calculated with the grid of 2.5°, and dots indicate 95% significant differences.

Table 3. Correlation coefficients between damages (the number of people who lost their homes (homelessness), casualties, and property loss) and wind, and between damages and rainfall, caused by weak tropical cyclones (WTCs) and strong tropical cyclones (STCs). Bold italic indicates that the correlation is statistically significant at the 90% confidence level.

		Wind	Rainfall
WTCs	Casualty	***0.34***	***0.41***
	Homelessness	***0.41***	***0.51***
	Property loss	***0.41***	***0.58***
STCs	Casualty	***0.50***	***0.57***
	Homelessness	***0.56***	***0.68***
	Property loss	***0.62***	***0.71***

Figure 6 shows the time series of STCs and WTCs that made landfall to South Korea. When we conduct the correlation analysis between the two time series. It appears that there is no significant correlation between the two, neither positive nor negative. To look more closely at the differences of the WTC tracks and STC tracks, we analyzed the large-scale steering flow (Figure 7), and its genesis and intensity development (Figure 8). First, for comparing the large-scale circulation, we use the seasonal composite method. For each of STC and WTC, we select the years having anomalously high number of landfall cases (above 1.5 times of standard deviation from mean). Then for those seven years for the two groups, we make composite plots. TC track is 80-90% determined by environmental steering flow. In this case, the subtropical high anomaly well matches with the steering flow, and it explains why WTC tracks are deviated to the west comparing to STC tracks. Also, WTCs experience Chinese mainland and it becomes weakened. So, the track difference further explains the landfall intensity differences.

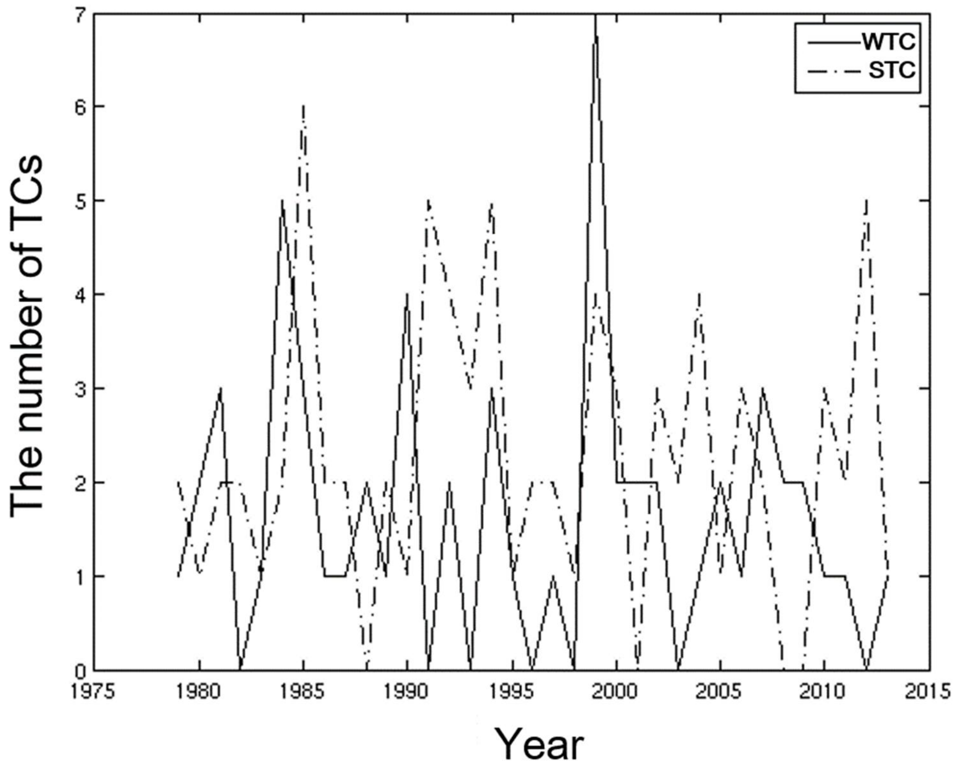

Figure 6. Time series of the number of WTC and STC landfall cases over South Korea. The correlation between the two is 0.06, which has a p-value larger than 0.7.

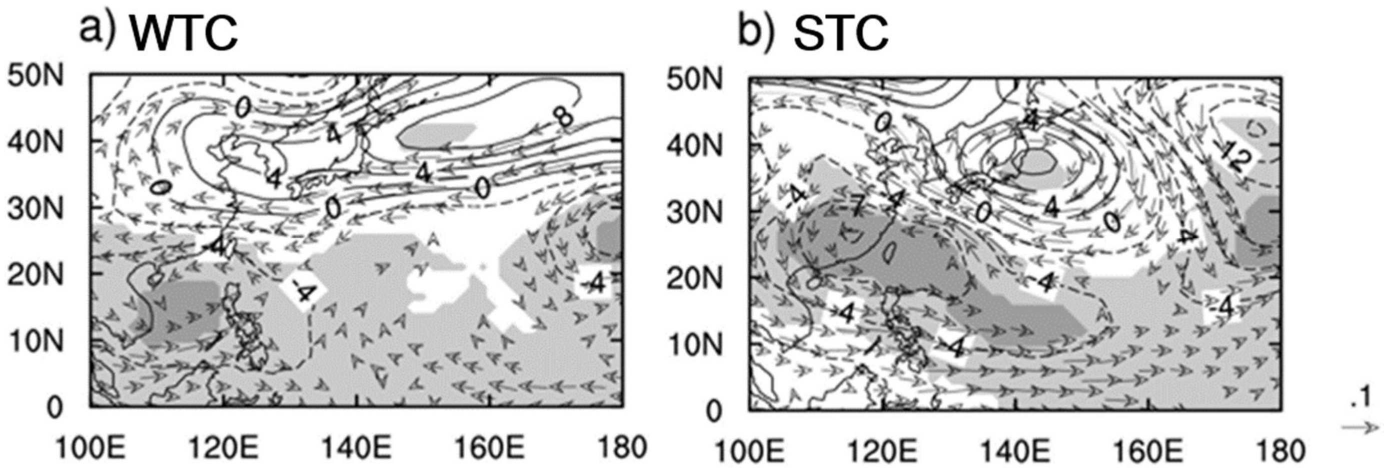

Figure 7. 500hPa geopotential height anomaly and steering flow (1000 to 200hPa, pressure weight mean) for a) WTC-frequent years and b) STC-frequent years. Light (dark) shading indicates significant at 90% (95%) confidence level. Steering flow vector is drawn for only the significantly different grids.

Furthermore, as shown in Figure 5, the genesis location is also significantly different between the strong and weakened groups. The genesis location of WTC is (18N, 130E) and that of STC is (18N, 139E), having significant longitudinal difference but no latitudinal difference. The more west-tilted genesis location can be a factor that WTC makes landfall to China without the help of large-scale circulation difference. Because of the earlier landfall of WTCs, it turned out that they have weaker lifetime maximum intensity (LMI) comparing to STCs (31m s^{-1} comparing to 41 m s^{-1}). The average LMI location of the WTCs and STCs were (22N, 123E) and (24N, 131E) respectively (figure not shown). LMI has a significant positive correlation with development time, and the development time is also shorter among WTCs, which implies that WTCs experience insufficient time to develop its intensity before landfall and get weaker by friction of the land. In addition, the track can is regulated by beta-effect. Given genesis location, 10-20% of the translation velocity is determined by beta-effect. Thus, beta-effect can be a factor that makes a difference too.

4. Priority structure of TC risk realization process

By comparing the risk of WTCs and STCs, we suggested that even though WTCs have weaker maximum winds than STCs according to the IBTrACS dataset, they cause similar amounts of socioeconomic damages—casualties, homelessness, and property losses—in the northwestern Korea, the most densely populated and richest area in the country. Moreover, in WTCs, both wind and rainfall are still significant factors to determine damages so that WTCs can lead various wind- and rainfall-induced extreme phenomena (e.g., gust, downpour, storm surge, and wind wave) just like STCs. In this section, I would like to compare the damaged and non-damaged cases for WTCs and STCs, and find out the most distinctive difference between the two, which in turn can be the primary factor in deciding the damage occurrence of TCs.

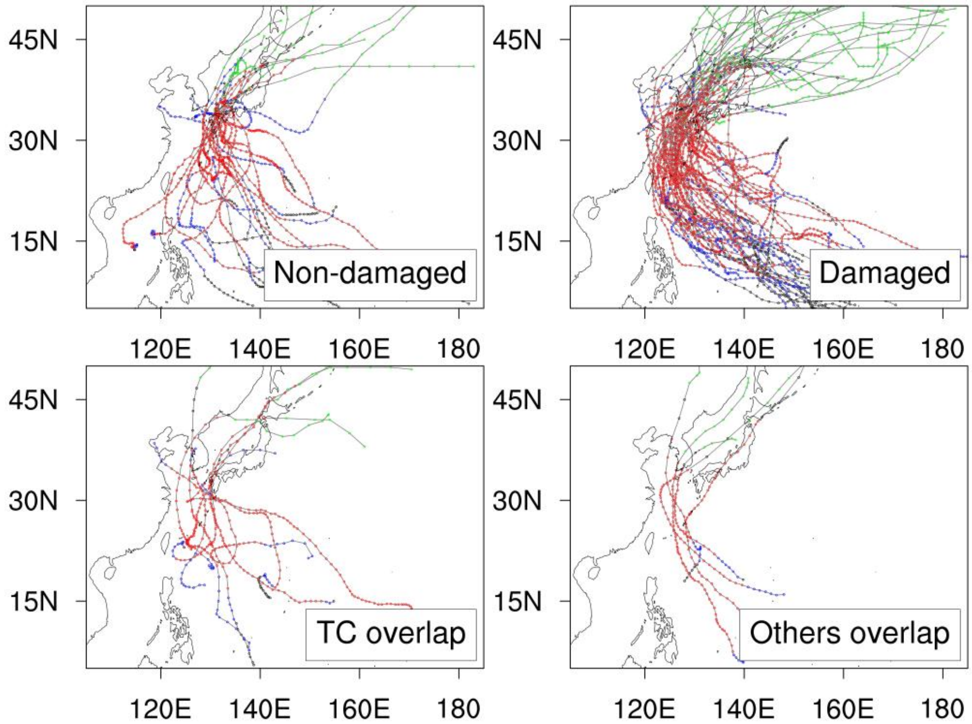

Figure 8. Comparison of the lifetime intensity and track for damaged and non-damaged cases of STCs. Red points indicate TS, blue is for TD, green for ET, and black is for unknown (unclassified).

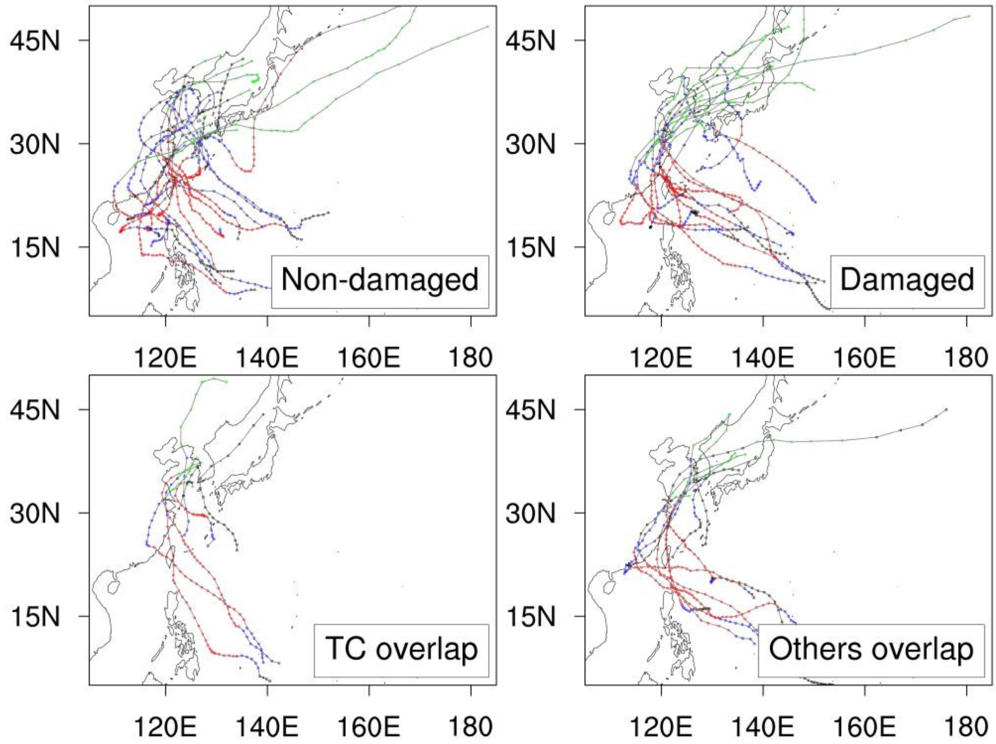

Figure 9. Same as Figure 8 for WTCs.

From Figure 8, we can say the almost all of non-damaged STCs made landfall on the eastside of South Korea. There are three STCs that went to the west but the non-damaged west-approaching STCs have rather very short track path, or propagated in a far distance from the coastline. This result implies that the track pattern could be a decisive factor in deciding STC damage occurrence. From Figure 9, unlike STCs, the damaged and non-damaged WTCs do not show very different track pattern. Rather, the color, indicating the intensity scale of the TC looks different. Comparing to non-damaged WTCs, there are much more green circles around South Korea for damaged WTCs. This means that the ratio of TCs who experience extra-tropical transition (ET) when making landfall to South Korea is higher in damaged groups. Thus, we hypothesized that whether a TC experiences ET or not is the most decisive factor in deciding WTC damage occurrence. In following sections of 4.1 and 4.2, we investigate if this hypothesis is true.

4.1 Extra-tropical transition in weak TC risk realization process

It is well known that a TC could be re-intensified after ET by previous studies, and this can be the reason why ET becomes a decisive factor for WTC risk. About 45 % of TCs undergo the extra-tropical transition often characterized by fast translational speed and rapid re-intensification (Jone et al. 2003). The re-intensified WTCs may accompany multiple severe phenomena, such as gust, downpour, storm surge, and wind wave. I have analyzed how WTC damage occurrence over South Korea is associated with ET. I checked a simple statistical indices of this relationship, called association analysis. I conducted an association analysis for two association rule "If a WTC experienced ET, then it damaged South Korea (ET -> damage)" and "If a WTC damaged South Korea, the WTC is under ET". Note that association analysis is for concurrence, not for correlation.

Table 4. Association analysis result confidence values for extra-tropical transition (ET) as a TC approaching to Korean coastline.

Confidence	ET at 7°	ET at 5°	ET at 3°	ET at 1°
If ET, then damaged	0.57	0.67	0.78	*0.9*
If damaged, then ET	0.27	0.4	0.47	0.6

In Table 4, the confidence of the two association rules is presented. Generally when confidence is higher than 0.5, the rule is regarded meaningful. For ET -> Damage rule, the confidence can be calculated as below, and the value will represent the probability of damage occurrence when ET occurs.

$$\text{Confidence} = \frac{\#\ of\ cases\ with\ ET\ and\ Damaged}{\#\ of\ cases\ with\ ET}$$

As a TC approaches closer to South Korea, the confidence of the rule is getting higher (Table 4). This means ET in closer distance is a better indicator for risk estimation rather than a far distance. There are in total 31 WTCs excluding 18 unavailable (overlapped) damage cases. Then, 15 WTCs made an effective damage over South Korea. On the other hand, when we consider ET at 1-degree distance from the coasts, in total 10 among 31 WTCs was marked as ET, and among them, 9 WTCs were damaged ones. In turn, we can improve the predictability two (=0.9/0.45) times more than random chance of damage occurrence. Thus, we can say that ET is certainly associated with damage occurrence.

Table 5. Rule-set model for Weak TC damage occurrence.

Rule	Attribute variable		Diagnosis variable	Number of cases	Hit rate	Lift
	TC status	Station precipitation				
1	ET	>31mm/day	Damaged	43	63%	2.3
2	Unknown	≤44.7mm/day	Damaged	23	52%	1.9
3		≤31mm/day	Undamaged	65	98%	1.3
4	No approach to 1-degree		Undamaged	60	95%	1.3
5	Unknown	>44.7mm/day	Undamaged	12	10%	1.3
6	TD		Undamaged	20	85%	1.1

From rule-set model, it is verified that consideration of ET is the most effective way to determine damage occurrence by WTCs. The rules are presented in Table 5. The rules are ordered from the large lift to the small lift. Lift means how much probability gain we can get from using this rule comparing to the random chance. For example, because of rule 1, the chance to diagnose damage case accurately, becomes 2.3 times more than without having the rule.

When an attribute is the most-related variable to target variable, the attribute should be used most frequently by a decision tree model classification. In this sense, the relative importance of the attributes are offered in terms of the usage rate by See5/C5.0 algorithm. In the rule-based model, TC status at 1-degree occupies the most usage, 96%. Then, station precipitation follows as 82%, neither station wind nor province variables are used for the model as an effective classifier that can divide damaged versus undamaged cases. The most interesting point I got from this analysis is that the TC was attribute was the mostly used for classifying damage occurrence even more than station precipitation, which is highly emphasized in Section 3.2. In Table 6, the overall accuracy of rule-based model is presented.

Table 6. Statistical measures of the performance of rule-based classifier for Weak TCs.

Validation		Observation		
		Damaged	Undamaged	Sum of forecast
Forecast	Damaged	39	27	66
	Undamaged	6	93	99
Sum of observation		45	120	165
Overall accuracy			80.0%	
Hit rate			86.7%	
False alarm rate			22.5%	

4.2 Track pattern in strong TC risk realization process

Now, to test out the relationship of track and TC risk we clustered the tracks and then compared its risk elements. 85 Korea influenced TCs for the period 1979 - 2010 are clustered into four with FCM, and the list of them is given in Table 5. The number of TCs are 22, 31, 16, and 16 each from Cluster 1 to Cluster 4. Four clusters of TC track patterns can be characterized by 1) east-short, 2) east-long, 3) west-long, and 4) west-short types based on the length and position of TC tracks around the Korean Peninsula (Figure 10).

Each track pattern cluster's temporal trend and monthly distribution is examined. Although there were some difference in trend but, for lack of the number of cases, any of the trends have not a significance. All the TCs regardless of clusters are concentrated in the month from June to September. TC genesis locations of the clusters showed significant differences in longitudes but not in latitudes. This means that the initial locations of TCs are relevant in their track patterns around the Korean Peninsula in east-west directions, but whether the TCs maintain their strength to the high latitudes are, in climatological point of view, irrelevant to the genesis location.

Hazard parameters derived from best-track data shows TC intensity and size are highly dependent on TC track patterns (Figure 11 (a) - (c)). These parameters are the values of the TCs when they are entering into 3 degree line from the Korean Peninsula (or approached to the nearest from South Korea for the

TCs not entering unto 3 degree distance). All the parameters appeared to have significantly different values among clusters (Kruskal-wallis test, 99% confidence level). Maximum wind speed and central pressure, which is well-known to be highly correlated with each other, indicate the intensity of the TC. Both of them shows that the longer track clusters (Cluster 2 and 3) are stronger than the shorter track clusters (Cluster 1 and 4). Cluster 2 is the strongest. Cluster 3 and 4 are similar but Cluster 3 is stronger in terms of maximum wind speed. The shortest track, Cluster 1 appears to be the weakest. It is natural that we observe the longer tracks generally have the stronger intensities. When we regard the TC intensity at 3-degree approaching as an initial value, with the same mid-latitude condition such as friction, shear, or energy source, the TCs having higher initial values will maintain their systems as tropical cyclone. In this sense, the intensity can be interpreted as the durability of the TC as well. However, we found that the background condition (geopotential height, sea surface temperature (SST), and vertical wind shear (VWS)) are also different for the track clusters. SST around the Korean Peninsula in longer cluster cases (Cluster 2 and 3) is significantly higher than that in shorter cluster cases (Cluster 1 and 4). Therefore, it seems that the internal strength of TC and the background condition together decide the length of TC track. Interestingly, the storm size distribution is very analogous to maximum wind speed distribution (Figure 11 (a) and (c)). The size is not necessarily correlated with TC intensity (Weatherford and Gray, 1987), but for influential TCs of Korea we see they are positively correlated.

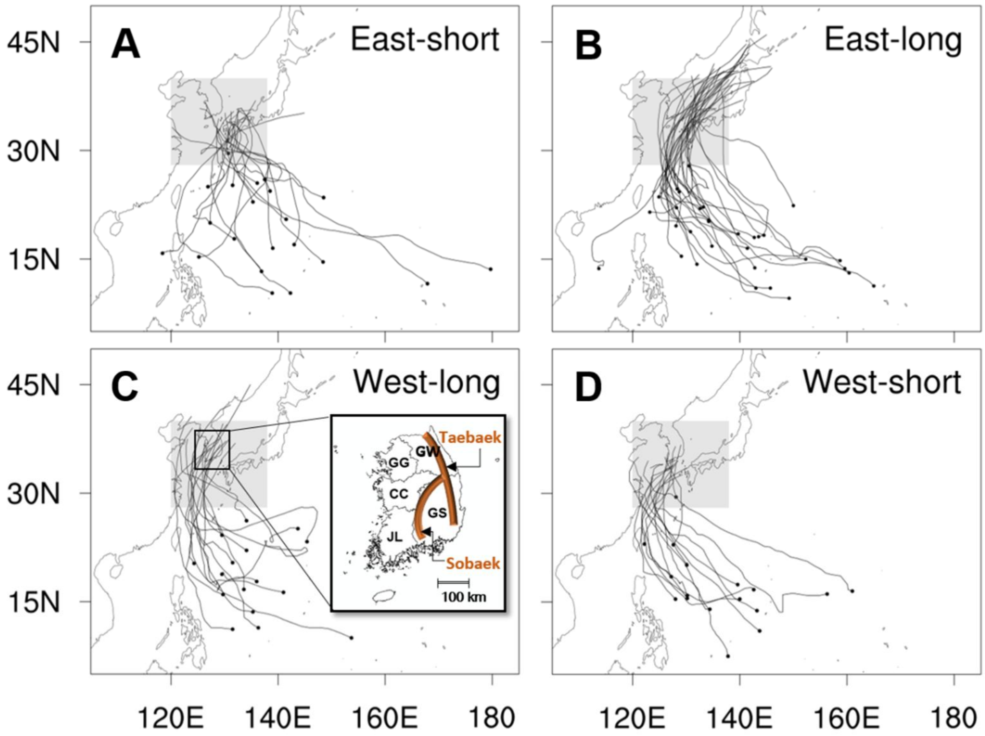

Figure 10. Four clusters of tropical cyclone tracks that made landfall to South Korea for 1979–2010. Box shaded in grey, covering 28N – 40N and 120E – 138E, indicates the clustering domain for the fuzzy c-means clustering method. A map of the five aggregated provinces of South Korea is displayed in **(C)**: Gyeong-gi (GG), Chung-cheong (CC), Jolla (JL), Gang-won (GW), and Gyeong-sang (GS). The Taebaek and Sobaek mountains are drawn with bold lines on the province map.

Table 7. The list of the clustered tropical cyclones that made landfall to South Korea for 1979 – 2010.

Year	Cluster 1	Cluster 2	Cluster 3	Cluster 4
1979			IRVING	JUDY
1980		ORCHID		JUNE
1981				AGNES
1982	KEN	BESS, ELLIS	CECIL	
1983				FORREST
1984	ED	HOLLY		
1985	ODESSA	PAT	JEFF, KIT,LEE	BRENDA
1986			VERA	NANCY
1987		DINAH	THELMA	
1988				
1989	ELLIS, JUDY			
1990	FLO	ZOLA		ROBYN
1991	GLADYS, noname	CAITLIN, KINNA, MIREILLE		
1992	IRVING, KENT	JANIS	TED	
1993	NATHAN, OFELIA	PERCY, ROBYN, YANCY		
1994	WALT	BRENDAN	ELLIE, SETH	DOUG
1995		FAYE, RYAN		
1996	EVE	KIRK		
1997	ROSIE, OLIWA	PETER	TINA	
1998	ZEB			YANNI
1999	PAUL	BART	OLGA	NEIL, ANN
2000	BOLAVEN		PRAPIROON	SAOMAI
2001				
2002			RAMMASUN	RUSA
2003	LINFA	MAEMI	SOUDELOR	
2004		NAMTHEUN, MEGI, CHABA, SONGDA		MINDULLE
2005		NABI		KHANUN
2006	WUKONG	SHANSHAN		EWINIAR
2007	MAN-YI	USAGI	NARI	
2008				
2009				
2010		DIANMU, KOMPASU, MALOU		
Number of TCs	22	31	16	16

Hazard parameters derived from best-track data shows TC intensity and size are highly dependent on TC track patterns (Figure 11 (a) - (c)). These parameters are the values of the TCs when they are entering into 3 degree line from the Korean Peninsula (or approached to the nearest from South Korea for the TCs not entering unto 3 degree distance). All the parameters appeared to have significantly different values among clusters (Kruskal-wallis test, 99% confidence level). Maximum wind speed and central pressure, which is well-known to be highly correlated with each other, indicate the intensity of the TC. Both of them shows that the longer track clusters (Cluster 2 and 3) are stronger than the shorter track clusters (Cluster 1 and 4). Cluster 2 is the strongest. Cluster 3 and 4 are similar but Cluster 3 is stronger in terms of maximum wind speed. The shortest track, Cluster 1 appears to be the weakest. It is natural that we observe the longer tracks generally have the stronger intensities. When we regard the TC intensity at 3-degree approaching as an initial value, with the same midlatitude condition such as friction, shear, or energy source, the TCs having higher initial values will maintain their systems as tropical cyclone. In this sense, the intensity can be interpreted as the durability of the TC as well. However, we found that the background condition (geopotential height, sea surface temperature (SST), and vertical wind shear (VWS)) are also different for the track clusters. SST around the Korean Peninsula in longer cluster cases (Cluster 2 and 3) is significantly higher than that in shorter cluster cases (Cluster 1 and 4). Therefore, it seems that the internal strength of TC and the background condition together decide the length of TC track. Interestingly, the storm size distribution is very analogous to maximum wind speed distribution (Figure 11 (a) and (c)). The size is not necessarily correlated with TC intensity (Weatherford and Gray, 1987; Knaff et al., 2014), but for influential TCs of Korea we see they are positively correlated.

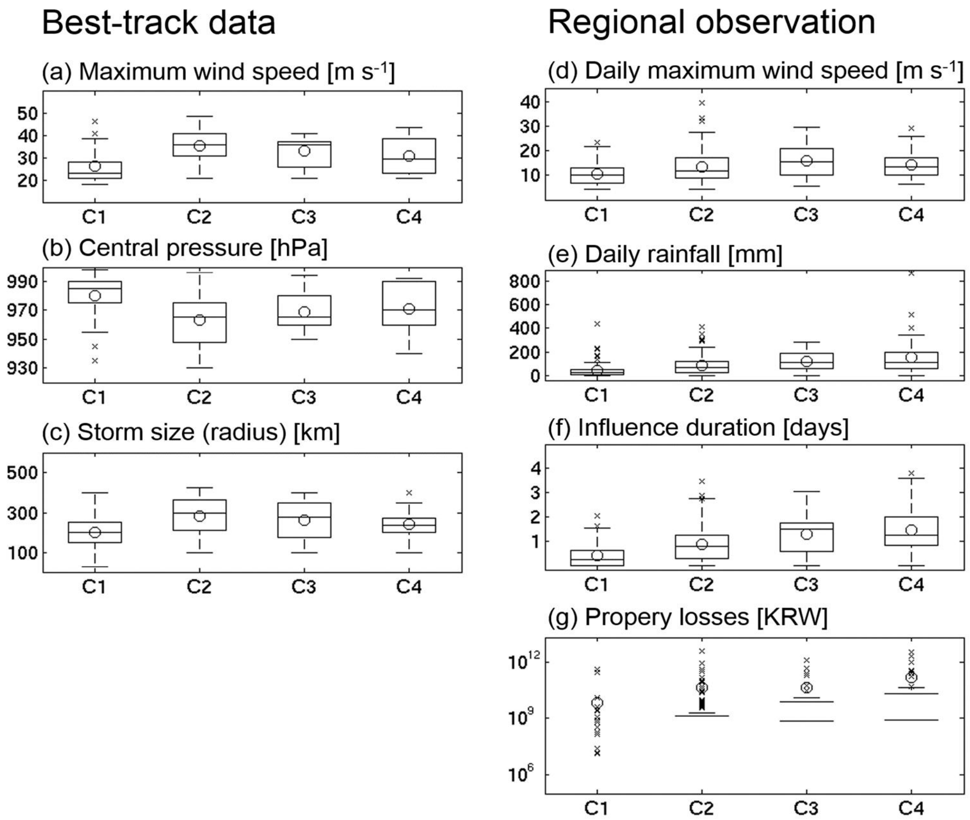

Figure 11. Boxplots of the for track-pattern clusters' hazrards and damages. (a) Maximum wind speed, (b) central pressure, and (c) storm size from RSMC best track data. The storm size is the longest radius of 30 knot winds or greater. (d) Daily max wind speed (10 minute averaged), (e) daily accumulated precipitation, (f) influenced period from 60 weather stations over the nation, and (g) property losses.

Hazard parameters obtained from weather stations have significantly different values among the clusters too (kruskal-wiallis test, 99% confidence level), but their distribution is quite different with best-track hazard parameters. The rank of their magnitude among the clusters are different, especially rainfall and duration. The long clusters (Cluster 3 and Cluster 4) have stronger station maximum wind speed than the short ones, which agrees with best-track hazard parameters. For rainfall and duration, the longest cluster (Cluster 2) has much lower values than the west-short cluster. In fact, Cluster 4 has the highest average and median value in rainfall and influence duration. Then damage ranking of the track clusters is in accordance with that of weather station driven hazard parameters, not with best-track data driven hazard parameters. In general, the long clusters have the strong near-center intensity (best track data) and the west-approach clusters have the high surface local hazards and damages (weather station and property loss data). Property loss data have highly discontinuous and extreme distribution, much more than near-center intensity of TCs nor local hazard data. 30% of the TCs are non-damaged TCs, whereas more than 30% of total TC damages are attributed to a single TC (RUSA, 2002). We observe the large deviation and discrepancy between average and median values (Figure 11 (g)).

Table 8. Each Pearson correlation of property losses with maximum daily wind speed, maximum daily precipitation, and sum of influenced periods of all 60 weather stations and maximum wind speed, central pressure, and storm radius (30 knot) of RSMC best-track data by each track cluster. The significances of correlations are shown with asterisks.

Hazard parameters	Clusters				All
	Cluster 1	Cluster 2	Cluster 3	Cluster 4	
Weather stations					
Daily max wind speed	0.45**	0.58**	0.66**	0.59**	0.62**
Daily rainfall	0.37**	0.66**	0.74**	0.80**	0.71**
Influence duration	0.48**	0.76**	0.59**	0.78**	0.76**
Best-track data					
Maximum wind speed	0.39**	0.17*	0.27*	0.39**	0.29**
Central pressure	-0.40**	-0.16*	-0.35**	-0.41**	-0.27**
Storm radius	0.39**	0.08	0.16	0.30*	0.24**

* Significant at 95%, ** significant at 99% confidence levels.

Table 6 further supports the discrepancy of the relationship that near-center intensity and local hazards make with regional damages. Local hazard parameters have much higher correlation with damages that near-center hazard parameters. It can be interpreted that there is an inherent difference of two hazards. Maximum wind speed and central pressure of a TC at landfall is the system's intensity which is yet in a latent state from the exposed society's point of view. On the other hand, local surface maximum wind speed and rainfall magnitude are already realized hazards, which is inevitably more directly linked to the regional damages. In other words, in risk analysis we view near-center intensity of a TC as in dormant hazard mode and local wind and rainfall intensity as active hazard mode.

Among all the hazards, influence duration is, which is dependent on the daily max wind speed, daily accumulated rainfall values and the station's normal experience of wind and rainfall. Rainfall has higher correlation that wind speed except for Cluster 1, the shortest and lowest-damage cluster. The importance of rainfall in TC risk analysis is recently been highlighted. The present study also suggest that one cannot estimate TC damage only with its wind intensity even though it is locally observed surface wind speed. Most of the best-track data hazards have significant correlation with property losses for each cluster. Cluster 2 have strongest best-track hazard values but relatively low damages (Figure 12), and the correlation of best track data and damage is very weak in Cluster 2's case. The correlation of storm radius has interesting difference between the track patterns. Only the short track clusters (Cluster 1 and Cluster 4) have significant positive correlation with the damages. It seems reasonable to say that the TCs having sufficiently long track have influenced the society regardless of its size but the damage from TCs with short track length is more sensitive to their sizes because a TC can reach to a society only if it has large storm radius.

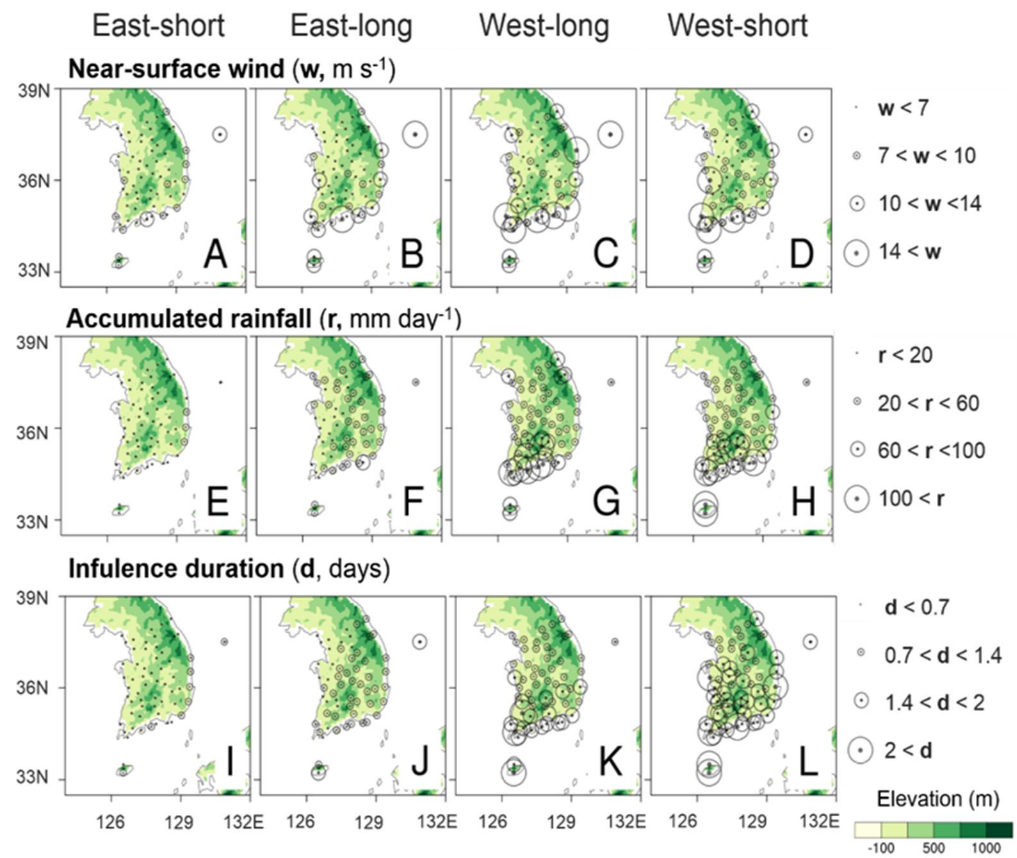

Figure 12. Three hazard parameters of wind, precipitation, and duration of tropical cyclones in each track cluster observed in 60 stations during the center of each tropical cyclone was within 5-degree distance from South Korea.

Now we examine the spatial distribution of local hazards (Figure 12) and property losses (Figure 13). The hazard maps attain both of the track dependent feature and locally originated features. Track pattern – approaching direction, and its intensity is evident; west-approaching clusters have higher hazards in western areas comparing to the east-approaching clusters, and long-strong clusters have higher wind impacts in northern areas. However, the fact that intense winds appear only in low-lying coasts whereas strong rainfall is concentrated in the mountainous areas hints the importance of TC interaction with land orography. Also the strangely high damages of weak west-short cluster (C4) can be explained by the orographic rainfall and long influence duration. Thus it can be summarized that TC track patterns with regard to the relative location of the TC from topography largely determine the overall hazard distributions. The main causes of the high risk of west-approaching clusters (Cluster 3 and Cluster 4) are appeared to be orographic rainfall and extended stay over the peninsula (Figure 12 (g), (h), (k), (l)), which was not allowed for east-approaching clusters to experience.

Damage map generally match well to the hazard maps (Figure 13). Again we interpret damage as a realization of total risk. More than the half of Cluster 1 TCs are non-damaged TCs, so the property loss medians of all provinces are zeros (Figure 13 (a)). Southern parts, where TCs hit most frequently and both rainfall and wind speed were high, are the most risky regions in total. However, for Cluster 3 and Cluster 4, western provinces are less risky despite more hazardous wind and rainfall are recorded there. This discordance is partly explained by exposure disparity. East southern province possesses higher wealth comparing to west southern province.

From climatological risk analysis based on track pattern classification, we have obtained evidences that show an extensive role of TC track in determining the total TC risk. Rather than the near-center intensity or size of the TC, local hazards that the exposed society directly experiences appeared to be more decisive, and the magnitude and spatial pattern of local hazards were dependent on the track pattern including direction and landfall location. To scrutinize the relationship of TC damage, local hazards, TC intensity and TC track, we have conducted decision tree analysis.

Two different decision tree models were designed to objectively classify whether a TC brought damage to the province or not; one decision tree includes local hazards variables (the maximum station wind and rainfall of the province) as inputs whereas the other decision tree does not have these variables but only adopt the TC information (intensity, size and track cluster) and regional information variable (Table 1). Damage data availability and the number of damaged/undamaged cases are presented in Table 9. Overall, we have 355 effective cases, composed of 160 damaged cases and 195 undamaged cases. From now on, we call the decision tree utilizing the station observation attributes (Table 1) as in-situ observation based decision tree. For the other model, in which the two local hazard variables (Station maxwind and Station rainfall) are excluded and using TC best-track information, we name it as best-track based decision tree.

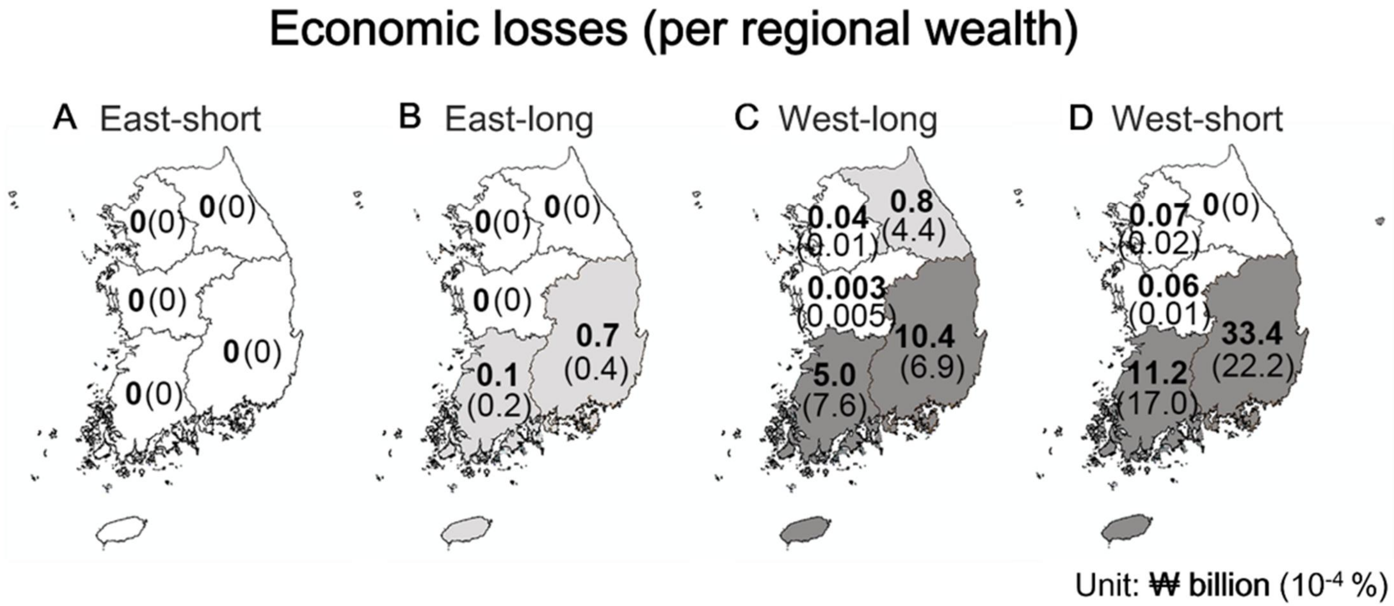

Figure 13. The medians of regional economic losses from a tropical cyclone (regional economic losses divided by regional wealth). The dark shading is for provinces having median losses larger than 1 billion KRW(₩), and the light shading is for provinces having median losses larger than 0.1 billion KRW and smaller than 1 billion KRW.

Table 9. Damage record availability by track-pattern clusters and provinces. Unavailable damage records are cases that have influence duration longer than five days or overlap of more than two TCs in the period. National undamaged cases are those who have no property loss from any of the provinces.

Cluster			East-short	East-long	West-long	West-short	Sum
All			22	31	16	16	85
Unavailable			1	3	4	6	14
Available	National	All	21	28	12	10	71
		Damaged	8	21	12	10	51
		Undamaged	13	7	0	0	20
	Gyeong-gi (GG)	All	21	28	12	10	71
		Damaged	1	9	9	6	25
		Undamaged	20	19	3	4	46
	Gang-won (GW)	All	21	28	12	10	71
		Damaged	2	9	7	4	22
		Undamaged	19	19	5	6	49
	Chung-cheong (CC)	All	21	28	12	10	71
		Damaged	2	9	6	8	25
		Undamaged	19	19	6	2	46
	Jolla (JL)	All	21	28	12	10	71
		Damaged	5	17	10	9	41
		Undamaged	16	11	2	1	30
	Gyeong-sang (GS)	All	21	28	12	10	71
		Damaged	7	21	10	9	47
		Undamaged	14	7	2	1	24
	Sum of province data	All	105	140	60	50	355
		Damaged	17	65	42	36	160
		Undamaged	88	75	18	14	195

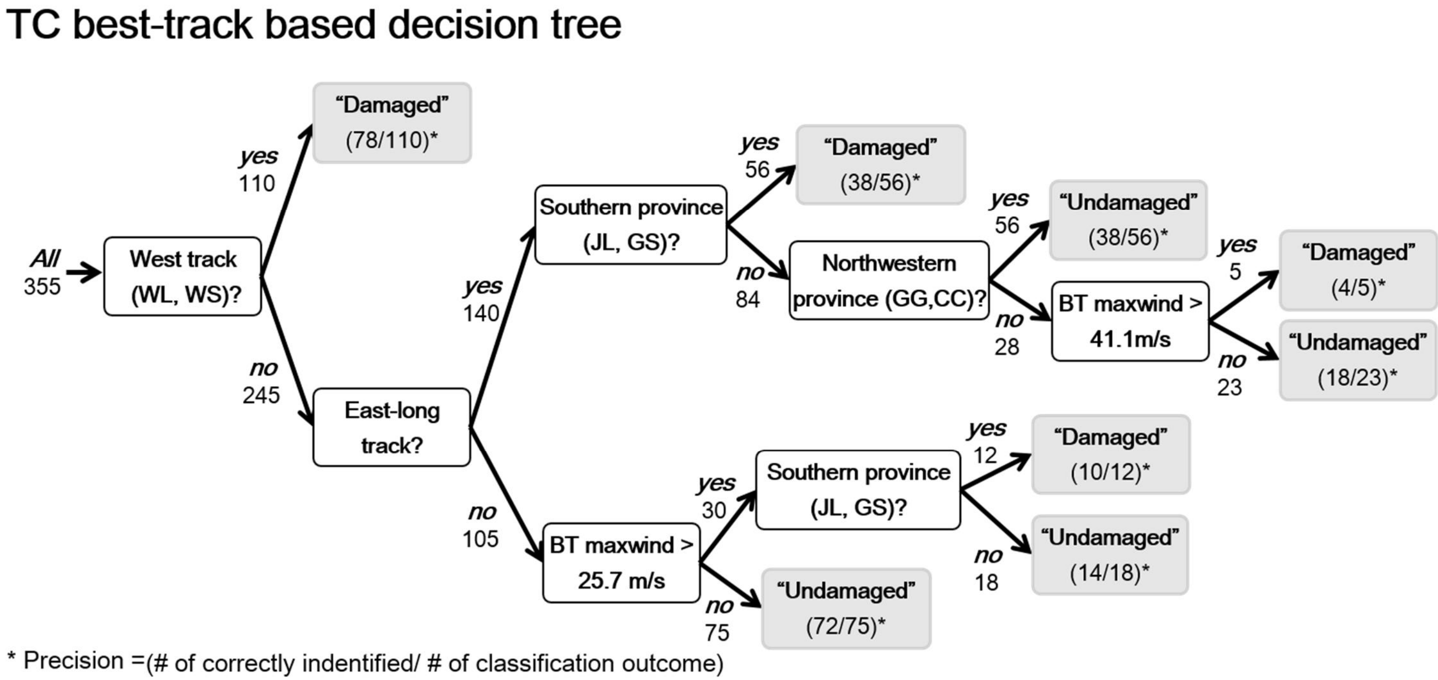

Figure 14. Decision tree model for damage occurrence using the four TC best-track attributes (maximum wind speed, central pressure, storm size, and track-cluster) and province information as input variables. The number of cases corresponding to each criteria is presented along each arrow. The shaded boxes indicate the final diagnosis boxes, in which the precision of the diagnosis is written in parentheses (the number of correctly identified cases / the number of cases diagnosed following the specific sequence of criteria).

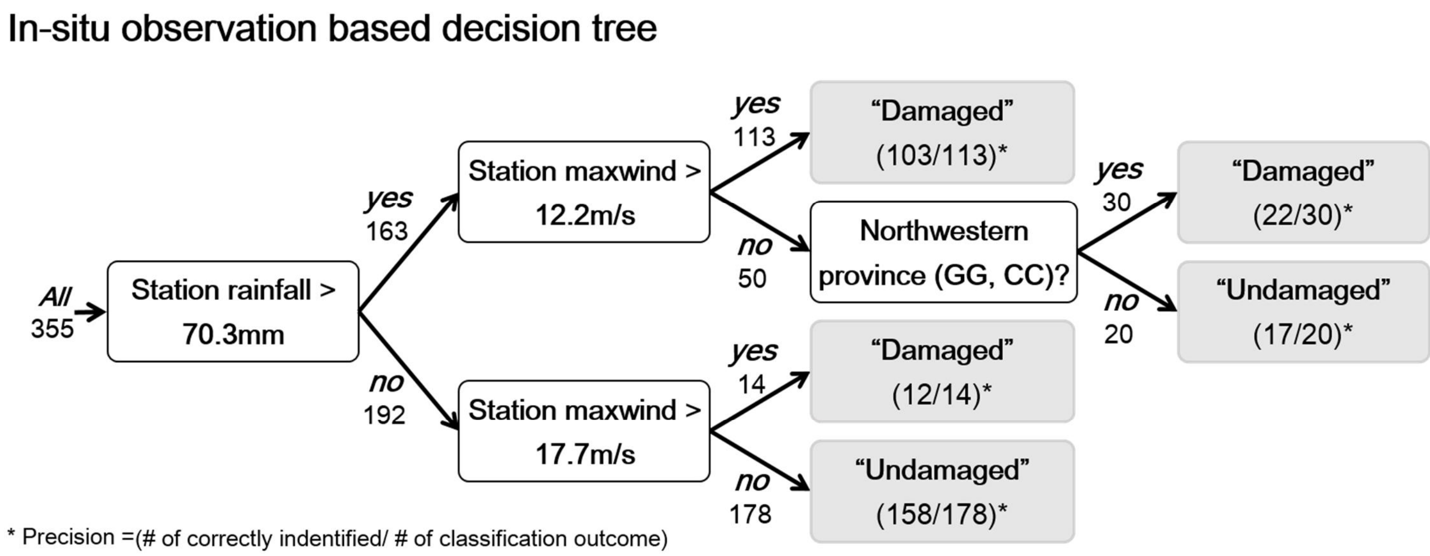

Figure 15. Same as Figure 14 except using two in-situ observation input variables, rainfall and surface wind, not TC best-track variables (intensity, size and track).

TC best-track based decision tree is displayed in Figure 15. The model nominates track-pattern as the first split attribute. This means all the 355 cases should be classified by their track clusters in advance to other decision nodes on the way to the end nodes (damage occurrence). The model simply puts west-approaching TC cases into end node of "Damaged". Despite 32 undamaged cases among 110 west approaching TC cases, the no-local-hazard decision tree selects track-pattern as the first split attribute. This is because all the other attributes such as TC intensity and/or size cannot make the split as efficient as the track pattern clusters in terms of information gain. In national point of view, it is true that all of the TCs in west approaching clusters have made damages, and all the TCs that did not generate damage from any of the provinces in South Korea are from either east-short or east-long (Table 9).

For east-approaching TCs to make damage in provinces, much more conditions are required. The cases of east-approaching TCs are classified by province variable and TC intensity (maximum wind speed). The combination of east-long track-pattern and Southern provinces (JL and GS) labeled the 56 corresponding cases "Damaged" while 56 east-long cases in North-western provinces are marked as "Undamaged". For a TC in east-long cluster to make damage in GW province, located in the North-eastern part of South Korea, the TC should have maximum wind speed larger than 41.1 m s-1. East-short cases, unlike to east-long cases, are sent to intensity criterion before province criterion. East-short TCs with weak intensity (maximum wind speed below 25.7 m s-1) are directly linked to "Undamaged". An east-short type TC with relatively strong intensity can incur damage in the Southern provinces (Figure 14).

In-situ observation based decision tree is displayed in Figure 16. It determines damage occurrence almost entirely depending on the station-measured local hazards. At first, we put all the seven attributes in the model (Table 1) including TC intensity, TC size and TC track-pattern, but the tree did not utilize none of TC information but only use station rainfall and wind observation in addition to province information. At the first node, Station rainfall is selected for generating the best split. Then next decision node is the criterion of Station maxwind. This result highlights again the importance of local hazards (especially rainfall) over a TC's near-center intensity and/or size regarding TC risk realization into damage. The statistical measures of the performance of the two decision trees including their accuracies are given in Table 10 and Table 11. The overall accuracy of in-situ observation based decision tree (87.9%) is about 11% higher than that of TC best-track based decision tree (76.6%). The False alarm rate of in-situ observation based one is about 17% lower than TC best-track based one. Here we recall that the station hazards showed much higher correlation (~0.7) with TC damage amounts than best-track hazards (~0.3) (Table 6). The local hazards are more directly linked to the regional TC risk materialization.

Figure 15 shows, if the maximum daily rainfall is above 70.3mm and daily maximum wind speed is above 12.2 m s-1, the case is classified as damage-recorded. Substantially higher wind (17.7 m s-1) is required to make damage in the province with weak rainfall cases (below 70.3mm). If both of the rainfall and wind impacts are weak then, the provinces are classified as "Undamaged". The cases with strong Station rainfall but weak Station maxwind should get through another node with province variable. If it is either GG or CC provinces, which are located in north-western part of South Korea, the cases are classified as damaged cases despite weak wind impact. As shown in 3.1, the impact of weakened TCs over South Korea and they pointed out that the same North-western region is the wealthiest and the most populated area in Seoul, so relatively weak rainfall or wind can generate serious damages.

Both of the TC best-track based and in-situ observation based decision trees utilize the province variable. The use of province variable by TC best-track based decision tree is mainly related to the relative location of the province from TC center along the track. Southern provinces are generally closer to the TC center regardless of the four track types because TC moves from the South (low-latitude) to the North (high-latitude). However, in addition to the impact on frequency and intensity of hazard due to location differences, it can be interpreted as showing the contribution of the TC-independent local risk elements. For example, the reason of using province variable as a separate node in in-situ observation based decision seems to be the exposure and/or the vulnerability of the provinces. The local geographic characteristics such as surface topography, regional exposure and/or vulnerability can control the sensitivity of the exposed society to a certain hazard.

When an attribute is the most-related variable to target variable, the attribute should be used most frequently by a decision tree model classification. In this sense, the relative importance of the attributes are offered in terms of the usage rate by See5/C5.0 algorithm. In the in-situ observation based decision tree, all 355 cases are classified by Station rainfall and maxwind above all. In the other words, the usage rate of these station variables are 100%. The thirdly important variable, province occupies 14%. When the local hazards information is unavailable, track-pattern information act as the priority decisive of TC risk. In the TC best-track based decision tree, the track cluster variable is 100% used, then province and BT maxwind follow with the rate of 48% and 37% respectively. Therefore we can say, for risk determination, TC track is the most important attribute other than the local surface observation. The TC intensity information is only contributed as thirdly important attribute only for best-track based one. TC size is not utilized by any model as an effective classifier that can divide damaged versus undamaged cases.

The results to sum imply that the TC intensity and size information is not sufficient for risk estimation. However, by using the two of TC track pattern and TC intensity together, it seems possible that we reconstruct regional TC risk although the accuracy would be lower than having the direct local hazards information. In a sense, TC track acts as bridging the information gap, when local hazards information is missing, between the TC and local risk that TC intensity or size information alone cannot fill. TC track is the path that literally brings the TC to a certain society. In this regard, it is natural that the decision tree models link local regional risk to TC track information in advance to TC intensity.

This section compares and contrasts TC risk differing by TC track types, and highlight the role of track in the priority structure in TC risk realization process over South Korea. TC intensity and size are significantly different among track clusters. East-long is the strongest and the largest, but the costliest TC track cluster is the relatively weak west-short and west-long TCs. This discrepancy is explained by local hazard distribution. Weather station observation witnesses the west-approaching TCs are more influential in terms of surface wind, rainfall, and influence duration over South Korea. The possible mechanisms that favors west-approaching TCs over east-approaching ones in deciding local hazards, are suggested as follows 1) the location of the dangerous semicircle, 2) topographic effect on rainfall in south-western part of the peninsula, and 3) the stay period of the TC over the Korean Peninsula. The decision tree analysis provides information about the relative importance of risk elements in TC damage materialization. Track verified its predominance over TC intensity and size in damage decision making process.

Table 10. Statistical measures of the performance of TC best-track based decision tree for Strong TCs.

Validation		Observation		
		Damaged	Undamaged	Sum of forecast
Forecast	Damaged	130	30	160
	Undamaged	53	142	195
Sum of observation		183	172	355
Overall accuracy		76.6%		
Hit rate		81.3%		
False alarm rate		27.2%		

Table 11. Statistical measures of the performance of in-situ observation based decision tree for Strong TCs.

Validation		Observation		
		Damaged	Undamaged	Sum of forecast
Forecast	Damaged	137	23	160
	Undamaged	20	175	195
Sum of observation		157	198	355
Overall accuracy		87.9%		
Hit rate		85.6%		
False alarm rate		10.3%		

Based on our findings, we emphasize that TC hazard can be activated only through track (see Figure 16). Our understanding parallels some previous frameworks of natural hazard processes, which have suggested that natural hazards result from conflicts at the interface between geophysical processes and humans (Alexander 2000, Jones et al. 2003). Track determines the location, and each location has its own sensitivity to TC risk in terms of its population, wealth, building code, warning system, topography, etc. The risk triangle is applied to active hazard, which is a product of a combination of TC characteristics (intensity and size) and local geography experiences. Note that not only local geography experience is dependent on track patterns, but TC characteristics also appeared to differ among track patterns (Figs. 11a–c). Therefore, we suggest that the integral TC risk is highly dependent on track. Figure 16 does not include the possible impact of mid-latitude background conditions on the precipitation and surface wind gust patterns independently. For example, interaction with the upper-level trough can change the structure of a TC (e.g., Vinet et al. 2012, Baek et al. 2015). However, the contribution of mid-latitude weather system cannot nullify the fact that it requires the cooperation of track for the TC hazard to be activated, and the dynamic interactions with large-scale weather systems are regarded as beyond the scope of this study.

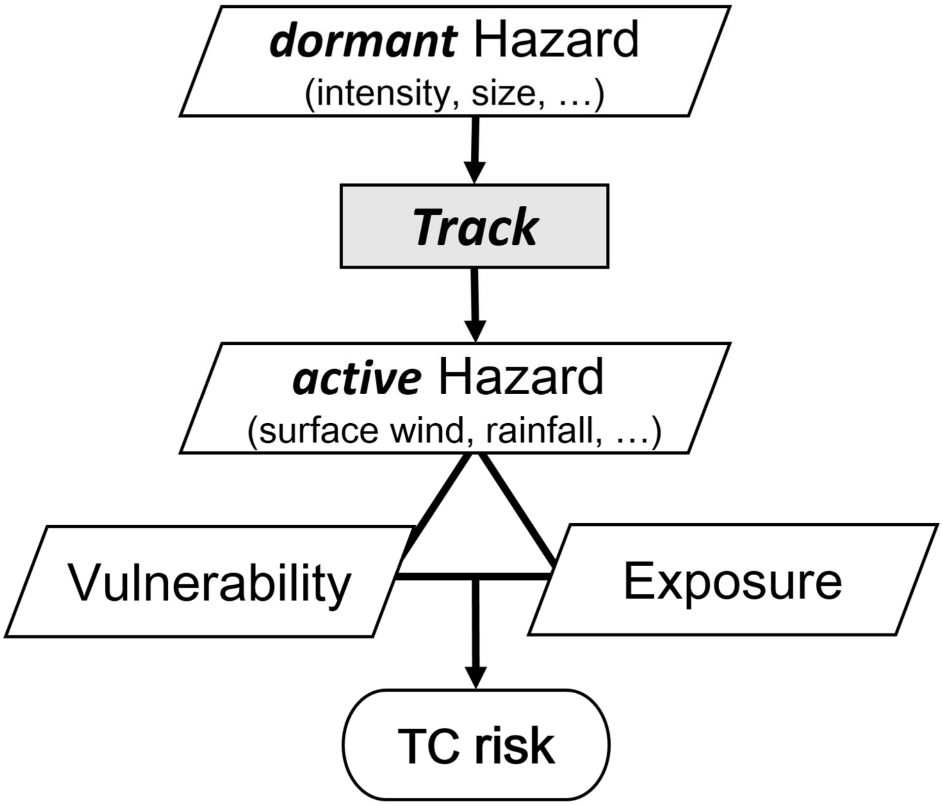

Figure 16. Flowchart for local risk materialization process with TC risk elements and their relationship.

5. Summary and discussion

In TC risk studies, hazard refers to TC-based hazard, such as intensity or size. Here, we present the gap between local active hazards (e.g., precipitation and surface wind) and the potential mode hazards (e.g., TC intensity and size) and highlight the impact of different track patterns and extra-tropical transition on activation of localized hazards. Here, we show that TC risk is most dependent on TC track and extra-tropical transition experience

This thesis first examines the damages caused by influential WTCs and STCs in Korea. Our results show that even though WTCs have weaker maximum winds than STCs according to the IBTrACS dataset, they cause similar amounts of socio-economic damages—casualties, homelessness, and property losses—in the northwestern Korea, the most densely populated and richest area in the country. Moreover, in WTCs, both wind and rainfall are still significant factors to determine damages so that WTCs can lead various wind- and rainfall- induced extreme phenomena (e.g., gust, downpour, storm surge, and wind wave, etc.) just like STCs. Thus, it may be advisable to apply the Typhoon Warning system to WTCs like STCs since using separate warning systems for different types of severe phenomena can be inefficient to warn people about WTC-induced complex risks.

Based on our findings, we suggest that the role of track is crucial in the TC risk determination process. The present study firstly compares and contrasts the amount and spatial distribution of TC risk elements with respect to TC track types for TCs that influenced South Korea over the last three decades. The results show that TC damage is more correlated with local active hazard compared to potential hazard. Then, track is suggested as the main reason why the localized active hazard substantially disagrees with potential hazard. Track is a sequence of TC locations, and location differences cause substantial changes to local active hazard distributions in association with 1) dangerous/navigable circle differences, 2) interaction with inhomogeneous topography, and 3) influence duration changes. Second, we analyzed the priority structure of the TC risk determination process, including track as an independent factor through decision tree analysis. When local active hazard information is missing, TC track acts to bridge the information gap between the TC system and local risk. TC track is the path that literally brings a TC to a given society. Analogously, the decision tree models link TC damage with TC intensity only through TC track. TC intensity or size information plays peripheral roles for filling the information gap.

In conclusion, we draw certain implications for risk research and management based on our finding that TC risk has a comprehensive track-dependency. First, our findings support the fundamental importance of accurate track forecast in disaster risk mitigation. Warnings should deliver information that is directly related to possible damages. Our results show that local hazards penetrating into the residents can be fairly different from that based on the forecasted TC information, which mostly concerns the maximum intensity observed in the small area near the center. The discordance between forecasts and actual hazards can aggravate the disaster resilience process. For example, avoidable casualties and economic losses have been caused by hurricanes and cyclones because of an excessive focus on wind gust in the forecast rather than on hydrological hazards (Colbert et al. 2013, Myer et al. 2014). Communication on TC risk should focus more on local impacts that residents in different areas are likely to experience. To achieve this, accurate track forecast is essential. As demonstrated here, TC risk is very sensitive to track. Second, a cautious consideration is needed regarding the uncertainty rising from track changes in the future TC damage projection. Anthropogenic contributions to TC track changes have been reported (Ho et al. 2004, Par et al. 2014, Kossin et al. 2016). Also, it has been shown that interdecadal changes of TC tracks in the western North Pacific are associated with the westward expansion of the subtropical northwestern Pacific high (Ho et al. 2004). This track variance needs to be considered more seriously in climatological risk research, as it is shown that a slight change in TC track distribution can cause the total amount of damage to be much larger or smaller given the same number and intensity of TCs in a particular basin.

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국문초록

본 학위연구는 여러 유관한 리스크 인자들 간의 관계를 분석하여 태풍 리스크의 결정 과정을 규명하는 것을 목적으로 한다. 특히, 태풍 리스크가 잠재적인 상태에서 실제 발현될 때 가장 중요하게 작용하는 인자들이 무엇인지를 밝히고자 한다. 지난 삼십여 년(1979 – 2010)동안 한반도에 상륙한 134개의 태풍을 상륙 당시 중심 근처 최대 풍속을 기준으로 17 m s^{-1} 이상인 태풍을 '강한 태풍'으로 명명하고 17 m s^{-1} 미만인 태풍들을 '약한 태풍'으로 분류하였다. 기상청에서는 여기서 말하는 강한 태풍들에 대해서만 태풍 경보를 발행하고 있다. 그러나, 본 연구 결과 약한 태풍들이 오히려 경기충청 지역에 대해서는 강한 태풍들보다 더 큰 피해를 야기하는 것으로 나타났다. 따라서 본 연구에서는 강한 태풍과 약한 태풍 각각에 대하여 위험도 분석을 수행했다. 분석 결과, 우리나라 상륙 태풍들 중 30%의 태풍은 피해를 기록하지 않은 무피해태풍이었다. 유피해태풍과 무피해태풍을 가르는 차이점이 무엇인지를 분석한 결과, 강한 태풍의 경우 무피해태풍은 모두 한반도 동편으로 진행한 태풍이라는 공통점이 있었고, 약한 태풍의 경우 유피해태풍 중 대다수가 한반도 주변에서 온대저기압화를 경험한 태풍인 반면 무피해태풍은 그렇지 않다는 점이 드러났다. 의사결정나무분석을 통해 피해유무를 진단하는 모형을 구축한 결과, 앞의 분석과 동일하게 강한 태풍의 피해유무 결정모형은 진로 유형을 가장 중요한 분류 인자로 사용하였고, 약

한 태풍의 피해유무 결정모형은 온대저기압화 경험유무를 가장 중요한 분류 인자로 지시하였다. 이제까지의 태풍의 위험도 연구와 현업 예보는 모두 태풍의 중심 근처 강도에 집중하였지만, 본 연구 결과에 따르면 태풍 진로 방향과 온대저기압화 경험 유무가 태풍 피해 결정에 있어 태풍 강도보다도 더 주목해야 할 인자인 것이다. 이는 각지에서 실제로 발현되는 태풍의 영향력(강수, 바람 등)은 태풍 중심강도와 직접 대응하지 않고 진로와 온대저기압화에 따라 민감하게 달라지기 때문인 것으로 보인다. 이 연구를 통해 얻는 제언은 첫째, 태풍 재난 경보가 실제적인 영향에 더 초점을 맞추어야 한다는 것과 둘째, 이를 위해서는 정확한 진로 예측과 우리나라 주변에서의 태풍의 온대저기압화에 대한 더 많은 연구가 필수적이라는 것이다.

주요어: 태풍, 피해, 위험도, 데이터 마이닝, 진로, 온대저기압화

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