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Highlighting socioeconomic damages caused by weakened tropical cyclones in the Republic of Korea

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Abstract To alleviate enormous socioeconomic damages by tropical cyclones (TCs), the Korea Meteorological Administration (KMA) retains a special warning system for strong TCs (STCs, maximum wind speed of the best-track data ≥ 17 m s^{-1}), but not for relatively weak TCs (WTCs) which are not regarded as threatening as STCs; the warning system encompasses complex extreme phenomena such as gust, downpour, storm surge, and wind wave possibly arising from STCs. However, it is necessary to examine if WTCs can be actually as harmful as STCs with various extreme phenomena. Here, we compare the risks and intensities of WTCs with those of STCs for each province by analyzing the national damage reports and the near-surface wind and rainfall records from 60 weather stations in the Republic of Korea. According to our result, WTCs bring huge damages comparable to STCs in the northwestern Korea, the most populated and the richest area in the country, while WTCs cause much less destruction than STCs in the southeast. The large damages in the northwestern Korea can be explained by different mean landfall locations between WTCs and STCs; the storm centers of WTCs make landfall closer to the northwestern coastline than STCs'. Significant correlations between wind/rainfall and the damage amount by WTCs suggest that WTCs can also induce multiple extreme phenomena like STCs. Thus, the KMA needs to develop a special warning system for WTCs like for STCs.

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1 Introduction

Most of Korean public and private sectors are concerned about tropical cyclone (TC) activities since TCs accompanying strong winds and torrential rainfalls incur enormous damages incomparable to other natural disasters in the Republic of Korea. The TC-induced economic losses in the past decades are three times as large as the cumulative losses caused by all other natural disasters such as flooding, landslides, and convective storms (http://www.emdat.be). This is somewhat surprising since the annual average number of TCs affecting Korea is only about 3, which are relatively small considering that about 27 TCs are formed over the western North Pacific basin during the TC season (June–October) (Ho et al. 2004; Kim et al. 2005).

To reduce TC-induced damages, the Korean Meteorological Administration (KMA) has put great efforts on improving the forecasts of TC activities. As a part of the efforts, the KMA has established the National Typhoon Center (NTC; http://typ.kma.go.kr/TYPHOON/index.jsp), an affiliated organization for forecast and research of TC activities over the western North Pacific. Detailed duties of the NTC are as follows: on no TC days over the western North Pacific, the regions with high probability of TC formation are watched, and the TC formation probability is quantified for an early forecast based on NTC's own guidance. After a TC forms, the TC is intensively monitored until its maximum wind speed drops below $17\ \mathrm{m\ s^{-1}}$. In addition, a 5-day forecast for the TC is produced every few hours by referring various data, such as satellite imagery, weather charts, numerical, and empirical models. In case that a TC is expected to come close to the Korean peninsula within a few days and to bring either one of four extreme phenomena— gust, downpour, storm surge, and wind wave—over the country, the KMA issues the Typhoon Warning. The Typhoon Warning can make people stay alert for all possible extreme phenomena by the TC since the KMA does not inform people about which extreme phenomena among the four extreme phenomena ring the alarm. However, if there was no special warning for TC like the Typhoon Warning, the KMA could has no choice but to issue the individual warnings. For example, only huge rainfall is forecasted by a TC, then the KMA might issue only the Downpour Warning. In this case, people might just pay attention to possible flood by rainfall but not to the other disasters. This could expose people to unexpected danger. This is because, aside from the fact that weather forecast is not always correct, TC usually brings diverse extreme phenomena at a time. In addition, it is not efficient to issue every individual warning for just one TC in case that all four extreme phenomena by TC are forecasted. Hence, the Typhoon Warning system appears to be more appropriate than to use individual warning systems for TC.

The above-mentioned activities, however, are performed only for strong TCs (STCs, maximum wind speeds of the best-track data $\geq 17\ \mathrm{m\ s^{-1}}$) but not for relatively weak TCs (WTCs, maximum wind speeds of the best-track data $<17\ \mathrm{m\ s^{-1}}$). This is because WTCs are weakened systems which seem not to accompany multiple extreme phenomena (e.g., high wind, torrential rainfall) like STCs, and thus, they are thought as not damaging as STCs. However, it has never been clarified whether 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 extratropical 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 baroclinicity (Klein et al. 2002; Jone et al. 2003; Hart et al. 2006). About 45 % of TCs undergo the extratropical 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, like STCs. For example, about 0.5 million homelessness, 4 hundred casualties, and 0.8 trillion Korean Won (KRW, 1000 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. This WTC damage is not ignorable. If WTCs are as harmful as STCs with diverse extreme phenomena, it can be recommended for the KMA to apply the same activities including the Typhoon Warning system for WTCs as well as STCs. Of course, there is an operational guideline for WTCs (Kwon and Kim 2005; Cha et al. 2008), and the individual warning systems can be working for each severe phenomenon possibly induced by a WTC (e.g., gust ≥ 14 m s^{-1}, downpour ≥ 70 mm 6 h^{-1}). However, if WTCs bring multiple extreme phenomena, one warning system like the Typhoon Warning can more efficiently inform people of WTC-induced high and complex risks.

This study 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 Sect. 2. The comparison of socioe-conomic losses and wind/rainfall intensities by WTCs and STCs is shown in Sect. 3. Finally, summary and discussion are given in Sect. 4.

2 Data and methods

2.1 Definition of WTCs and STCs

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, which 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 sta-tistical 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 2008). However, the possibility whether 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-h interval which is too coarse to get a precise influential period of TC over Korea, the 6-h interval is interpolated into an 1-h interval (Park et al. 2011, 2014). Based on the 10 min 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.

2.2 The explanation on TC-induced socioeconomic loss data

Data on the socioeconomic losses are issued by the National Disaster Information Center (NDIC) of Korean government (http://www.safekorea.go.kr). The raw data are poorly organized for research so that the raw data are reorganized for this study. The data include the amount of losses from all types of extreme weather with their start and end dates. However, some of the loss data do not have any information on their causes, which should be determined. Here, a loss is regarded as TC origin if the period of damage in the NDIC dataset overlaps with any days on which a center of TC stays within 3° from the Korean coastline based on the IBTrACS dataset or the influence period in the White Book. Then, the damage period is newly defined by the union of the three damage periods from the

Fig. 1 Five classified areas of the Republic of Korea. Dots indicate locations of 60 weather stations recording wind and rainfall
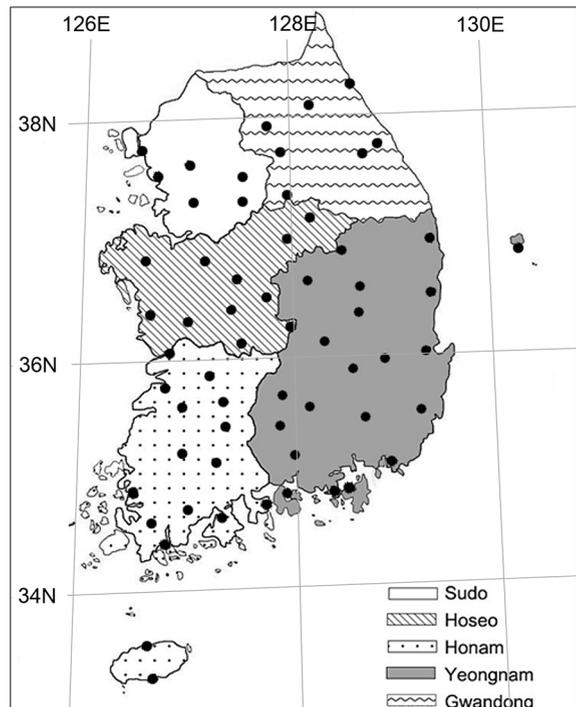
NDIC, IBTrACS, and the White Book. For multiple successive extreme phenomena, the NDIC usually aggregates the damage amounts and periods. Hence, to avoid misrepresenting the TC damage by the aggregated data, we have excluded the cases whose damage period exceeds 5 days from the starting of TC influence. Note that exclusion of such cases does not affect our main conclusion (not shown).

Here three major types of damages are considered: the number of casualties (the dead, missing, and injured combined), the number of homeless (the people who lost their homes by the extreme phenomena), and the amount of property losses (the monetary damages of industrial, public, and private facilities in total economics, standardized by taking into account inflation based on the value of money in 2005). The loss data are counted by local governmental offices so that most of the losses are collected regardless of insured and uninsured. Some light losses would not be gathered because people who got the light losses often do not report their damages to the local offices.

To look into the spatial distribution of damages within the country, the province-level aggregated damage data are used as following Park et al. (2015). The province-level districts considered are Sudo, Hoseo, Honam, Yeongnam, and Gwandong (Fig. 1). Since the growth rates of population and wealth vary by provinces (see Fig. 2 of Park et al. 2015), it is necessary to minimize the effect of the distinct growth rates on damage data. The loss data are normalized to the reference year of 2005 taking the population and wealth per capita for each province into account (Park et al. 2015). It is noted that the wealth per capita varies only by years while the population is changing by both of years and provinces. The normalized damages in terms of homelessness, casualties, and property losses caused by the i-th TC are calculated by the following equations.

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

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

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

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.

2.3 The calculation of near-surface wind and rainfall intensities of TC

In this study, the wind and rainfall records from the 60 weather stations showing fairly uniform distribution over Korea (Fig. 1) are utilized to examine TC-induced extreme phenomena; wind record is for representing gust, storm surge, and wind wave while rainfall record is for downpour. The weather station data can account more for the regionally varying socioeconomic losses than the maximum wind speed of the IBTrACS dataset that represents the only one maximum point of a TC. Actually, the wind and rainfall data from the weather stations well explain the spatiotemporal variation of the TC-induced damages, whereas the maximum wind speed from the best-track dataset does less efficiently. Moreover, the IBTrACS dataset does not provide TC-induced rainfall intensity at all. We define a TC's wind and rainfall intensities for a province as the highest daily

maximum wind and daily accumulated rainfall records of the weather stations located in the province over the influential period defined for the TC. Hence, each TC case is assigned with wind intensity, rainfall intensity, the number of casualties, the number of homelessness, and the amount of property losses for each province.

3 Results

In 1979–2010, 49 WTCs and 85 STCs have affected Korea with a notable seasonality; both TC types are active in June–September and only 5 % of all TCs have affected the country in other months (Table 1). The peak month for both WTC and STC is August in which a recurring TC track pattern toward the Northeast Asia is the most frequent (Kim et al. 2011, 2012; Ho et al. 2013). On the other hand, no STCs and WTCs influence Korea in November–April, a season safe from any TCs. 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. Sixteen WTCs and twelve STCs have damage periods longer than 5 days, and the cases possibly accompanied with the Changma. On the other hand, two STCs' damage period is shorter than 5 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 1935 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, implying that half of WTCs probably experienced re-intensification process. This ratio is very similar to the probability that TCs undergo extratropical transition processes (Jone et al. 2003). 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. TCs were named by the Joint Typhoon Warning Center (JTWC) at Guam until 1999 and are now named by the Regional Specialized Meteorological Center, Tokyo (RSMC—Tokyo), after 2000 when their lifetime peak intensity goes beyond 17 m s^{-1}. The IBTrACS dataset includes the records on unnamed TCs of which the maximum wind speeds do not reach 17 m s^{-1} through their lifetime. According to Table 2, only 6 of 33 WTCs are not named, meaning that TCs with lifetime peak intensities of <17 m s^{-1} do not frequently affect Korea. This is because of the geographical location of the Korean peninsula, which is placed on the Northeast Asia far from the main development region of TCs (e.g., Ho et al. 2004; Lin and Chan 2015;

Table 1 Monthly and total frequency of weak tropical cyclones (WTCs) and strong tropical cyclones (STCs) in 1979–2010

	May	June	July	August	September	October	Total
WTCs	1 (1)	8 (3)	9 (6)	20 (14)	9 (7)	2 (2)	49 (33)
STCs	1 (1)	5 (5)	22 (17)	34 (28)	20 (17)	3 (3)	85 (71)

The parentheses indicate the number of TCs used in this study

Table 2 List of weak tropical cyclones (WTCs) and strong tropical cyclones (STCs) affecting the Republic of Korea

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

Table 2 continued

WTCs		STCs
Krosa (2007)	Kalmaegi (2008)	Malou (2010)
Wipha (2007)	Morakot (2009)	
Noname *(2008)*	Linfa (2009)	
Meranti (2010)		

Parentheses indicate the years of occurrence. Bold italic represents the TCs damaging longer than 5 days or affecting the country with successive TCs

Park et al. 2015). Meanwhile, one TC not named in 1991 is classified into STCs. This could be strange since STCs are defined as of which intensity higher than 17 m s^{-1}. The lifetime peak intensity of the non-named TC was not regarded to reach 17 m s^{-1} by the JTWC in 1991. Hence, it was not named. However, it was reconsidered as a TC of $\geq$17 m s^{-1} by the RSMC-Tokyo.

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 such as the Student's t test cannot be applied. Hence, all of the significance tests are done by nonparametric 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.

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

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

Fig. 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*

(a) Wind

(b) Rainfall
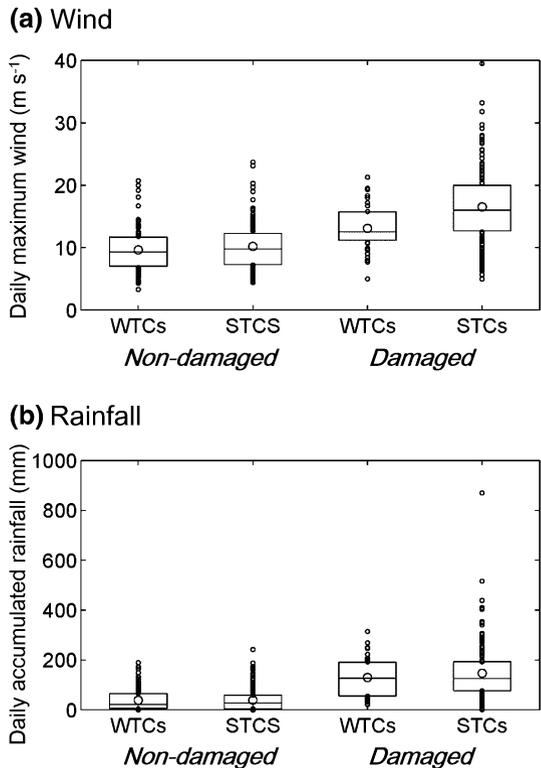
analysis is utilized to get correlation coefficients between damages and intensity parameters (Daniel 1990). The Spearman's rank correlation analysis is as follows.

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

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.

As discussed above, the skewed probability distributions particularly come from a lot of zeros, indicating that there are many non-damaging cases. About 55 and 30 % of WTCs
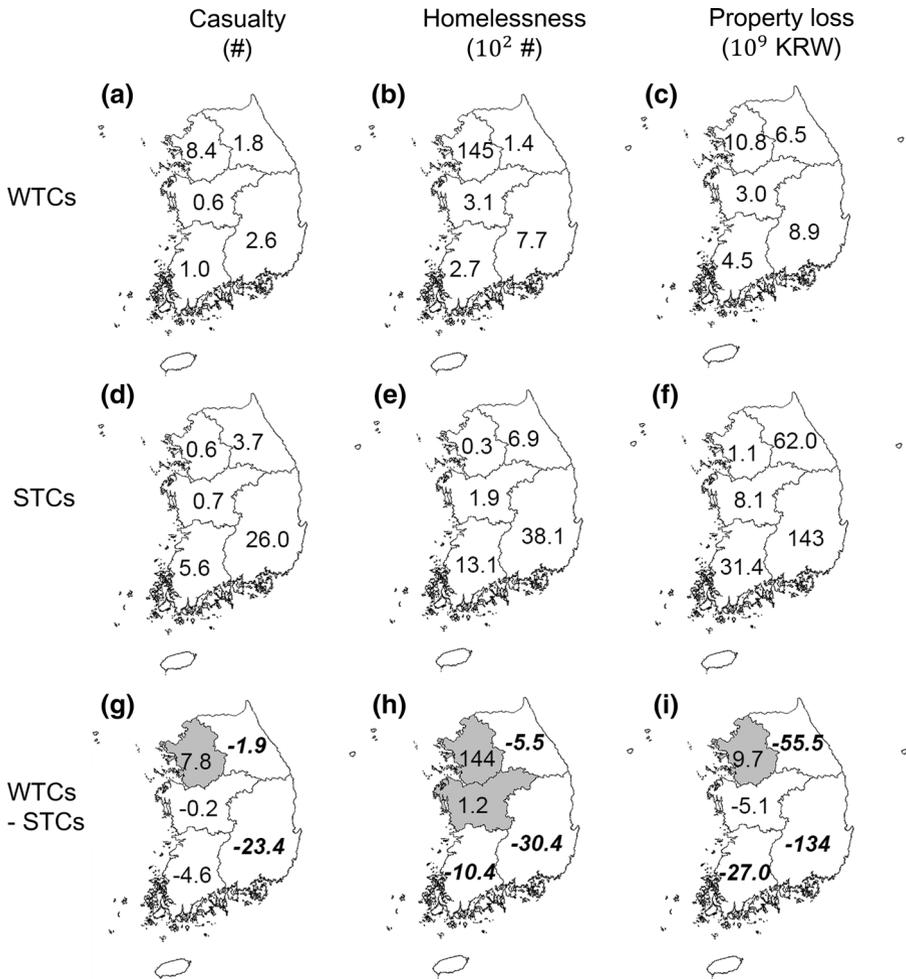
Fig. 3 Averages and differences in the number of homelessness, casualties, and property loss caused by weak tropical cyclones (WTCs) and strong tropical cyclones (STCs) for the five areas. *Shading* indicates that the WTC-induced value is larger than the STC one. *Bold italic* indicates that the difference is statistically significant at the 90 % confidence level based on the Mann–Whitney *U* test

and STCs that have affected Korea do not have any records on losses in the NDIC dataset, respectively. It is necessary to check whether 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 (Fig. 2). For both WTCs and STCs, wind and rainfall intensities of the non-damaging cases are significantly weaker than those of the damaging cases. In other words, the intensities for the non-damaging cases are not strong enough to cause any damages. Meanwhile, the average wind in the damaging cases of STCs is significantly larger than that of WTCs while average rainfalls for damaging cases
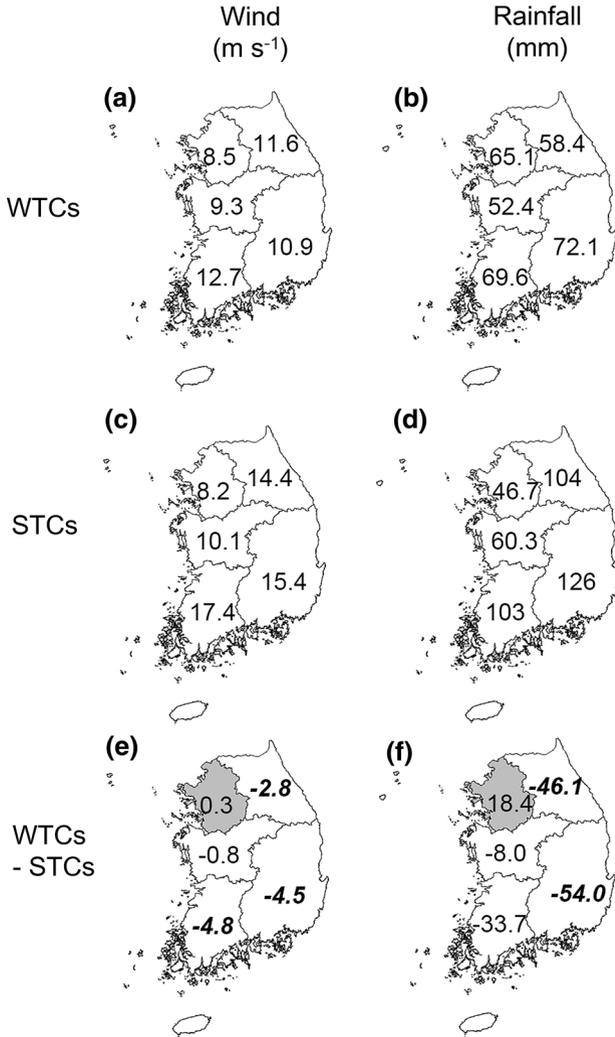

Fig. 4 Averages and differences in near-surface wind and rainfall caused by weak tropical cyclones (WTCs) and strong tropical cyclones (STCs) for the five areas. *Shading* indicates the WTC-induced value is larger than the STC one. *Bold italic* indicates that the difference is statistically significant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

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 $\geq$17 m s^{-1}). In contrast, this discrepancy in wind intensities is not found for non-damaging cases. The mean wind and rainfall intensities of non-damaging 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-damaging cases, to determine whether a TC including both WTC and STC is non-damaging or damaging.

Spatial distributions of the damages are different between WTCs and STCs (Fig. 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 (Fig. 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.

The geographical variations in the socioeconomic losses caused by WTCs and STCs can be well explained by that in the near-surface wind speed and rainfall by WTCs and STCs (Figs. 3, 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 Fig. 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 (Fig. 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
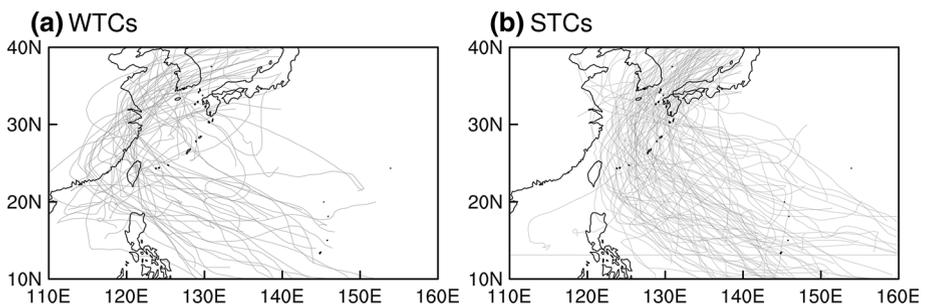

Fig. 5 Tracks of weak tropical cyclones (WTCs) and strong tropical cyclones (STCs)

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 (Fig. 5), WTCs can affect the northwest part of the country as much as STCs despite 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 (Fig. 4), the existence of high mountains along south and east coasts may be responsible related to orographic updraft (Park and Lee 2007). On the other hand, the average wind and rainfall intensities for non-damaging 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.

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 whether 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.

Table 3 Correlation coefficients between damages (homelessness, casualties, and property loss) and wind, and between damages and rainfall, caused by weak tropical cyclones (WTCs) and strong tropical cyclones (STCs)

TC Type	Damage Type	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*

Bold italic indicates that the correlation is statistically significant at the 90 % confidence level

4 Summary

This study 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 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. 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. Meanwhile, the annual frequencies of influential WTCs and STCs show little correlation between them (not shown), meaning that the favorable oceanic and tropospheric conditions for their approaching Korea may be very different. In a future study, the large-scale oceanic and tropospheric conditions for WTC- and STC-frequent years need to be examined and compared.

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