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Characteristics of landfalling tropical cyclones in the Asia-Pacific region during 2007-2017

XIAO ZHOU*,** and NING LI*

**Academy of Disaster Reduction and Emergency Management, Beijing Normal University, Beijing, China*

***Shanghai Typhoon Institute of China Meteorological Administration, Shanghai, China*

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e mail : zhoux@typhoon.org.cn

सार - दुनिया के अन्य हिस्सों की तुलना में एशिया-प्रशांत क्षेत्र के देशों में प्राकृतिक आपदाओं का खतरा अधिक है। एशिया-प्रशांत क्षेत्र में सबसे सामान्य प्रकार की आपदाएं उष्णकटिबंधीय चक्रवातों (टीसीएस) से होने वाले दुष्प्रभावों से जुड़ी हैं। जलवायु परिवर्तन, आर्थिक और जनसंख्या वृद्धि उष्णकटिबंधीय चक्रवातों की आवृत्ति और प्रचंडता दोनों की वृद्धि में योगदान कर रहे हैं। इस शोध पत्र में 2007-2017 की अवधि के उपलब्ध आंकड़ों के आधार पर ESCAP / WMO टाइफून समिति के सात सदस्यों के भीतर उष्णकटिबंधीय चक्रवातों के बनने की विशेषताओं का अध्ययन प्रस्तुत किया गया है। इस अवधि के दौरान, 167 उष्णकटिबंधीय चक्रवातों के स्थल प्रवेश से 17059 लोग हताहत (मृत और लापता) और 44492 लोग घायल हुए, 271 मिलियन लोग प्रभावित हुए और 101.89 बिलियन अमरीकी डालर (2010) की संपत्ति का नुकसान हुआ। उष्णकटिबंधीय चक्रवातों के स्थल प्रवेश की इन विशेषताओं की जांच करके, लेखकों को आशा है कि इस अध्ययन के निष्कर्ष टाइफून समिति क्षेत्र के भीतर सरकारों और जनता के बीच उपयोगी जानकारी प्रदान करेंगे और साथ ही बेहतर आपदा रोकथाम और तैयारी के लिए प्रभावी अंतर्राष्ट्रीय और क्षेत्रीय सहयोग के बारे में जागरूकता बढ़ाएंगे।

ABSTRACT. Countries in the Asia-Pacific region are more prone to natural disasters than those in other parts of the world. The most common types of disasters in the Asia-Pacific region are associated with impacts caused by tropical cyclones (TCs). Climate change, economic and population growth are contributing to an increase in both the frequency and severity of TCs. This paper studies the characteristics of TCs making landfall within seven Members of the ESCAP/WMO Typhoon Committee based on available data from 2007-2017. During this period, 167 landfalling TCs resulted in 17059 casualties (dead and missing) and 44492 injured, affected the lives of 271 million people and caused 101.89 billion USD (2010) in damage. By examining the characteristics of these landfalling TCs, the authors hope the findings of this study will provide useful information to the governments and the public among Members within the Typhoon Committee region as well as to raise awareness of effective international and regional cooperation for improved disaster prevention and preparedness.

Key words – Landfalling tropical cyclones, Socioeconomic impacts, Asia-Pacific region, Disaster prevention and preparedness.

1. Introduction

Tropical cyclones (TCs) are one of the world's most devastating natural events, causing significant casualties and billions of losses each year within the coastal regions. Around 80-90 TCs form globally every year (Frank and Young, 2006) and the Asia-Pacific region is one of the most active areas with 20-30 TCs annually (Mohanty and Gopalakrishnan, 2016).

In 2013, the United Nations Intergovernmental Panel on Climate Change (IPCC) indicated in its Fifth Assessment Report that climate change poses clear implications to the frequency and intensity of high-impact weather (IPCC, 2013). A number of studies also indicate increasing trends in the frequency of intense TCs in the Northwest Pacific (Elsner *et al.*, 2008; Holland and Cindy, 2014; Kang and Elsner, 2012)

In view of this, the United Nations Economic and Social Commission for Asia and Pacific (UNESCAP) and the World Meteorological Organization (WMO) Typhoon Committee has evolved into a collaboration of 14 Members (Cambodia; China; Democratic People's Republic of Korea; Hong Kong, China; Japan; Lao People's Democratic Republic; Macao, China; Malaysia; the Philippines;

Republic of Korea; Singapore; Thailand; Socialist Republic of Viet Nam and the United States of America).

The Typhoon Committee has growing concern regarding the possible impacts of climate change on TC activity and TC - related effects in the region. The Committee considers it a high priority to understand the possible effects brought about by climate change, such as changes in TC frequency and intensity and to improve the quality of life of the Members through integrated cooperation to mitigate impacts and risks of TC - related disasters. Therefore, this study analyzes the characteristics of landfalling TCs in the Asia-Pacific region during 2007-2017 to develop a more regionally-oriented approach for the purpose of providing insight to the governments and the public within the Typhoon Committee region.

Given the limited data from Cambodia, Democratic People's Republic of Korea and Lao People's Democratic Republic and since no landfalling TCs were recorded in Malaysia and Singapore during this period, these Members are not considered in this study. In addition, this study only includes landfalling TCs named by Regional Specialized Meteorological Center (RSMC) Tokyo. Thus, the Members evaluated in this study are China (including Hong Kong, China and Macao, China), Japan, the Philippines, Republic of Korea and Viet Nam. These members account for almost all landfalling TCs during the period 2007-2017.

The term "TC" used in this paper refers to storms of tropical storm intensity (17.2 m/s - 24.4 m/s) or greater (*i.e.*, tropical storm, severe tropical storm, or typhoon, severe typhoon, or super typhoon).

2. Data and methodology

2.1. *Data*

Due to the lack of a complete dataset in earlier years for some Typhoon Committee Members, this study focuses on those TCs with relatively complete records which made landfall in the Asia-Pacific region from 2007 to 2017. This study relied on information from the Members Report published each year by Typhoon Committee Members during 2007-2017. These reports include data such as maximum sustained wind speed and minimum central pressure as well as disaster indicators that reflect TC - related socioeconomic impacts such as the population affected, dead and missing persons and total damages in local currency.

Data also consist of the best-track dataset for TCs that occurred in the Asia-Pacific region provided by the Shanghai Typhoon Institute of China Meteorological Administration. During the 2007-2017 period, the best-track dataset is believed to contain relatively accurate information for landfalling TCs since data were carefully recorded using all available observations. These data are used to define whether the TC has made landfall and the location of its landfall. In this study, only TCs named by RSMC Tokyo are analyzed but the best track data comes from STI, not RSMC Tokyo.

For more comprehensive details on socioeconomic impacts, we also collect data on fatalities, missing and injured persons and economic losses in Japan from White Paper-Disaster Management in Japan 2017; a TC damage listing from the Japan National Institute of Informatics; data for the Republic of Korea from the National Typhoon Center of Korea Meteorological Administration; data for the Philippines from the Philippine Atmospheric, Geophysical and Astronomical Services Administration; and data for Viet Nam from the Central Steering Committee for Natural Disaster Prevention and Control.

Many open-access databases related to natural disasters have also been examined for this study. For example, population affected, casualties, injured and missing persons and economic losses caused by landfalling TCs in US dollars are provided by the Emergency Event Database (EM-DAT, http://www.em-dat.net/), Asian Disaster Reduction Center (ADRC, http://www.adrc.asia/) and United Nations Office for the Coordination of Humanitarian Affairs (OCHA, http://www.unocha.org/) .

In this study, the societal influences of landfalling TCs are measured by damages in direct economic losses and losses in human life. These data are available for 2007-2017 and thus limit the scope of this study. To make the data comparable from year to year, the direct economic losses are adjusted based on 2010 GDP. Economic data are from United Nations Economic and Social Commission for Asia and the Pacific Database (http://data.unescap.org/), the World Bank Development Dataset (www.econstats.com) and the World Bank Database (https://data.worldbank.org/). These databases constantly update worldwide data.

2.2. *Methodology*

2.2.1. *Normalization of direct economic loss*

Due to rapid economic changes in the Asia-Pacific region, this study normalizes direct economic losses to analyze trends in economic loss from TC - related disasters. The normalization of direct economic losses offers an estimate of the damage if a historical TC had occurred under a different year's socioeconomic condition.

TABLE 1

TC classifications used by different agencies

Comparison of the Tropical Cyclone Classification

Maximum Sustained Wind Speed near the centre of the tropical cyclone			western North Pacific				North Atlantic, central/eastern North Pacific
			Hong Kong, China (10-minute average)	China (2-minute average)	Japan (10-minute average)	United States (1-minute average)	United States (1-minute average)
kt	km/h	m/s	HKO	CMA	RSMC, Tokyo	JTWC	CPHC, NHC
< 34	< 63	< 17.1	Tropical Depression (TD)				
34 – 47	63 – 87	17.2 – 24.4	Tropical Storm (TS)			Tropical Storm	
48 – 63	88 – 117	24.5 – 32.6	Severe Tropical Storm (STS)				
64 – 80	118 – 149	32.7 – 41.4	Typhoon (T)		Typhoon 64 – 84 kts	Typhoon 64 – 129 kts	Hurricane categories 1: 64 – 82 kts
81 – 99	150 – 184	41.5 – 50.9	Severe Typhoon (ST)		Very Strong Typhoon 85 – 104 kts		2: 83 – 95 kts
≥ 100	≥ 185	≥ 51.0	Super Typhoon (SuperT)		Violent Typhoon ≥ 105 kts	Super Typhoon ≥ 130 kts	3: 96 – 112 kts 4: 113 – 136 kts 5: ≥ 137 kts

Note : the conversion between kt to km/h and kt to m/s may vary slightly subject to rounding practices and conversion factor decimal places.
Acronym: HKO: Hong Kong Observatory; CMA: China Meteorological Administration; RSMC: Regional Specialized Meteorological Centre, Tokyo; JTWC: Joint Typhoon Warning Center; CPHC: Central Pacific Hurricane Center, Hawaii; NHC: National Hurricane Center, Miami
References:
-WMO Tropical Cyclone Program Operational Plan / Manual (http://www.wmo.int/pages/prog/www/tcp/operational-plans.html); Typhoon Committee Operational Manual - Meteorological Component, Appendix 1-A Regional Association IV (North America, Central America and the Caribbean) Hurricane Operational Plan
-WMO Severe Weather Information Centre (http://severe.worldweather.org/);
-Hong Kong Observatory, Classification of Tropical Cyclones (http://www.hko.gov.hk/informtc/class.htm)

(Source: http://www.typhooncommittee.org/tropical-cyclone-classification/)

In this study, Consumer Price Index (CPI), used as a measure of inflation, reflects the variation of price changes related to economic development. Economic losses from TCs were normalized to 2010 levels. An equation adapted from (Wang *et al*., 2016) for normalized losses can be written as follows:

$$DEL' = DEL \times \frac{CPI_S}{CPI_t}$$

where, DEL' is the inflation-adjusted current direct economic losses, DEL represents the original direct economic losses, CPI is the Consumer Price Index for each Member, s is the base year (2010) and t is the year in which damage occurred.

2.2.2. *Classification of TCs*

TC classifications vary between Members of the Typhoon Committee. Table 1 shows the different intensity categories used by Hong Kong, China; Japan; and China. For reference, TC classifications used by the Joint Typhoon Warning Center (JTWC) of the United States and classifications for the North Atlantic and eastern and central North Pacific are also included (Table 1).

3. Results & discussion

3.1. *Frequency and intensity of landfalling TCs*

Within the 11-year period, landfalling TC trends vary between Typhoon Committee Members. From 2007 to 2017, a total of 167 TCs made landfall among the seven Members' regions with an average of 15 TCs annually. The variations of landfalling TCs are shown in Fig. 1. The highest number (20) of landfalling TCs occurred in 2017, while the lowest number (11) occurred in 2010. An upward trend in the number of landfall TCs since 2007 can be identified.

The total number of TCs making landfall in different months in the Asia-Pacific region from 2007 to 2017 are shown in Fig. 2. The peak months are September (45), followed by July (34) and August (29). About 64.6% of the 167 TCs made landfall in these three months. No landfalling TCs occurred in February, only one occurred in March and three each occurred in January, April and May. More than half of landfalling TCs (92 or 55%) reached at least typhoon intensity at landfall.

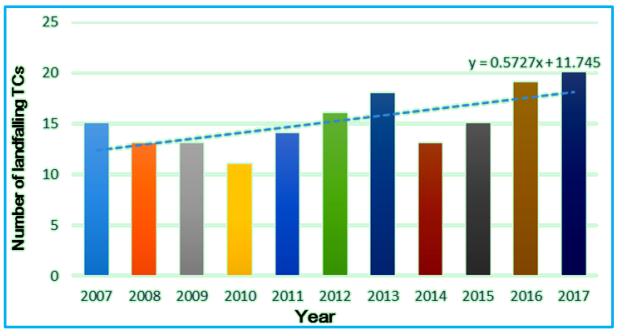

Fig. 1. Annual frequencies of landfalling TCs in the Asia-Pacific region during 2007-2017 (frequency: column; linear trend: dotted line)

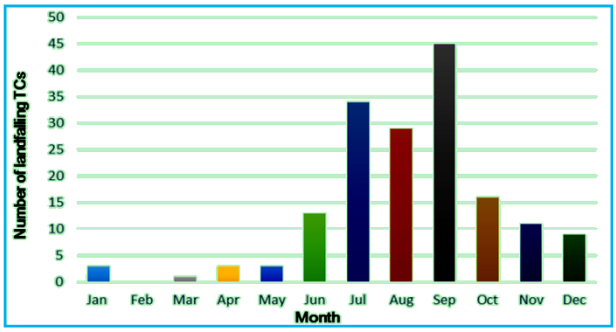

Fig. 2. Frequency of landfalling TCs in the Asia-Pacific region by month during 2007-2017

3.2. *Distribution of landfalling TCs by countries*

China and the Philippines show the greatest risk from TC landfalls, as 82 TCs made landfall in China and 57 in the Philippines (Fig. 3). Viet Nam, Japan and the Republic of Korea each had 40, 31 and 7 landfalls, respectively. In China, the most landfalls occurred in 2008 with 10 events, followed by 2009 when 9 TCs made landfall. Japan had no landfalling TC in 2008. The Republic of Korea had TCs made landfall only in 2007, 2010, 2012 and 2016. The trends for landfalling TCs by country varies. An upward trend exists in Japan, the Philippines and Viet Nam, but a downward trend occurs in China. There was no visible trend in the number of landfalling TCs in the Republic of Korea.

3.3. *Casualties*

Based on historical data of losses caused by TC - related disasters during 2007-2017, the total number of casualties in the 11 years was 17059, with an annual average of 1550 casualties (including dead and missing persons) due to landfalling TCs. The largest number occurred in 2013 (Fig. 4). Super Typhoon Haiyan caused the most casualties that year in the Philippines with 7391 deaths. On average, landfalling TCs kill 1401 people in the Philippines, 174 in China and 99 in Vietnam annually

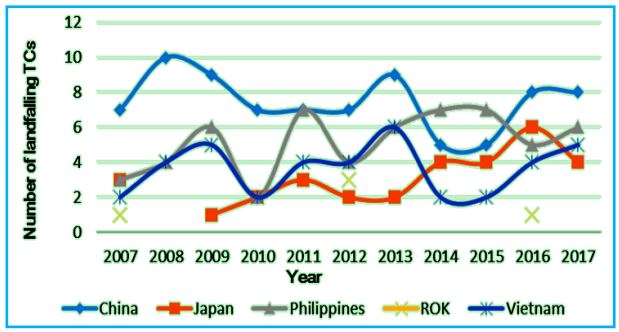

Fig. 3. Number of landfalling TCs among the seven evaluated Members in the Asia-Pacific region (In the figure, ROK represents the Republic of Korea)

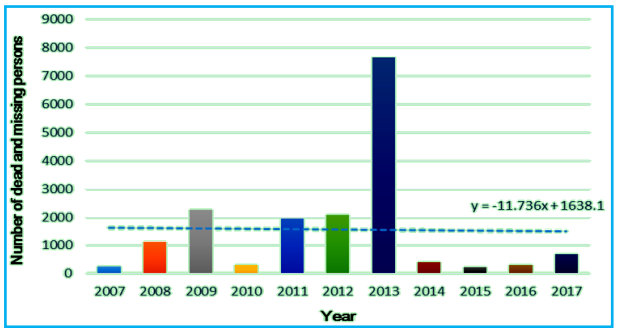

Fig. 4. Casualties (dead and missing persons) per year during 2007-2017

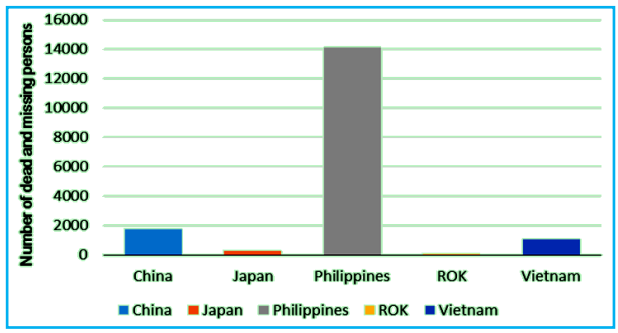

Fig. 5. Casualties (dead and missing persons) per evaluated Member during 2007-2017

(Fig. 5). The number of casualties caused by landfalling TCs from 2014-2017 was significantly lower than earlier years, yet more landfalling TCs were recorded in 2016-2017. The main reason for this decrease is attributed to the Typhoon Committee's Members conducting a strategic plan to protect their people's lives and to improve their quality of life through regional coordination and cooperation.

3.4. *Affected persons*

Based on historical data of affected population caused by TC disasters during 2007-2017, the total

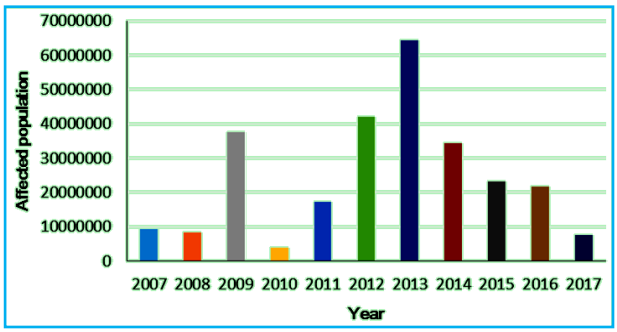

Fig. 6. Affected population in the Asia-Pacific region during 2007-2017 by year

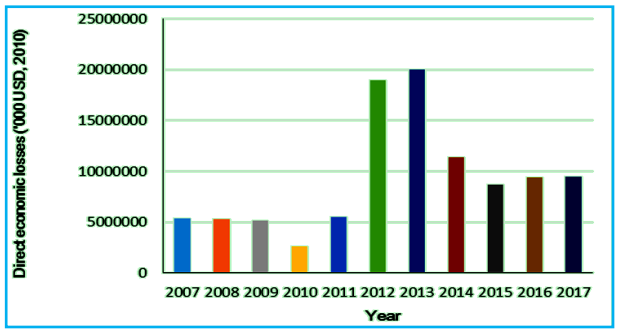

Fig. 8. Direct economic losses per year in the Asia-Pacific region during 2007-2017

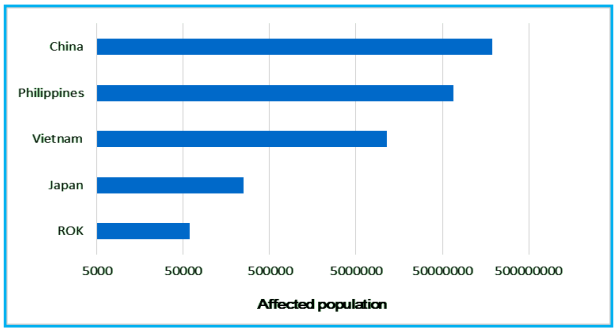

Fig. 7. Affected population in the Asia-Pacific region during 2007-2017 among evaluated Members

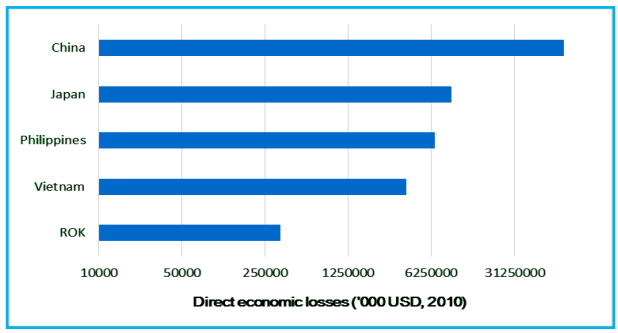

Fig. 9. Direct economic losses in the Asia-Pacific region during 2007-2017 among evaluated Members

number of affected persons in the 11 years was 271,549,432, with an annual average of 24,686,312 due to landfalling TCs (Fig. 6). The population affected by landfalling TCs steadily decreases after 2013. The area with the most affected population is China, followed by the Philippines, Viet Nam, Japan and the Republic of Korea (Fig. 7).

3.5. *Variability of direct economic losses*

From 2007 to 2017, the CPI - normalized direct economic losses caused by 167 landfalling TCs among seven Members were 101.89 billion USD (2010), with an annual average of 9.26 billion USD (2010). Fig. 8 might imply steadily increasing economic losses during the 11-year period, but much of the trend is caused by extremely heavy economic losses in 2012 and 2013. The highest loss was 19.99 billion USD in 2013. The subsequent costliest years were 2012 (18.97 billion USD). Severe Typhoon Fitow of 2013 was the costliest TC to occur between 2007 and 2017. Fitow made landfall in Fujian and Zhejiang provinces in China. It caused 9.03 billion USD (2010) in direct economic losses in China.

3.6. *Direct economic loss by Members*

The annual losses of the seven Members in the Asia-Pacific region varies. China experienced the highest losses (81.7 billion USD, 2010), followed by Japan and the Philippines with 9.2 billion and 6.7 billion USD respectively (Fig. 9). Heavy economic losses can be attributed to high frequency of landfalling TCs and also by one or several individual costly landfalling TCs. Economic loss caused by landfalling TCs in relation to the total gross domestic product (GDP) (2010 USD) is 0.102% in China, 0.014% in Japan, 0.003% in the Republic of Korea, 0.267% in the Philippines and 0.264% in Viet Nam.

4. Conclusions

The Asia-Pacific region is heavily impacted by TCs. It suffers severe damage and numerous casualties each year. From 2007 to 2017, 167 TCs made landfall in the seven Members' area of the Asia-Pacific with an average of 15 TCs annually. The highest number (20) of landfalling TCs occurred in 2017, while the lowest number (11) occurred in 2010. The peak months of landfalling TCs are September (45), followed by July (34) and August (29), comprising 64.6% of TCs that made landfall within the eleven-year period. An upward trend in the number of landfalling TCs since 2007 can be identified, though it must be noted that only 11 years are examined in this study. During the 2007-2017 period, 92 landfalling TCs reached the intensity of typhoon or higher

at landfall, which accounted for 55% of the total. Spatially, China and the Philippines are at the greatest risk of TC landfall. The most landfalling TCs occurred in China (82), followed by the Philippines (57), Viet Nam (40), Japan (31) and the Republic of Korea (7).

TCs are high-frequency natural disasters that cause serious losses. The total number of casualties (including dead and missing) in the 11 years was 17059, with an annual average of 1550 casualties. The number of casualties caused by landfalling TCs from 2014-2017 was significantly lower than earlier years, even though more landfall TCs were recorded in 2016-2017. The main reason for this decrease is attributed to the Typhoon Committee's Members conducting strategic plans to protect their people's lives during TC landfall events through regional coordination and cooperation. The total number of affected population in the 11 years was 271 million, with an annual average of 24.6 million people. After a peak in 2013, the population affected by landfalling TCs steadily decreases.

From 2007 to 2017, the CPI-normalized direct economic loss has been steadily rising with a total of 101.89 billion USD (2010) and an annual average of 9.26 billion USD (2010). China experienced the highest losses (81.7 billion USD, 2010), followed by Japan and the Philippines with 9.2 billion and 6.7 billion USD respectively. TC-induced risks have been rising mainly due to the region's rapid economic growth and the increasing exposure of people and assets to TC hazards.

The authors hope the findings of this study will enhance the scientific knowledge on the characteristics of landfalling TCs and provide useful information to the governments and the public among Members within the Typhoon Committee region. With improved understanding of landfalling TC impacts, the Typhoon Committee will move closer to the goal of substantially reducing total mortality caused by typhoon-related disasters within the Members and reducing direct economic losses caused by typhoon-related disasters as a fraction of total GDP of the Members by 2030.

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