ARTICLE IN PRESS

Int J Appl Earth Obs Geoinformation xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag

Increasing threat of landfalling typhoons in the western North Pacific between 1974 and 2013

Shoude Guan, Shuiqing Li*, Yijun Hou, Po Hu, Ze Liu, Junqiao Feng

Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences and Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

A R T I C L E I N F O

Keywords:
Western North Pacific
Landfalling typhoon
Long-term change
Landfall intensity
Tropical cyclone heat potential
Power dissipation index

A B S T R A C T

Long-term changes between 1974 and 2013 were investigated in western North Pacific typhoons making landfall in East and Southeast Asia. Landfalling typhoon parameters, including the percentage of typhoons making landfall, the annual mean landfall intensity (LFI), and the annual accumulated power dissipation index at land, all increased significantly (at the 99% confidence level), by 14%, 17%, and 94%, respectively, over the study period. The increase in probability of a typhoon making landfall was attributed to an eastward shift of the typhoon genesis location. The LFI was decomposed into the product of the intensification rate and intensification duration. The product reproduced variations in the observed LFI well, and the correlation coefficient was high at 0.82. Although the intensification duration decreased slightly, an unprecedented increase in the intensification rate was observed, this increased the LFI. Warming of the upper ocean in the western North Pacific typhoon main intensification region, giving a higher tropical cyclone heat potential, yielded better oceanic conditions and overcame the worsening atmospheric conditions (increasing vertical wind shear), allowing typhoons to intensify. The increase in the annual accumulated power dissipation index was mainly caused by the increase in the LFI, and the annual number of typhoons and typhoon duration contributed much less. Increasing typhoon landfalling activities might heighten the threat posed by typhoons to populations and infrastructure in coastal regions.

1. Introduction

Typhoons are among the most destructive and deadly natural disasters on earth (Emanuel, 2003). They are more frequent and intense in the western North Pacific (WNP) than in the other oceans, with more than 25% typhoons occurring in the WNP (Webster et al., 2005). Every year, typhoons in the WNP severely threaten nearly a billion people in East and Southeast Asia. Typhoons are becoming more intense as the climate warms (Emanuel, 2013; Jin et al., 2014; Knutson et al., 2010), and Pielke et al. (2008) found that economic losses caused by typhoons have recently increased considerably because more intense typhoons generally cause much more damage than less intense ones. Considering that typhoons making landfall with strong wind gusts and heavy rainfall cause the major disasters (e.g., storm surges and floods), any variability and long-term changes in the frequencies and intensities of typhoons making landfall in the WNP are of great interest to East and Southeast Asian countries.

It has been shown in previous studies that interannual-to-decadal variability in typhoon activity (represented by parameters such as typhoon intensity, frequency, and lifetime) is strongly influenced by the phases of the El Niño-southern oscillation (ENSO) (Camargo and Sobel, 2005; Chan, 2000; Wang and Chan, 2002; Wang et al., 2007; Wang et al., 2013; Zheng et al., 2015). The typhoon genesis region usually shifts south-eastwards in El Niño years, allowing typhoons to travel for longer periods and over longer distances over the warm ocean, which in turn allows them to become more intense. The situation may be reversed in La Niña years. The ENSO could also affect the landfall pattern of WNP typhoons by shifting the locations of typhoon genesis towards or away from land and by altering the large-scale atmospheric circulation (Camargo et al., 2007; Elsner and Liu, 2003; Kim et al., 2011; Wu et al., 2004). The Pacific decadal oscillation further modulates typhoon activity on a multidecadal timescale by altering large-scale atmospheric and oceanic conditions over long periods (Chan, 2008; Sun et al., 2017; Wang and Liu, 2015).

Long-term increases in typhoon activity in the WNP have been found in many studies, and have been ascribed to upper-ocean warming

Abbreviations: ENSO, El Niño-southern oscillation; ID, Intensification duration; IR, Intensification rate; JTWC, Joint Typhoon Warning Center; LFI, Landfall intensity; LMI, Lifetime maximum intensity; PDI, Power dissipation index; SST, Sea surface temperature; TCHP, Tropical cyclone heat potential; VWS, Vertical wind shear; WNP, Western North Pacific

* Corresponding author at: No. 7 Nanhai Road, Qingdao 266071, China.
E-mail addresses: guanshoude@qdio.ac.cn (S. Guan), lishuiqing@qdio.ac.cn (S. Li), yjhou@qdio.ac.cn (Y. Hou), hupo@qdio.ac.cn (P. Hu), liuze@qdio.ac.cn (Z. Liu), fengjunqiao@qdio.a.cn (J. Feng).

https://doi.org/10.1016/j.jag.2017.12.017
Received 30 September 2017; Received in revised form 27 December 2017; Accepted 31 December 2017

Please cite this article as: Guan, S., Int J Appl Earth Obs Geoinformation (2018), https://doi.org/10.1016/j.jag.2017.12.017

in response to climate change (Emanuel, 2005; Mei et al., 2015; Webster et al., 2005). For example, Webster et al. (2005) found that the number and proportion of intense typhoons reaching categories 4 and 5 have increased considerably since the 1970s. Emanuel (2005) reported that the power dissipation indices (PDIs) of WNP typhoons have increased by 35%, linked to increasing sea surface temperature (SST). Mei et al. (2015) attributed increased lifetime maximum intensities (LMIs) of typhoons to upper-ocean warming at low latitudes of the WNP, and predicted a further 14% increase by 2100 due to further upper-ocean warming. Although the projected changes in typhoon frequency by global warming vary widely and are sometimes contradictory among different modelling experiments, a consistent increase in the typhoon intensity is projected through the global warming (Emanuel, 2013; Knutson et al., 2015).

Given that nearly all typhoon-related damage is associated with landfalling typhoons, and the populations of coastal regions are growing steadily, variability and long-term change of typhoon landfalling activities are of great concern to Asia and Southeast Asian countries. The ENSO and global warming not only modulate typhoon activity at sea but also influence typhoon landfalling activities. Kubota and Chan (2009) suggested that strong interdecadal variability in the number of landfalling typhoons in the Philippines is related to the ENSO phases and to Pacific decadal oscillation. Park et al. (2011) demonstrated that the number of landfalling typhoons over Japan and Korea increased significantly between 1977 and 2008 due to enhanced northward steering flows over the East China Sea. Typhoon activity in the WNP and the relationships between typhoon activity and the ENSO and climate change have been investigated extensively in numerous studies, but few studies have focused on long-term changes in typhoon landfall in East and Southeast Asia. Mei and Xie (2016) focused on long-term increases in the LMIs of landfalling typhoons since the late 1970s, but they did not examine long-term changes in landfall intensity (LFI). The main objectives of the present study were to investigate variability and long-term changes in WNP typhoon landfall parameters (mainly focusing on LFI) between 1974 and 2013, and to identify the atmospheric and/or oceanic factors that control changes in LFI.

2. Data and methods

The best-track datasets for WNP typhoons were obtained from the US Joint Typhoon Warning Center (JTWC). The JTWC provides six-hourly locations and intensities of typhoons (measured as the 1-min sustained maximum wind speed, V_{max}), from 1945 to the present. The JTWC estimates the tracks and intensities of typhoons using the Dvorak method (Chu et al., 2002), based on data sources from multi-sensor satellite images, taking *in situ* observations into account (for example, aircraft dropsondes, ships, and buoys). In this study, long-term changes in typhoon LFI over the period 1974–2013 were investigated because the global ocean has experienced unprecedented warming since the mid-1970s. In addition, with the application of satellite observations, the estimation of typhoon intensity is more consistent since the 1970s.

According to the widely used Saffir–Simpson tropical cyclone scale, tropical cyclones are categorized as tropical depression ($V_{max} < 18\,m\,s^{-1}$), tropical storm ($18\,m\,s^{-1} < V_{max} < 33\,m\,s^{-1}$), and typhoons ($V_{max} > 33\,m\,s^{-1}$). Typhoons in categories 1–5 are defined as tropical cyclones with V_{max} 33–43, 43–50, 50–56, 56–67, and > 67 $m\,s^{-1}$, respectively. Because of their large destructive potential, we only focus on the landfalling typhoons with LMI reaching at least category 1. In this study, a typhoon is defined as making landfall when its centre is within 10 km of the coastline (Fig. 1). About 640 tropical cyclones reached typhoon intensity and nearly 400 made landfall on the Asian continent during the study period. On average, more than 60% of all WNP typhoons made landfall in the study period.

The LFI of a typhoon is defined as the maximum wind speed when the typhoon first makes landfall. The widely used metric of typhoon intensification rate (IR) is adopted here to explore the dependence of the intensification process on large-scale atmospheric and oceanic conditions. For each typhoon location, the IR (in $m\,s^{-1}$ per 12 h) was computed by central differencing the maximum wind speed at 12-h intervals. A mean IR was then determined for each typhoon by simply averaging the IRs for all locations during the intensification period from genesis to first landfall. The length of the intensification period is called the intensification duration (ID).

Changes in typhoon intensity are controlled by the surrounding atmospheric and oceanic conditions, including vertical wind shear (VWS), SST, and tropical cyclone heat potential (TCHP). The European Centre for Medium-Range Weather Forecasts monthly interim reanalysis database, produced on a $1^\circ \times 1^\circ$ grid, was used to calculate VWS based on the difference between the wind vectors at 200 and 850 hPa. SST and TCHP changes between 1979 and 2013 were obtained from the monthly ORA-S4 reanalysis dataset ($1^\circ \times 1^\circ$). All the variables were averaged over the typhoon season (July–October) to represent the long-term changes of atmospheric and oceanic conditions.

In the present study, we focused on long-term changes in the annual mean typhoon intensity, IR, and ID, calculated by averaging the intensities, IRs, and IDs for all landfalling typhoons in a given year. Furthermore, to exclude noise from interannual variations and highlight the long-term changes in typhoon activity, a five-weight filter was applied to the related variables (Emanuel, 2007). The filter equation is

$$s_n^f = \frac{(s_{n-2} + s_{n+2}) + (s_{n-1} + s_{n+1}) \times 3 + s_n \times 4}{12}, \quad (1)$$

where s_n^f is the filtered value of the variable for the target year, s_n is the raw value for the target year, and $s_{n \pm i}$ is the raw value for the year i years before or after the target year.

3. General characteristics of landfalling typhoons

Typhoons in the WNP generally make landfall over mainland China, Japan, Korea, the Philippines, Taiwan, and Vietnam. The categories and locations of typhoons at and after landfall between 1979 and 2013 are shown in Fig. 1. The LFI of a typhoon is usually smaller than its LMI due to decay related to decreased moisture supply and increased friction as the typhoon approaches land. The LMI and LFI probability distribution functions, and their differences for the different typhoon categories, are shown in Fig. 2. Only those typhoons with LMIs reaching at least category 1 were considered in this study, but nearly 40% of them made landfall as tropical depressions or tropical storms. About 39% of all typhoons during the study period reached categories 4 or 5, but only 5% of these were at categories 4 or 5 when they made landfall.

It can be seen from Fig. 3a that most typhoons made landfall south of 25°N. South China, Taiwan, and the Luzon islands suffered the most frequent typhoons (~3.7 y^{-1}) during the study period. North of 25°N, the landfalling typhoon frequency decreased rapidly, but there was a secondary peak (~2.2 y^{-1}) at about 35°N. These typhoons mostly made landfall over Korea and Japan because of the strong westerly steering flow at mid-latitudes, thus these typhoons tended to recurve east of Taiwan and head for Korea and Japan.

Fig. 3b shows that the mean and historical maximum LFIs both gradually decrease from south to north. It should be noted that Taiwan and the Philippines, which are closest to the main typhoon intensification region (Mei et al., 2015), suffered the strongest typhoons (Figs. 1 and 3b). The highest historical maximum LFI during the study period, 85 $m\,s^{-1}$, occurred when super typhoon Haiyan (2013) hit the Philippines, causing catastrophic destruction (Lander et al., 2014; Lin et al., 2014).

Between 1974 and 2013, the total annual number of typhoons decreased slightly, by 0.3 typhoons per decade, but the number of landfalling typhoons increased slightly, by 0.4 typhoons per decade, although both trends had low confidence levels (Fig. 4a). However, the ratio of the number of landfalling typhoons to the total number of typhoons increased significantly (at the 99% confidence level), by nearly