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An abrupt increase of intense typhoons over the western North Pacific in early summer

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Abstract
The frequency and intensity of typhoons have been a focus in studying typhoon-related climate changes. In this study, we focus on a seasonal cycle of intense typhoons (category 4 and 5) over the western North Pacific, particularly changes in the number of intense typhoons in early summer. In general, 81% of intense typhoons occur in July–November (JASON), with maxima in September and October. Our analysis shows that intense typhoons have tended to occur more frequently in May since the year 2000. Before 2000, intense typhoons seldom occurred in May, with a frequency of around once per decade. After 2000, however, the frequency of intense typhoons has become much higher in May—almost once per year. We have also examined changes in the large-scale environment in the past few decades. The results show that the large-scale environment did become more favorable for intense typhoons in the 2000s, which is consistent with a larger tropical cyclone genesis index. The changes include warmer sea surface temperature, higher sea surface height, larger upper-ocean heat content, weaker vertical wind shear, increased tropospheric water vapor, and greater water vapor in the mid-troposphere. The last two might be more important than the others.

Keywords: intense typhoon, global warming, seasonal cycle, abrupt change

1. Introduction
Long-term changes in intensity and frequency of tropical cyclones have been studied intensively in the past few years. Emanuel (2005) finds a great increase in hurricane power dissipation, which is related to hurricane lifetime and intensity, in the North Atlantic and the western North Pacific in the past 30 years. Webster et al (2005) indicate a large increase in the number of category 4 and 5 hurricanes on the Saffir–Simpson hurricane scale and the associated hurricane days over the past 35 years, with the largest increase in the North Pacific, the Indian Ocean and the Southwest Pacific. However, other studies show a small or nonexistent trend in tropical cyclones in most oceans (Klotzbach 2006, Kossin et al 2007), or an interdecadal oscillation, rather than a trend, in the western North Pacific (Chan 2006). The inconsistency in the long-term change of tropical cyclone activity might be due to the quality of tropical cyclone datasets (Landsea et al 2006). Besides tropical cyclone intensity and frequency, changes in the track have also been detected (Wu et al 2005, Tu et al 2009).

Warm sea surface temperature (SST) could provide a favorable environment for tropical cyclone development (Emanuel 2007). Subsurface ocean structure is also important, particularly for intense tropical cyclones, because a deep warm ocean layer can weaken the typhoon-induced cooling effect (Lin et al 2008, Lynn and Brewster 2010). Thus, tropical
cyclone activity is strongly linked to local oceanic conditions. Since the SST has had an upward trend in the past few decades, which might be due to global warming, the increasing trend of tropical cyclone activity, particularly over the Atlantic, is often thought to be caused by this SST warming trend (Emanuel 2005, Webster et al 2005, Hoyos et al 2006, Santer et al 2006, Elsner et al 2008, Saunders and Lea 2008). Some studies, on the other hand, propose that the spatial distribution of SST should be more responsible for changes in tropical cyclone activity than local warm SST (Vecchi and Soden 2007, Vecchi et al 2007, Knutson et al 2010).

Previous studies focus mainly on changes in typhoon frequency and intensity. In this study, we would like to shift our attention to a seasonal cycle of typhoon occurrence, particularly for intense typhoons over the western North Pacific (WNP). In section 2, we briefly describe the datasets that we used here. Changes in the seasonal cycle of typhoon occurrence, particularly in the frequency of intense typhoons during early summer, are discussed in section 3. In section 4, we examine changes in the large-scale environment that might be responsible for the early occurrence of intense typhoons, followed by discussion and conclusions.

2. Data

In this study, the best track typhoon data from the Joint Typhoon Warning Center (JTWC) for the period of 1970–2009 was primarily used. Here typhoons are defined as having a maximum surface wind speed of over 34 knots, and intense typhoons are defined as having a maximum surface wind speed of over 114 knots, which is equivalent to category 4 and 5 hurricanes in the Saffir–Simpson hurricane scale. The surface wind speed is a 1 min average. Some studies show a possible inconsistency among best track datasets (Nakazawa and Hoshino 2009, Wu et al 2006), so two other typhoon track datasets are also examined and compared with the JTWC dataset. One is from the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center and the other is from the International Best Track Archive for Climate Stewardship (IBTrACS) project (Knapp and Kruk 2010, Knapp et al 2010). The surface wind speed used to define typhoons in these two datasets is the 10 min average. There are no simple and consistent formulas to convert the 10 min wind speed to a 1 min wind speed, but the intense typhoons defined in the JTWC dataset, i.e., with the maximum surface wind speed stronger than 114 knots, are roughly equivalent to the typhoons with the maximum surface wind speed stronger than 93 knots in the RSMC and IBTrACS datasets, based on a remapping method discussed in Knapp and Kruk (2010).

Several atmospheric and oceanic variables were examined to understand the influences of the large-scale environment on intense typhoons in the WNP. Water vapor, relative humidity and winds in 1980–2009 were derived from the NCEP/DOE AMIP-II Reanalysis (Reanalysis-2) (Kanamitsu et al 2002). Monthly extended reconstruction SST version 3 in 1980–2009 (Smith et al 2008) was used. Sea surface height anomalies (SSHA) in 1993–2009 derived from the Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) (Ducet et al 2000), ocean temperature derived from the Simple Ocean Data Assimilation (SODA) in 1980–2007 (Carton et al 2000b, 2000a), and upper-ocean (0–700 m) heat content in 1980–2009 derived from the National Oceanographic Data Center (NODC) were also used.

3. Occurrence of intense typhoons

Figure 1 shows the occurrence of typhoons and intense typhoons from JTWC, which is defined as the time when the maximum surface wind speed of tropical cyclones first reaches 34 knots and 114 knots, along with annually accumulative numbers for typhoons and intense typhoons in the WNP, respectively. Based on the record for 1970–2009, the annual average number of typhoons is 26.4. The most active years are 1971, 1994 and 1996, in which there are over 32 typhoons per year; the least active years are 1977 and 1998, in which
there are fewer than 20 typhoons per year. The annual typhoon number also shows a decadal variation, with an active period in 1989–1998 (average of 30.2 typhoons per year) and inactive periods in 1975–1988 (average of 24.7 typhoons per year) and 1998–2009 (average of 23.8 typhoons per year). However, no clear long-term trends are found in the past four decades, which is consistent with previous studies (Chan and Liu 2004, Webster et al. 2005). Besides typhoon numbers, typhoon occurrences also show clear interannual and decadal variations for the occurring time of the first typhoon in each year. In the interannual variation, the first typhoon has occurred in the WNP as early as January, as in 2005 and 2008, and as late as July, as in 1998. In the decadal variation, the first typhoon occurred late in the periods of 1979–1984 and 1993–2001, but earlier in the periods before 1979 and 1985–1992 (figure 1(a)).

For intense typhoons, on the other hand, the variation of typhoon frequency is different from the total number of typhoons (figure 1(b)). First, the averaged number of intense typhoons is $6.4 \text{yr}^{-1}$ in 1970–2009. There is a clear increasing trend in the number of intense typhoons. Prior to 1990, the annual averaged number of intense typhoons is about 5. This number goes up to 7.3 in the 1990s and increases to 8 in the 2000s. However, this increasing trend is not as clear as in RSMC and IBTrACS (not shown). Another interesting feature of intense typhoons is the occurring time of the first intense typhoon in each year, which can also be found in figure 1(b). Intense typhoons show clear interannual and interdecadal variations. Intense typhoons can occur as early as January, but they can also occur as late as November.

Before further discussing the change in the occurrence of intense typhoons, we first examine the seasonal variation of intense typhoons over the WNP, which is similar in all three datasets. In 1970–2009, 254 intense typhoons were detected, based on JTWC. Most intense typhoons (81%) occur in July–November (JASON). Intense typhoons are rare in January–March, and sharply increase in July when the Asian summer monsoon trough appears (LinHo and Wang 2002, Chou et al. 2009), with the maximum in September and October. We next examine changes in the seasonal cycle of intense typhoons. Figure 2(b) shows that not only the total number of intense typhoons, but also the associated seasonal cycle is changed. Intense typhoons have clearly increased in the last two decades and most of the increases occurred in four individual months, May, June, August and September. In this study, we focus on the increase of intense typhoons in May, which is the most significant change in the seasonal cycle of intense typhoons. The number of intense typhoons is five times larger in the last decade than in the previous three decades. The increased number of intense typhoons in May implies that more intense typhoons have occurred earlier in the last decade, i.e., 2000–2009. Figure 2(c) further shows the accumulation of intense typhoons in May in 1970–2009. Only one intense typhoon is found in the 1970s and 1980s and two are found in the 1990s, so intense typhoons seldom occurred in May in the first three decades. However, they have been found almost every year since 2000, and even two in 2008. Overall, intense typhoons over the WNP have tended to occur much more frequently in May after 2000.

Two other best track datasets, RSMC and IBTrACS, are also examined. Here an intense typhoon is defined as having a maximum surface wind speed larger than 93 knots, based on Knapp and Kruk (2010). There are no differences in the number of intense typhoons in May between RSMC and IBTrACS (figure 2(c)). With this definition, changes in the seasonal cycle of intense typhoons are similar to those found in the JTWC data (figure 2(c)). The increase in the number of intense typhoons in May after 2000 is consistently found in all three datasets. In other words, the change of intense typhoons in May is robust. We also examine the change of intense typhoons in May with different definitions of the maximum surface wind speed. We note that the interval for the maximum surface wind speed is 5 knots in all three best track datasets. The change, i.e., the abrupt increase in the 2000s, is similar, even though the typhoon numbers are different (table 1). Thus, the abrupt increase of intense typhoons in May is not sensitive to the definition of intense typhoons. Besides May, the increase of intense typhoons is also found in June, August and September for both RSMC and IBTrACS (figure 3), similarly to JTWC (figure 2(b)).
Figure 3. As in figure 2(b), but for (a) RSMC and (b) IBTrACS.

Table 1. Numbers of intense typhoons in three decades, the 1980s, 1990s and 2000s, for different definitions of intense typhoons, 85, 90 and 95 knots, using three best track datasets, JTWC, RSMC and IBTrACS.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>JTWC</th>
<th>RSMC</th>
<th>IBTrACS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition (knots)</td>
<td>85</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>1980s</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>1990s</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2000s</td>
<td>10</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

We further examine changes in different strengths of typhoons over the WNP (figure 4). Here we use typhoon frequency, instead of typhoon numbers, since typhoon frequency, which is similar to typhoon days (not shown), shows more robust results among best track datasets (Kamahori et al. 2006). Typhoon frequency is the occurrence of typhoons counted for each 6 h interval for each grid box of 2.5° × 2.5° (e.g., Tu et al. 2009). For weaker typhoons, category 1 or less in JTWC and typhoons with the maximum surface wind speed less than 65 knots in RSMC and IBTrACS, no clear and consistent trends are found among these three best track datasets. For medium-strength typhoons, category 2 and 3 in JTWC and the maximum surface wind speed between 65 and 94 knots in RSMC and IBTrACS, the corresponding typhoon frequency increases in the 2000s. This increase is not found in the typhoon number (not shown), which is mainly due to changes in the lifespan of medium-strength typhoons. For intense typhoons, an increase in typhoon frequency in the 2000s also exists, with a relatively larger increase in JTWC than in RSMC and IBTrACS.

4. Large-scale environment in May

What causes the early occurrence of intense typhoons over the WNP? Previous studies have listed some favorable oceanic and atmospheric conditions for typhoon development, such as a warmer ocean, increased moisture in the mid-troposphere and weaker vertical wind shear (Gray 1979, DeMaria 1996, Frank and Ritchie 2001, Kaplan and DeMaria 2003, Goldenberg et al. 2001, Emanuel 2007, Latif et al. 2007, Zeng et al. 2007). Some recent studies found that an increase of intense typhoons in the Atlantic in the past few decades is associated with a warmer ocean condition (Emanuel 2005, Webster et al. 2005, Elsner et al. 2008, Saunders and Lea 2008, Bender et al. 2010, Knutson et al. 2010). These warm and favorable conditions not only exist in the Atlantic but also occur globally (Levitus and Boyer 2000, Levitus et al. 2005, Church and White 2006, Held and Soden 2006, Domingues et al. 2008, Lyman et al. 2010). Thus, they could also induce changes in typhoon activity in other basins, such as the WNP. In this section, we will examine these large-scale environmental changes in May, particularly via comparisons between 1980–99 and 2000–9.
Figure 5. Large-scale environmental changes before and after 2000 in May for (a) SST, (b) SSHA, (c) mid-troposphere relative humidity, and (d) vertical wind shear. The data length is from 1980 to 2009, except for SSHA, which is from 1993–2009. The dots represent the intense typhoon tracks in May 2000–9.

The relationship between upper-ocean thermal structure and typhoon intensity has been discussed in many studies for a summer season (Emanuel et al. 2004, Emanuel 2005, Webster et al. 2005, Lin et al. 2005, 2008, Wu et al. 2007), so we first examine changes in the upper ocean in May only. Figures 5(a) and (b) show differences in oceanic conditions between the 1990s and 2000s. Since changes in upper-ocean heat content and the depth of the 26°C isotherm are similar to changes in SSHA, we only show SSHA here. Warmer SST and higher SSHA are found in the 2000s, especially over the area of 130°E–160°E and 10°N–15°N, a region where most typhoons develop into intense typhoons. We further examine the atmospheric conditions in May. The mid-troposphere (500 hPa) becomes moister (figure 5(c)) and vertical wind shear, which is defined as the difference of winds between the upper (200 hPa) and lower troposphere (850 hPa), is weakened in the most recent decade, i.e., 2000–9. Overall, both oceanic and atmospheric conditions shift to favoring typhoon development.

In May of 1970–2009, more than 95% of intense typhoons over the WNP occurred within the box of 122°E–160°E and 5°N–25°N. Thus, we next examine temporal variations of large-scale variables averaged over this region, which include SST, SSHA, upper-ocean heat content (0–700 m), tropospheric water vapor, mid-tropospheric relative humidity, vertical wind shear, and the depth of the 26°C isotherm (figure 6(a)). We note that all changes shown in figure 6 are normalized by their own standard deviation. It is clear that almost all large-scale variables, except vertical wind shear, sharply increase around 2000 and maintain the changes throughout almost the entire 2000s. These changes imply that the large-scale environment over the WNP suddenly becomes favorable for
typhoon development in May. Vertical wind shear shows a much stronger interannual variation, with maxima in 1983 and 1998, the decaying years of the two strongest El Niño in the 20th century. Besides the interannual variation, vertical wind shear also shows a slightly downward trend in the past few decades. Thus, vertical wind shear did become weaker in the last decade, which is consistent with the result in figure 5(d).

A tropical cyclone genesis (TCG) index (Tippett et al 2011) has been developed to measure the influence of the large-scale environment on tropical cyclone genases. The larger the TCG index, the more favorable tropical cyclone genesis. The TCG index includes four large-scale variables, low-level absolute vorticity, relative humidity, relative SST, and vertical wind shear. Figure 6(a) shows a clear increase in the TCG index in the 2000s.

We further examined the variation of large-scale environment in June (figure 6(b)), when the mean state is similar (Chou et al 2009), but the number of intense typhoons did not increase as much as in May. Compared to the variation in May (figure 6(a)), the most distinct differences between these two months are changes in water vapor. In June, tropospheric water vapor and mid-tropospheric relative humidity, which are larger than the climatology in May, are slightly smaller than the climatology in the 2000s. This implies that moisture in the troposphere might be more important in inducing the abrupt increase of intense typhoons in May than the other factors. The importance of the mid-tropospheric water vapor has also been discussed in previous studies for an intraseasonal time scale (Camargo et al 2009, Huang et al 2011). Besides changes in water vapor, the TCG index in June did not show any clear increase in the 2000s (figure 6(b)), such as in May (figure 6(a)). This also implies a less favorable condition for tropical cyclone genases in June.

5. Discussion and summary

Long-term variability of intense typhoon activity has attracted a lot of attention recently. Many studies show the increasing intensity of tropical cyclones in a warming environment over the past 40 years, particularly over the Atlantic (Emanuel 2005, Webster et al 2005, Elsner et al 2008, Saunders and Lea 2008, Bender et al 2010, Knutson et al 2010). In this study, we shifted the focus to a seasonal cycle of intense typhoons, with particular emphasis on an abrupt increase of intense typhoons over the WNP in May. Our study shows that intense typhoons over the WNP have tended to occur more in early summer since 2000. Here we examined the frequency of intense typhoons in May. Intense typhoons were very rare in May before 2000, occurring only once per decade. However, the number has increased to almost one per year after 2000. We further examined those large-scale variables that might be responsible for the increase of intense typhoons in May. We found that most large-scale conditions have become favorable for intense typhoons, such as warmer SST, higher upper-ocean heat content, greater water vapor in the troposphere, higher mid-troposphere relative humidity, and possible weaker vertical wind shear, which are all consistent with a larger tropical cyclone genesis index. Among them, increases in tropospheric water vapor and mid-tropospheric relative humidity might be more important than the others. However, why the large-scale environment has become favorable for intense typhoon development in May after 2000 is an ongoing research topic that will be further examined in the near future.

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