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Possible impacts of global warming on typhoon activity in the vicinity of Taiwan

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1. Introduction

Typhoons are one of the most extreme natural events over the western North Pacific–East Asian (WNP–EA sector). Typhoons often affect the spatial distribution of regional precipitation in summer since they are a major source of rainfall over this region. For example, in 2004, 10 typhoons occurred in Japan and brought more than usual precipitation, causing widespread damage, whereas drought occurred in the Philippines and southern China (Kim et al., 2005; Levinson et al., 2005; Wu et al., 2005). Typhoon-related climate studies often focus on the variation of typhoon intensity, frequency, and track in multitemporal scales ranging from intraseasonal to interdecadal (Chan, 1985, 2000; Chia and Ropelewski, 2002; Chu, 2004; Ho et al., 2006; Matsuura et al., 2003; Wang and Chan, 2002). In recent years, the influence of global warming on the intensity of tropical cyclones has received much attention. Emanuel (2005), Hoyos et al. (2006), and Webster et al. (2005) found increasing trends in the western Pacific and Atlantic based on some available best-track datasets. Chan and Liu (2004) and Klotzbach (2006) found small or no trends using alternate analysis techniques. Other studies (e.g., Landsea et al., 2006) have shown opposite trends to those found by Emanuel in the west Pacific by examining other best-track datasets. Besides observations, model simulations also show that intense tropical cyclones will be more frequent in the future warmer climate, while the total number of tropical cyclones tends to decrease (Bender et al., 2010; Emanuel et al., 2008; Zhao et al., 2009).

In addition to the increase in tropical cyclone intensity, one study also found a detectable shift of the typhoon track over the WNP–EA in the past four decades (Wu et al., 2005). Such a change also affects regional precipitation (Ren et al., 2006). For a future climate projection, the typhoon track over the WNP–EA region may potentially be affected by global warming (Wu and Wang, 2004). In our study, we also focus on the variation of typhoon tracks,

particularly on the abrupt change of typhoon tracks from a historical perspective. Observational data for Taiwan are useful for studying variations of typhoon tracks over the WNP–EA region because of the island's unique location. Taiwan is located at the turning point of the track for most typhoons in the WNP–EA region (Camargo et al., 2007). Figure 1 shows two major typhoon paths over the WNP–EA region: one is moving westward to the South China Sea directly and the other is turning north to either Japan or Korea. Taiwan is located just between these two major tracks, so the number of typhoon landfalls on Taiwan is sensitive to the shift of the typhoon track. Thus, we use the number of typhoons that passed through the vicinity of Taiwan (21°–26°N, 119°–125°E) as an index to examine the variation of the typhoon track in the WNP–EA region. The results here are mainly from Tu et al. (2009), along with a discussion of global warming impacts on typhoon track. The data and statistical methods used in this study are briefly discussed in section 2. We first identified the abrupt shift of the typhoon track in section 3 and then discussed its association with large-scale environmental changes in section 4. A possible association of this change in typhoon track with global warming was discussed in section 5, followed by a discussion and conclusions.

2. Data, statistical methods, and climate model

2.1 Data

The number of typhoons in the vicinity of Taiwan from 1970 to 2006 is provided by the Central Weather Bureau (CWB) in Taiwan (Chu et al., 2007). Independently, the typhoon-track information for the period of 1970-2009 is obtained from the Regional Specialized Meteorological Center (RSMC) Tokyo—Typhoon Center. Here we defined the maximum surface wind over 34 kt as a typhoon case. To understand the influence of the large-scale environment on typhoon activity, the following two global datasets were analyzed: (1) a monthly optimum interpolation (OI) sea surface temperature (SST) with 1° spatial resolution from January 1982 to December 2009 (Reynolds et al., 2002), and (2) other large-scale variables, such as the geopotential height and wind field, are derived from (1979–2009) the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) Reanalysis 2 (NCEP-2) data (Kanamitsu et al., 2002), with a horizontal resolution of 2.5° latitude × 2.5° longitude.

2.2 Statistical Methods

To detect abrupt shifts in tropical cyclone records, we use a Bayesian changepoint analysis (Chu and Zhao, 2004; Zhao and Chu, 2006). Because typhoon occurrence in the study domain is regarded as a rare event, a Poisson process is applied to provide a reasonable representation of typhoon frequency. Poisson process is governed by a single parameter: the Poisson intensity. A detail description can be found in Tu et al. (2009).

Besides tropical cyclones, it is also of interest to investigate whether there is any change point in the SST records or typhoon passage frequency series. Since these variables do not follow a Poisson process, we use a different method to detect abrupt shifts in the temperature or passage frequency series: a log-linear regression model in which a step function is expressed as an independent variable is adopted. If the estimated slope is at least twice as large as its standard error, one would reject the null hypothesis (i.e., slope being

zero) at the 5% significance level. This model is similar to that used in Elsner et al. (2000) and Chu (2002).

To evaluate the difference in the mean circulation between two samples, we use a classic nonparametric test, known as the Wilcoxon-Mann-Whitney test (Chu, 2002). To perform this test, the two data batches need to be pooled together and ranked. The null hypothesis assumes that the two batches come from the same distribution. The details can also be found in Tu et al. (2009).

To calculate the trends of SST and typhoon activity in 1982-2009 and 1970-2009 respectively, these variables are computed for each typhoon season by a rank regression method, i.e., minimizing a product of usual variable times its rank in a centered ranking system (Hollander and Wofle, 1999; Neelin et al., 2006). A Spearman-rho test is used to examine the statistical significance of the trend.

2.3 Model

A coupled ocean–atmosphere–land model of intermediate complexity (Neelin and Zeng, 2000; Zeng et al., 2000) is used in this study. Based on the analytical solutions derived from the Betts–Miller moist convective adjustment scheme (Betts and Miller, 1993), typical vertical structures of temperature, moisture, and winds for deep convection are used as leading basis functions for a Galerkin expansion (Neelin and Yu, 1994; Yu and Neelin, 1994). The resulting primitive-equation model makes use of constraints on the flow by quasi-equilibrium thermodynamic closures and is referred to as the quasi-equilibrium tropical circulation model with a single vertical structure of temperature and moisture for deep convection (QTCM1). Because the basic functions are based on vertical structures associated with convective regions, these regions are expected to be well represented and similar to a general circulation model (GCM) with the Betts–Miller moist convective adjustment scheme. Instead of coupling a complicated ocean general circulation model, a slab mixed layer ocean model with a fixed mixed layer depth of 50 m is used. By specifying Q flux, which crudely simulates divergence of ocean transport (Hansen et al., 1988, 1997), SST can be determined by the energy balance between surface radiative flux, latent heat flux, sensible heat flux, and Q flux. The Q flux can be obtained from observations or ocean model results (Doney et al., 1998; Keith, 1995; Miller et al., 1983; Russell et al., 1985). In general, the Q flux varies from ocean to ocean as well as from season to season. QTCM version 2.3 is used here, with the solar radiation scheme slightly modified.

3. Abrupt shift of typhoon track

A small area of 21°–26°N, 119°–125°E is defined as the vicinity of Taiwan (Chu et al., 2007). If a typhoon passes through this area, we count it as one that influences Taiwan. Figure 2 shows that a majority (over 90%) of typhoons pass through this region in June–October (JJASO), which is a typical typhoon season over the WNP–EA region (Chu et al., 2007). Thus, we count the number of typhoons only for these months of each year, instead of for the entire 12 months. Figure 3a is the time series of seasonal (JJASO) typhoon numbers in the vicinity of Taiwan from 1970 to 2006. The interannual variation is relatively small before 1982, but becomes much stronger after 1982. An increase of the number of typhoons in recent years is also evident. Figure 3b displays the posterior probability mass function of the changepoint plotted as a function of time (year). High probability on year *i* implies a more

likely change occurring, with year *i* being the first year of a new epoch, or the so-called changepoint. In Fig. 3b, we note a great likelihood of a changepoint on the typhoon rate in 2000. The average typhoon rate is 3.3 yr^{-1} during the first epoch (1970–99), but increased to 5.7 yr^{-1} during the second epoch (2000–06), thus almost doubling from the first to the second. Because there are two parameters to estimate for each epoch, given a changepoint, the minimum sample size is two. To achieve robust results, however, Chu and Zhao (2004) and Zhao and Chu (2006) suggested the use of 5 yr at each end of the dataset to estimate the prior parameters. Because the data observed after the changepoint year in 2000 are quite consistent, showing higher typhoon counts relative to the first epoch, we feel that our approach and the sample size (n=7) are appropriate to establish a consistent estimation for the "after changepoint" period. Separately, a nonparametric test also shows that the difference of the mean of typhoon numbers (Fig. 3a) between the two epochs is significant at the 5% level. To further substantiate the abrupt shift in typhoon activity, Fig. 3c displays the posterior density function of the rate parameter before and after the changepoint year. The posterior distribution represents a combination of the prior distribution and the likelihood function. Note the very little overlapping areas in the tail areas between two posterior distributions in Fig. 3c, supporting the notion of a rate increase from the first epoch to the second.

To understand the association of the variation of typhoon number over the vicinity of Taiwan with the spatial distribution of typhoon activity over a larger area, such as the entire WNP–EA region, the frequency of the typhoon occurrence is counted for each 6-h interval for each grid box of 2.5°× 2.5° (Stowasser et al., 2007; Wu and Wang, 2004). Figure 3d shows the difference in the mean typhoon rate between the two epochs, that is, the period of 2000–06 minus the period of 1970–99. The spatial distribution exhibits a pronounced increase of typhoon frequency north of 20°N and a decrease south of 20 °N over the western part of the WNP–EA region (100°–140°E), implying a northward shift of the typhoon frequency since 2000. The area with a significance level at the 5% in Fig. 3d (northeast of the Taiwan vicinity) is slightly different from the vicinity of Taiwan defined in Fig. 3a. This is because of the way typhoon counts constructed in Fig. 3a are somewhat different from the typhoon frequency in Fig. 3d, which contains mixed information of typhoon numbers and typhoon translation speed. Examining the total number of typhoon formations over the entire WNP, no noticeable changes are found. However, on a regional scale, we did find a reduction of the formation number over the South China Sea and the Philippine Sea, but little change over the vicinity of Taiwan (not shown). Overall, this suggests that the typhoon track over the western part of the WNP–EA region has shifted northward from the South China Sea and the Philippine Sea toward the vicinity of Taiwan and the East China Sea since 2000. Thus, the increased typhoon number over the vicinity of Taiwan after 2000 (Fig. 3a) is not an isolated local feature, but is consistent with the northward shift of the typhoon track over the WNP–EA region.

We further examined the variation of the typhoon frequency in three subregions of the WNP–EA region with large changes of typhoon frequency (Fig. 4): the South China Sea (15°–20°N, 110°–120°E), the Philippine Sea (15°–20°N, 120°–130°E), and the Taiwan–East China Sea region (25°–30°N, 120°–130°E). Over the South China Sea (Fig. 4a), a clear interannual variation and a downward linear trend of typhoon frequency, which is obtained from a simple best-fit (least squares) method, are found during the past 37 yr (1970–2006). The linear trend is consistent with the findings of Wu et al. (2005). This downward trend is

related to a reduction in the number of typhoon formations over the South China Sea. Over the Philippine Sea (Fig. 4b), the variation is more likely characterized by a decadal variation with a phase shift around 1975, 1985, and the late 1990s. Over the Taiwan–East China Sea region (Fig. 4c), it shows a similar variation of typhoon frequency to that in Fig. 3a, with a statistically significant shift occurring in 2000 at the 5% level, as confirmed by the classical changepoint analysis described in section 2b. In other words, the abrupt shift of the typhoon frequency in the vicinity of Taiwan is a part of the change over the Taiwan–East China Sea region (Figs. 3a and 4c), not associated with the changes in the South China Sea and the Philippine Sea.

4. The association with the large-scale pattern

To understand possible causes for such a northward shift of the typhoon track, we examine variations of the large-scale environment, such as the westward extension of the Pacific subtropical high ridge between two epochs. Because the SST data start in 1982, the period of 1982–99 is used to represent the first epoch, instead of 1979–99, for consistency in analyzing the spatial distribution of large-scale variables. We note that the difference of the analyzed periods between the typhoon data (e.g., Figs. 3 and 4) and the large-scale variables (Figs. 5 and 6) may cause an inconsistency. Moreover, the small sample size of the second epoch may also create some uncertainties in the composite analysis. However, the composite analysis may yield insight to the possible mechanisms that induce the abrupt shift of the typhoon number in the Taiwan vicinity.

The ridge of the Pacific subtropical high in the WNP–EA region is the main steering flow controlling the typhoon track (Ho et al., 2004; Wu et al., 2005). Figure 5 shows the 500-hPa geopotential height in the first (dotted line) and second epochs (solid line). The 5880-gpm contour is commonly used to represent the variation of the subtropical high ridge over the WNP–EA region (e.g., Chang et al., 2000). However, the 5875-gpm contour is used in this study because it is closer to the vicinity of Taiwan than the 5880-gpm contour. The results discussed below are not sensitive to the contour that we chose. Averaged over the entire typhoon season (JJASO), the subtropical ridge tends to retreat eastward from the first to the second epoch (Fig. 5a). Because of this possible weakening of the subtropical high, the typhoon track during the second epoch tends to move a little more northward than those in the first epoch.

We further examined the subseasonal variation of the subtropical high over this region since the subtropical high over this region experiences a strong subseasonal variation (e.g., LinHo and Wang, 2002). According to LinHo and Wang (2002), the entire typhoon period (JJASO) is dominated by three major natural periods in the WNP–EA region: June (the first period of summer), July–September (JAS; the second period of summer), and October (early fall). In June, the subtropical high during the second epoch tends to retreat eastward relative to the first epoch (Fig. 5b). In this period, most typhoons move westward into the South China Sea because of the strong westward extent of the subtropical high. The area where the height difference between two epochs is statistically significant is observed over the Taiwan Philippine region. When the subtropical high retreats eastward, such as shown in Fig. 5b, the typhoon track tends to move northward. In JAS, on the other hand, the subtropical high moves northward slightly during the second epoch (Fig. 5c). This period is the peak phase of the typhoon season over the vicinity of Taiwan, which has the most typhoons passing

through (Fig. 2). In this period, the subtropical high tends to move northward, so most typhoons move straight to Taiwan or turn northward to Japan and Korea. Thus, the possible northward retreat of the subtropical high (Fig. 5c) also favors the typhoon track shifting northward. In October, unlike the other two periods discussed before, the subtropical high actually becomes stronger and extends more westward (Fig. 5d), so it is not favorable for typhoons moving northward. However, the typhoon frequency in this period is lower than those in the other two periods (Chu et al., 2007). Overall, the eastward retreat of the subtropical high in JJASO, which is associated with the northward shift of typhoon track, could be a result of change of the subtropical high in summer, that is, June–September (JJAS). We note that the differences of the 500-hPa geopotential height over the western North Pacific in the peak season (JAS) are not statistically significant, possibly resulting from the small sample size of the second epoch, so the weakening of the subtropical high should be examined in the future when the second epoch becomes long enough.

We also examined the changes of other large-scale variables between two epochs. Figure 6a shows the change of low-level winds at 850 hPa. A cyclonic circulation anomaly is found between 30°N and the equator over the WNP–EA region during the second epoch, which implies a strengthening of the Asian summer monsoon trough, a favorable condition for typhoon activity. In Fig. 6b, positive and statistically significant vorticity anomalies are also found over the abovementioned region, including Taiwan, which supports the notion of an enhanced Asian summer monsoon trough. Thus, the strengthening of the Asian summer monsoon trough is accompanied by the weakening or eastward retreat of the subtropical high shown in Fig. 5a. We note that positive low-level vorticity anomalies may also favor tropical cyclone genesis. However, it is not a dominant factor here because the number of typhoon formations is decreased over the South China Sea and the Philippine Sea. Vertical wind shear is another factor that may affect typhoon activity (Chia and Ropelewski, 2002; Frank and Ritchie, 2001; Gray, 1979; Kurihara and Tuleya, 1981). Figure 6c does show an increase of vertical wind shear in the region of 0°–15°N, 105°–150°E, which is unfavorable for typhoon formation and development, but this increase of vertical wind shear is not statistically significant. On the other hand, to the north of 15°N in the area where the low-level vorticity anomalies are positive and the cyclonic circulation anomaly dominates, the vertical wind shear has not changed appreciably, so this condition is at least not unfavorable for typhoon activity.

Another important environmental condition for tropical cyclone activity is SST. Warmer SST tends to create a favorable thermodynamic condition for tropical cyclones through the air–sea heat flux exchange (Emanuel, 1999). In the North Atlantic, it is well established that SST is one of the factors impacting the number and severity of tropical cyclones (Landsea et al., 1998; Shapiro, 1982; Shapiro and Goldenberg, 1998). Thus, SST is examined here. In Fig. 6d, warm SST anomalies are found over the equatorial region from 120°E to 120°W. However, only the warm SST anomalies west of the date line are statistically significant. Another region with warm SST anomalies is in the North Pacific region from 30° to 50°N, which is associated with a negative phase of the Pacific decadal oscillation (Mantua et al., 1997). Both regions are away from the region with strong typhoon activity. However, SST anomalies can alter large-scale atmospheric circulation, and thus affect the typhoon track.

To understand which regions of the warm SST anomalies are responsible for creating the favorable conditions of typhoon activity over the WNP–EA region, a climate model with an intermediate complexity (Neelin and Zeng, 2000; Zeng et al., 2000) is used. In these

simulations, the warm SST anomalies are prescribed separately in the equatorial region (5°S–5°N, 130°–175°E) and the midlatitude region (25°–45°N, 140°E–120°W), while a mixed layer ocean is used outside those two regions. The experiment design is similar to that used in Lau and Nath (2000). The results shown in Fig. 7 are averages of 10 ensemble runs. Given the warm SST anomalies in the equatorial region, low-level cyclonic circulation anomalies are noted over the WNP–EA region (Fig. 7a). This is a typical Rossby wave response to the equatorial warm SST anomalies (e.g., Gill, 1980; Wang et al, 2003). This pattern over the WNP is qualitatively similar to that in Fig. 6a. In contrast, the warm SST anomalies over the midlatitude region have little bearing on the tropical circulation over the WNP (Fig. 7b). We note that the simulated low-level wind anomalies over the midlatitude Pacific (Fig. 7) are different than the observation shown in Fig. 6a. Thus, both the equatorial and midlatitude warm SST anomalies are not responsible for the wind anomalies over midlatitude Pacific, which may be contributed to by some complicated effects. Accordingly, the warm SST anomalies over the equatorial western and central Pacific are postulated as a possible cause for inducing the favorable conditions for the northward shift of the typhoon track. We then examine the temporal variation of the SST over the equatorial region.

Figure 8 shows the time series of monthly SST anomalies, with the annual cycle removed, along the equatorial western and central Pacific (5°S–5°N, 130°–175°E) from 1982 to July 2007. The SST anomalies exhibit an interannual variation, which is roughly related to the three strongest El Niño events of the twentieth century: 1982/83, 1991/92, and 1997/98, a sharp reduction of the SST anomalies from the growing year (the year before the El Niño peak phase, such as 1997) to the decaying year (the year after the El Niño peak phase, such as 1998). We used the regression model discussed in Chu (2002) to analyze the variation of the monthly SST anomalies. A statistically significant shift occurs in August 2000 (Fig. 8). Specifically, before August 2000, the average of the SST anomalies is about -0.1 °C, but it increases to 0.3°C after August 2000. Although this difference seems to be small, it is considerable when viewed in the context of multiyear seasonal means at the equator. In the interannual time scale, the typhoon number over the vicinity of Taiwan is also strongly associated with the SST anomalies over the equatorial western and central Pacific (C.-T. Lee, 2008, personal communication).We also examined the six typhoons that passed through the vicinity of Taiwan in 2000 and found that five out of six typhoons occurred in or after August 2000.After further examining the SST anomalies in 2007, we found that warm SST anomalies still exist over the equatorial western and central Pacific (Fig. 8), which is consistent with the above-normal number of typhoons (five) that we found so far in 2007. Thus, combining results from observations, especially in Figs. 3 and 8, and model simulations, the warm SST anomalies over the equatorial western to central Pacific appear to be main factors that induced the abrupt change of the northward shift of the typhoon track over the WNP–EA region.

5. Impacts of global warming

Global warming has been observed for more than one hundred years (e.g., Trenberth et al., 2007). Under global warming, El Niño–like warm SST anomalies are often found over the equatorial Pacific region (Meehl and Washington, 1996; Meehl et al., 2007; Teng et al., 2006). In this study, we also found that the mean state of the equatorial Pacific SST transitioned from a cold to a warm phase in 2000. The question that arises is as follows: Do the equatorial

SST anomalies that are associated with the abrupt northward shift of the typhoon track over the WNP–EA region result from global warming?
Figure 9 shows the variation of globally averaged SST in 1982-2009. A clear upward trend of SST is found, which is consistent to the global warming found in the previous studies (e.g., Trenberth et al., 2007). The spatial distribution of the SST trend is shown in Figure 10. This clearly resembles the SST anomalies shown in Fig. 6d. In other words, the SST anomalies that induce the abrupt shift of the typhoon track are similar to the warming trend of SST over the past three decades. Thus, it implies that global warming could be at least partially responsible for the abrupt shift of the typhoon track over the western North Pacific. We further examined the trend of typhoon activity in 1970-2009 and found decreasing trends over the South China Sea and slightly increasing trends north of Taiwan (Fig. 11). We note that the decreasing trends are statistically significant, but the increasing trends are not. The decreasing trend is similar to the pattern found in Fig. 3d, while the increasing trend is much weaker than that shown in Fig. 3d even though the tendency is same. It is consistent with the results shown in Fig. 4: a clear decreasing trend of typhoon activity over the South China Sea (Fig. 4a) and an abrupt increase of typhoon activity north of Taiwan (Fig. 4c). Overall, the warming trend of SST does show an influence on the abrupt shift of the typhoon track over the western North Pacific.

6. Discussion and conclusion

Long-term climate variability of typhoon activity over the western North Pacific–East Asian (WNP–EA) sector has been analyzed here. Because Taiwan is located at a unique location along the typhoon path, the number of typhoons that pass through the vicinity of Taiwan is used to study the movement of the typhoon track over this region. Our analysis suggests an abrupt change in typhoon numbers in 2000, which is consistent with the northward shift of the typhoon track over the WNP–EA region and the abrupt increase of typhoon frequency over the Taiwan–East China Sea region. This northward shift of the typhoon track is mainly associated with warm SST anomalies over the equatorial western and central Pacific, which exhibited an abrupt change in August 2000, concurrent with the change of the typhoon track. Both observations and model simulations show that the equatorial warm SST anomalies tend to induce an eastward and northward retreat of the subtropical high, an enhanced low-level vorticity, and a monsoon trough, which all favor the northward shift of the typhoon track.
A further examination shows that the equatorial warm SST anomalies are partially associated with a global warming trend of SST. Is this global warming trend of SST in 1982-2009 induced by anthropogenic forcings, such as the greenhouse effect? This is an interesting question that should be answered in the future.

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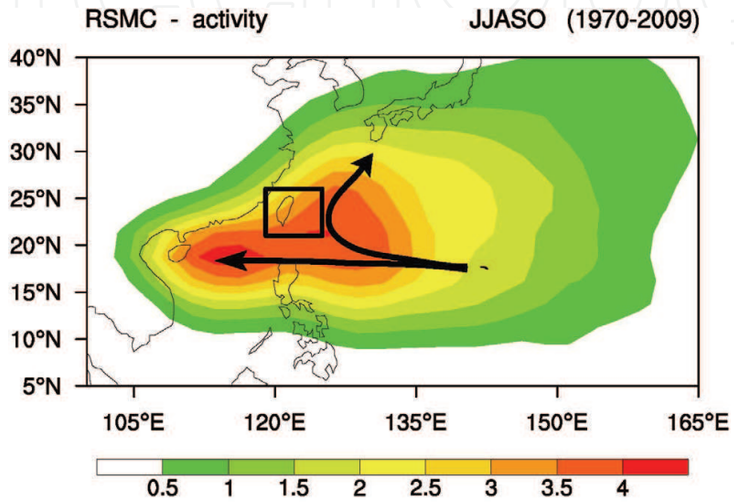


Fig. 1. June-October (JJASO) typhoon frequency climatology averaged over the period of 1970-2009. The contour interval is 0.5 per season (JJASO) per grid box (2.5°×2.5°). The bold arrows represent the majority of typhoon paths in the Western North Pacific–East Asian region. The box represents the area in the vicinity of Taiwan.

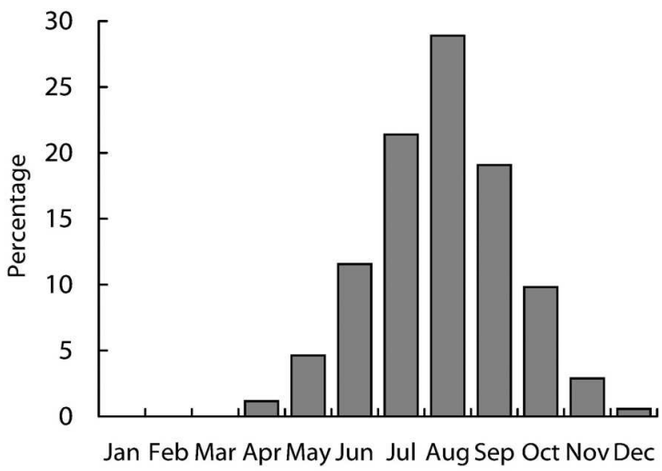


Fig. 2. Monthly percentage of typhoons impacting Taiwan averaged over the period of 1970-2009.

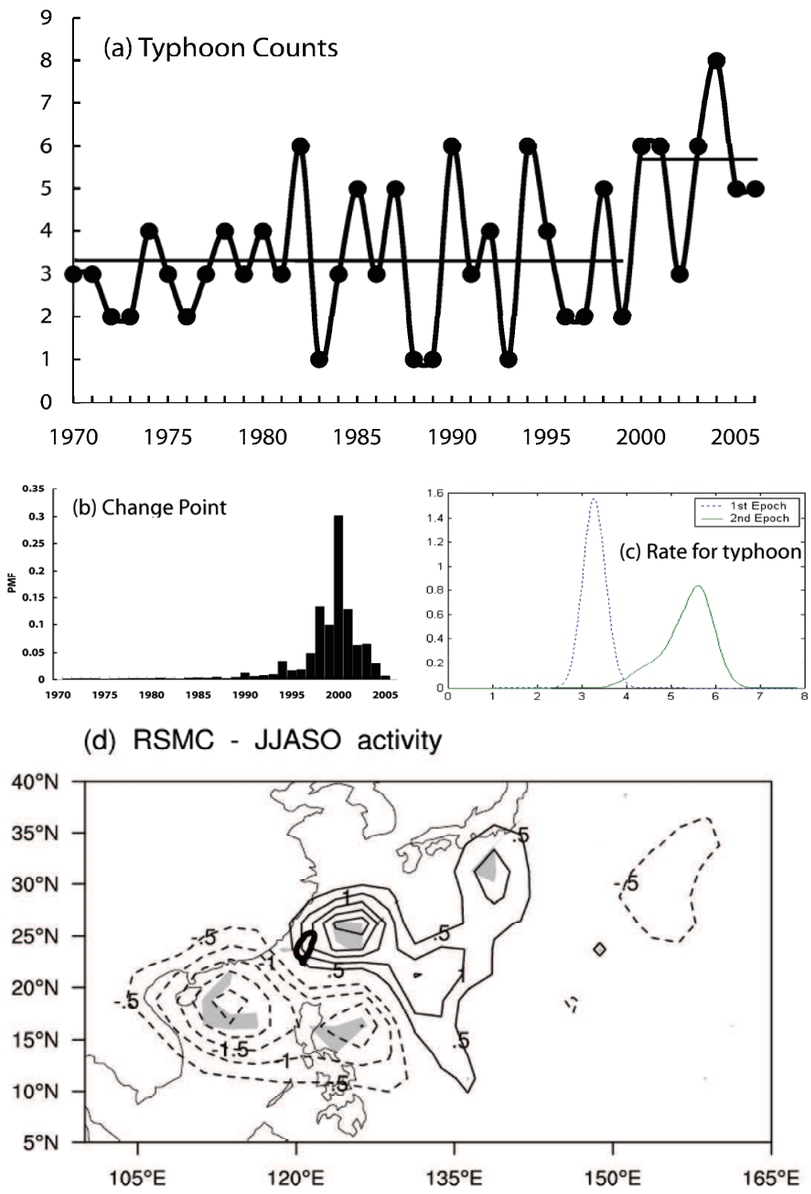


Fig. 3. (a) Time series of seasonal (JJASO) typhoon numbers passing the vicinity of Taiwan from 1970 to 2006 as compiled by the Central Weather Bureau. The vicinity was defined as 21°N-26°N and 119°E-125°E. (b) The conditional posterior probability mass function of change-points is plotted as a function of time. (c) Posterior density function of seasonal typhoon rate before (dashed line) and after (solid) the shift, with the change-point year being set in 2000. (d) June-October typhoon frequency differences for the period of 2000-2006 minus the period of 1970-1999 from the Regional Specialized Meteorological Center, Tokyo. The contour interval is 0.5; shading denotes that the difference between the mean of the two epochs is statistically significant at the 5% level. Adapted from Tu et al., (2009).

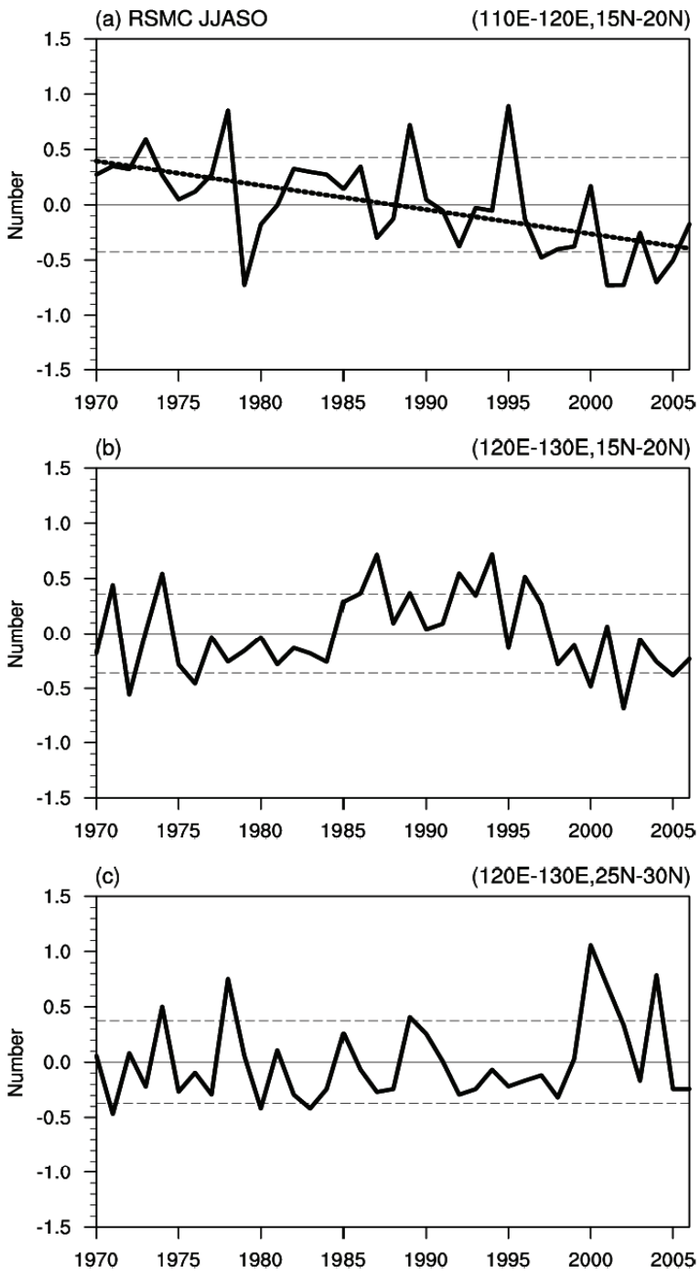


Fig. 4. Time series of seasonal (JJASO) typhoon frequency departure from 1970 to 2006 for three sub regions of the western North Pacific: (a) the South China Sea, (b) the Philippine Sea and (c) the Taiwan and East China Sea region. The thicker dashed line in the upper panel is a best-fit least square linear trend and the thinner dashed lines denote one standard deviation for each area. The unit in the y-axis is the typhoon number per season (JJASO) per grid box (2.5°×2.5°). Adapted from Tu et al. (2009).

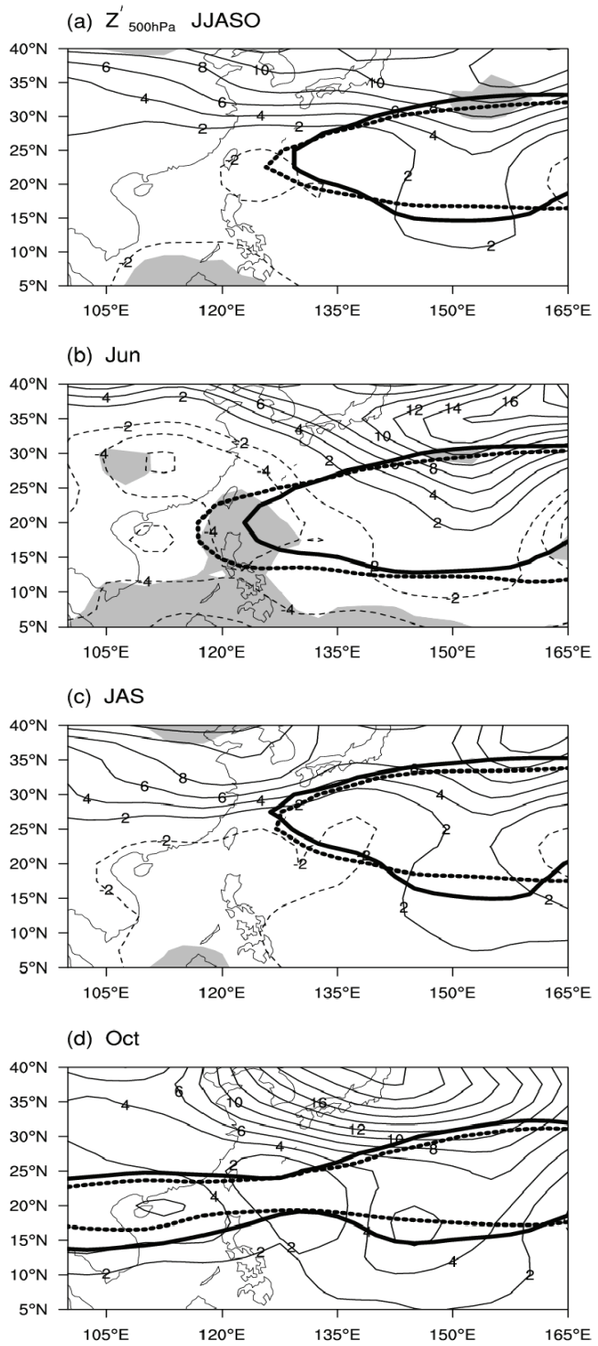


Fig. 5. The 5875 gpm contour of 500hPa geopotential height for the period of 1982-1999 (thick dotted line) and 2000-2006 (thick solid line) in (a) June-October (JJASO), (b) June, (c) July-September (JAS) and (d) October. The contours are the 500hPa geopotential height differences of the second minus first epoch, shaded by the 10% significance level. Adapted from Tu et al. (2009).

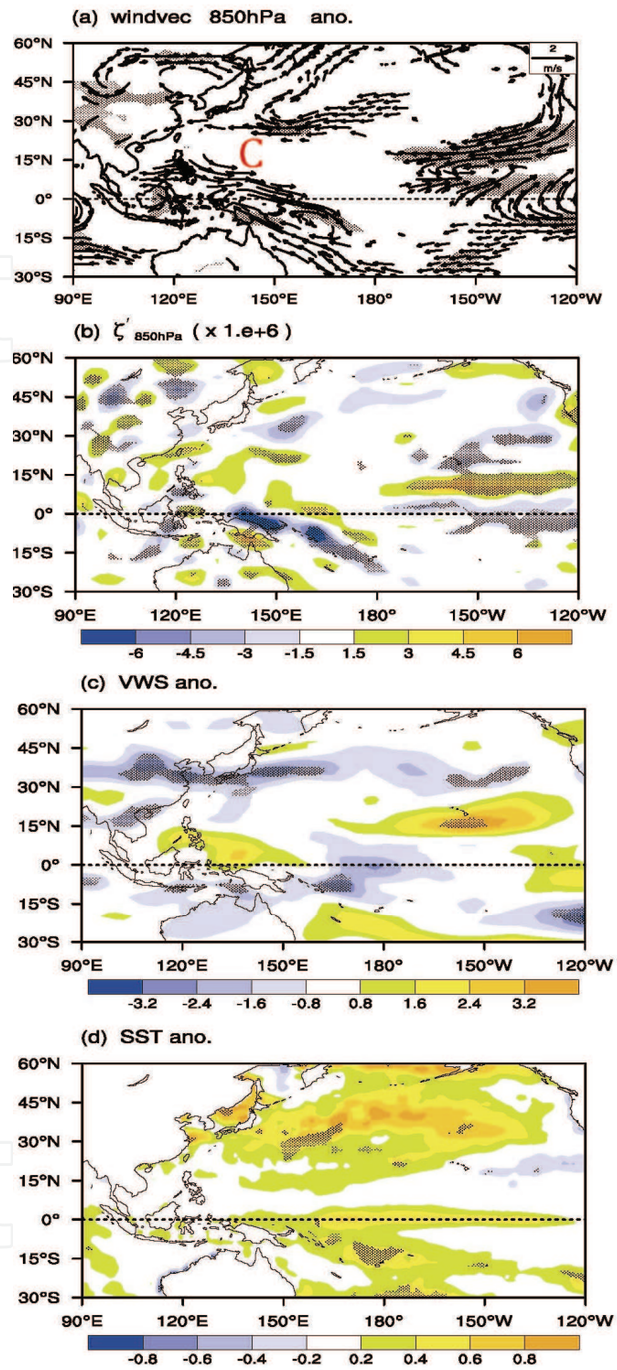


Fig. 6. (a) 850 hPa wind difference between 2000-2006 and 1982-1999 for JJASO; (b) same as (a) but for 850 hPa relative vorticity; (c) same as (a) but for vertical wind shear (200hPa-850hPa); and (d) same as (a) but for sea surface temperature (SST). The contour interval for 850 hPa relative vorticity is 1.5E+6 (s^{-1}), for vertical wind shear is 0.8 (m s^{-1}), and for SST anomalies is 0.2°C. Dotted areas indicate regions where the difference in the mean between two epochs is significant at the 5% level. In (b), (c), and (d), negative values are dashed. Adapted from Tu et al. (2009).

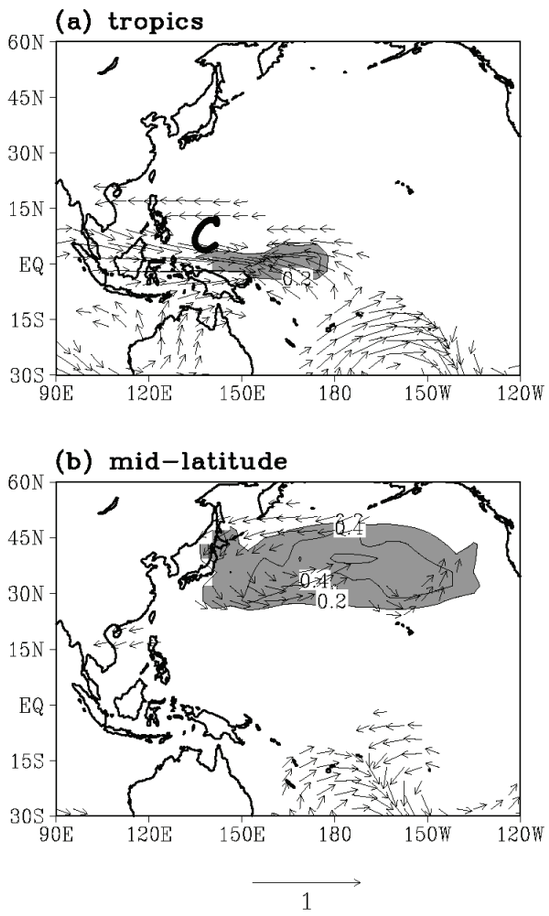


Fig. 7. SST anomalies (contour) and 850 hPa wind anomalies from the model simulations with the prescribed SST anomalies over (a) the equatorial region (130°E-175°E, 5°S-5°N) and (b) mid-latitudes (140°E-120°W, 25°N-45°N). Adapted from Tu et al. (2009).

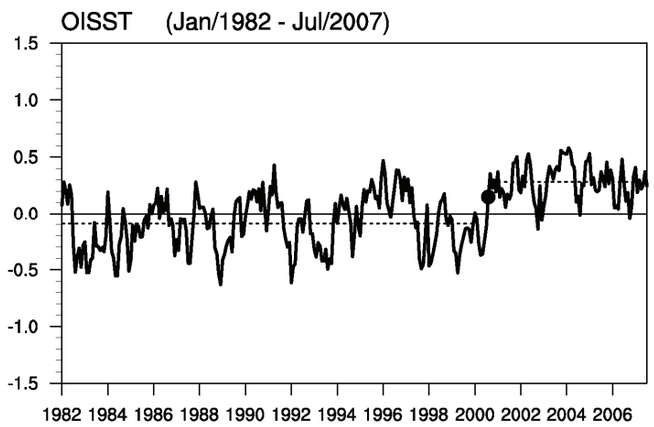


Fig. 8. Variation of monthly SST anomalies averaged over the area of 130°E-175°E and 5°S-5°N from January 1982 to July 2007. The short dashed lines are the means averaged over 1982-1999 (-0.1°C) and 2001-2006 (0.3°C) respectively. Adapted from Tu et al. (2009).

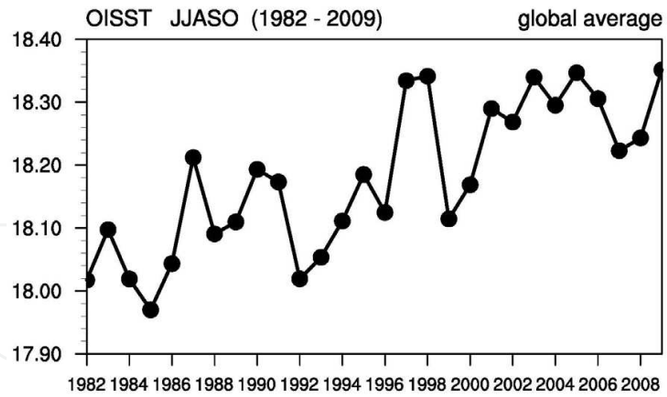


Fig. 9. Globally averaged SST in JJASO for the period of 1982-2009.

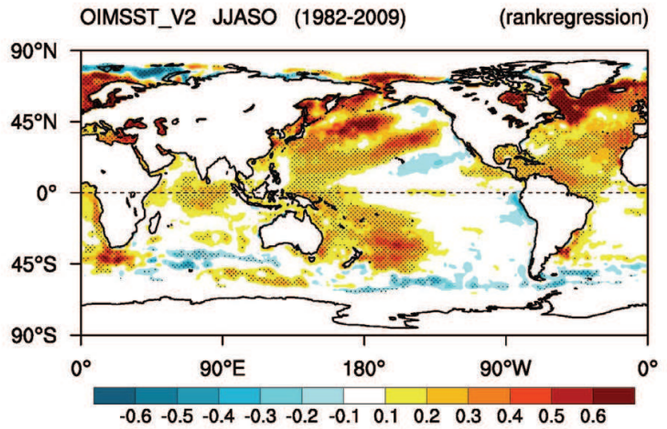


Fig. 10. Trend of SST in JJASO for the period of 1982-2009. The unit is ºC per decade. The dotted area denotes that the trend is statistically significant at the 5% level.

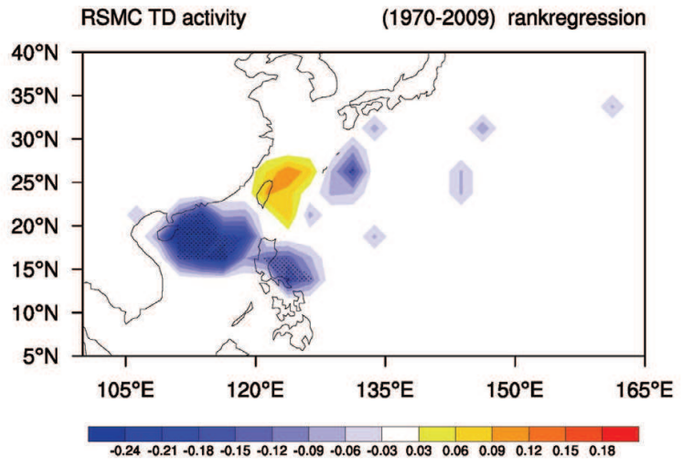
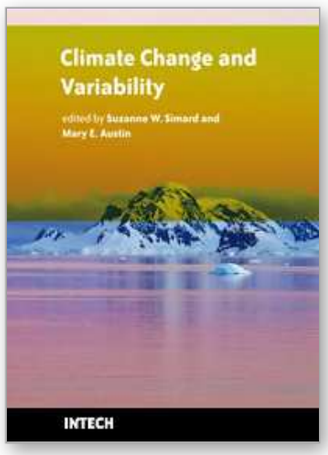


Fig. 11. Trend of typhoon frequency in JJASO for the period of 1970-2009. The unit is per season (JJASO) per grid box (2.5°×2.5°). The dotted area denotes that the trend is statistically significant at the 5% level.



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Climate change is emerging as one of the most important issues of our time, with the potential to cause profound cascading effects on ecosystems and society. However, these effects are poorly understood and our projections for climate change trends and effects have thus far proven to be inaccurate. In this collection of 24 chapters, we present a cross-section of some of the most challenging issues related to oceans, lakes, forests, and agricultural systems under a changing climate. The authors present evidence for changes and variability in climatic and atmospheric conditions, investigate some the impacts that climate change is having on the Earth's ecological and social systems, and provide novel ideas, advances and applications for mitigation and adaptation of our socio-ecological systems to climate change. Difficult questions are asked. What have been some of the impacts of climate change on our natural and managed ecosystems? How do we manage for resilient socio-ecological systems? How do we predict the future? What are relevant climatic change and management scenarios? How can we shape management regimes to increase our adaptive capacity to climate change? These themes are visited across broad spatial and temporal scales, touch on important and relevant ecological patterns and processes, and represent broad geographic regions, from the tropics, to temperate and boreal regions, to the Arctic.

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