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Inter-annual and inter-decadal variations of landfalling tropical cyclones in East Asia. Part I: time series analysis

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ABSTRACT: This paper is the first of a two-part series that presents results of a comprehensive study of the variations in the annual number of landfalling tropical cyclones (ATCs) in various parts of East Asia during the period 1945–2004. The objective is to identify possible trends and cycles in such variations, from inter-annual to inter-decadal, and the possible reasons for such variations. The East Asian region is divided into three sub-regions: South (south China, Vietnam and the Philippines), Middle (east China), and North (Korean Peninsula and Japan). Variations in the annual number on various time scales in each region are examined separately. Part I reports on the results of wavelet analyses of the time series of the annual number in each region, and Part II examines the possible reasons for the cycles identified in Part I.

An important finding from the time series analysis is that none of the ATC time series shows a significant linear trend, which suggests that global warming has not led to a higher frequency of landfalling tropical cyclones or typhoons in any of the regions in Asia. Instead, each time series shows large inter-annual (2–8 years) and multi-decadal (16–32 years) variations. In some periods, the annual number of ATCs varies in unison among all regions of Asia. In others, one region would have an above-normal number of landfalling events, while the other regions have below-normal numbers. In general, at multi-decadal time scales, the number of ATCs in each region correlates very well with that of the total number of tropical cyclones over the western North Pacific. Copyright © 2008 Royal Meteorological Society

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1. Introduction

Tropical cyclones (TCs) are among the most destructive of all natural disasters. Thus, understanding the nature and causes of variations in TC activity will help risk assessment, and the most significant impact on society of such activity is landfall. While some recent studies have claimed that the number of intense TCs is on the increase as a result of global warming (e.g. Emanuel, 2005; Webster *et al*., 2005), others pointed that such a claim (e.g. Landsea, 2005, 2007) is not valid as the trend was calculated based on data with large uncertainties in the pre-satellite era. Chan (2006) also argued that the trend for TCs in the western North Pacific (WNP) found in Webster *et al*. (2005) is actually part of a multi-decadal variation. Landsea (2005, 2007) further pointed out that the number of TCs making landfall in the USA has not been increasing. Such a debate suggests that more studies need to be carried out to ascertain whether trends do exist under a global warming scenario, and especially whether such trends can be found for landfalling TCs. While Landsea (2005, 2007) has performed a study for Atlantic landfalling TCs, a comprehensive study of landfalling TCs in Asia has not been carried out.

This paper is the first of a two-part series that examines the temporal variations of landfalling TCs over the East Asia region for the period 1945–2004, and the possible reasons for such variations. Because each landfall is likely well documented by each of the countries affected, the data on the number of landfalling TCs should be quite accurate although the intensity at landfall might still be of some concern. In Part I, results from wavelet analyses of these variations are presented. The possible physical processes responsible for such variations are reported in Part II.

Section 2 describes the data used and how the landfalling TCs in different regions of East Asia are grouped. Analyses of possible trends and other temporal variations of the time series of the annual number of these TCs in different sub-regions are presented in Section 3. Such variations are then related to the frequency of occurrence of TCs over the WNP in Section 4. A summary of the results is given in Section 5 together with a discussion.

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2. Data and methodology

2.1. Data

The basic TC data used in this study are obtained from the Joint Typhoon Warning Center (JTWC) (Available online at website http://weather.unisys.com/hurricane/w_pacific/index.html). The data period is 1945–2004. For TCs that made landfall in China, data for the period 1951–2000 are from the Annual Tropical Cyclone Data Book edited by the Shanghai Typhoon Institute (Shanghai Typhoon Institute, 2006), those from 1945 to 1950 from unpublished records of the Institute, and those after 2000 from the best tracks of the Institute. These latter data are used so as to have a better estimate of the intensity of the TCs (in terms of maximum sustained winds) around the landfall time. Because of the possible large errors in counting the number of tropical depressions, TCs in this paper refer only to tropical cyclones that reached tropical storm intensity (with maximum surface wind greater than 17 m s^{-1}), whether it is over the open ocean or at the landfalling time. The phrase 'landfalling TC' refers to any TC with its centre crossing the coastline. At landfall, the TC must have at least tropical storm intensity or higher. Note that the intensity at landfall is the best-track intensity at the time closest to landfall. Sub-categories of landfall for TCs with typhoon intensity have also been made. The results are largely similar to those to be presented in this paper. They will therefore not be discussed.

2.2. Groupings

The annual percentage of TC occurrence in the WNP shows a maximum just to the northeast of the Philippines, with a secondary maximum west of the Philippines (Figure 1). Connecting the vertices of the percentage contours gives roughly four major tracks: west-northwestward at low latitudes with possible landfall in south China (thick solid curve in Figure 1), Vietnam, Philippines, northwestward with possible landfall in east China (including Taiwan) (long-dashed curve in Figure 1), northward and northeastward with possible landfall in Korea and Japan (dotted curve in Figure 1), and towards the northeast with no landfall anywhere in East Asia. The East Asia region is, therefore, divided into three sub-regions, and the landfalling TCs are then accordingly grouped as follows: (Figure 1):

- South TCs (STC) – those making landfall in south China, Vietnam and the Philippines
- middle TCs (MTC) – those making landfall in east China (Taiwan, Fujian, Zhejiang and Jiangsu provinces, and Shanghai municipality)
- north TCs (NTC) – those making landfall in the Korean peninsula and Japan.

A fourth group, Asia TC is also created, which is the annual total number of landfalling TCs in Asia (ATC). Note that this number for a particular year is not necessarily the sum of the numbers of the three groups in that year as one TC may make landfall in, say, East China (giving one landfall count in the MTC series), then re-curve and make landfall again in Korea (giving one landfall count in the NTC series). In this case, an ATC will also have only one landfall count. In addition, if a TC makes landfall in two places within the same sub-region (e.g. the Philippines and then Vietnam), it is only counted once. These two counting procedures are adopted

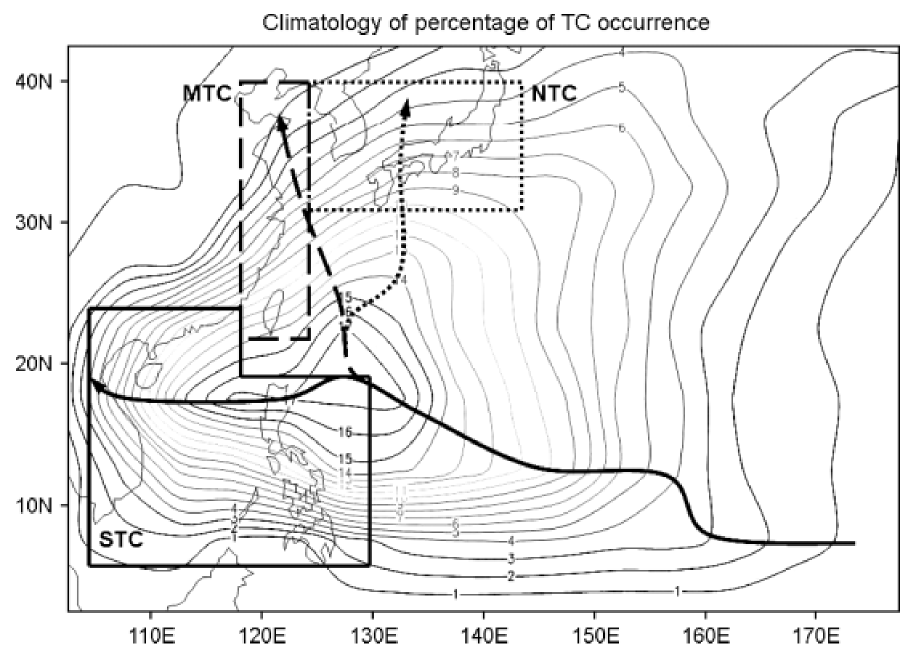

Figure 1. June–October mean percentage of TC occurrences derived from the JTWC best-track data from 1960 to 2006. The three boxes mark the different groups of landfalling TCs studied in the paper. STC – south TCs, MTC – middle TCs, and NTC – north TCs. The three lines with arrows at the end connect the vertices of the contours to indicate the possible maximum likelihood of tracks associated with each of these three groups of landfalling TCs. See the text for further details of the places included in each group.

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because the focus here is on the flow pattern that leads to landfall within a broad region. Landfalls over relatively small islands over the open WNP such as Okinawa or Guam are not counted.

For each group, the annual number of TCs that made landfall is counted and a time series is formed. The trends and variations of these series are analysed in the next section.

2.3. Wavelet analysis

Because each time series has oscillations of varying periods and at different times, the best way to analyse the time series is through the method of wavelet analysis, which is a common statistical tool to identify such localized oscillations of different frequencies. Basically, a wavelet transform is applied to the time series. This method also allows the reconstruction of the time series for a certain band of oscillation frequencies using the coefficients at each of the frequencies from the resulting wavelet transform. Such a reconstruction then provides information on how the amplitudes of the oscillations in these frequencies vary with time.

Many wavelets have been used for various applications. In this study, the so-called Mexican hat wavelet is used. Using this as the wavelet basis function has the advantage that it captures both the positive and negative oscillations of the time series, which is useful for examining anomalies. For details of the wavelet technique, the reader is referred to Torrence and Compo (1998).

2.4. Tests for significance

Correlations among the time series are made to determine whether two series are significantly correlated. However, as filtering of the time series is performed in order to study the correlations at low frequencies, the test for statistical significance needs to take into account the reduced degrees of freedom. Therefore, in estimating the statistical significance, the effective degrees of freedom (von Storch and Zwiers, 1999) is calculated and used in making the Student's t-test for significance.

3. Trends and temporal variations

The long-term trend of each series (Figures 2–5) is examined by calculating the linear correlation with time. None of the correlation coefficients of the four series passes the significance test. A least-square fitting also yields no statistically significant result. In other words, during the period 1945–2004, no significant trend exists in the number of landfalling TCs in the WNP.

In the following, the major oscillations identified through the wavelet analysis in each of the four series are discussed.

3.1. STC series

The wavelet analysis suggests that the strongest oscillation appears to shift towards lower frequencies from the mid-1970s, with those with periods shorter than 16 years dominating before this time, and those with periods longer than 16 years, thereafter (Figure 2(a)). On the inter-annual time scale (2–8 years), the largest amplitude appears to be before the 1970s (Figure 2(b)). The peak value also shows a decreasing trend. In the intermediate time scale of 8–16 years, the oscillation seems to hover around 10 years. On the multi-decadal time scale (16–32 years), 3 below- and 2 above-normal eras appear. It is noted that all the 3 oscillations have below-normal values since around 1999. In other words, the number of landfalling TCs in the South region has been on the decrease during the last several years, as can be seen from the time series of the actual number in Figure 2(b).

Table I. Percent of variance of the original time series explained by each of the three reconstructed time series and their various combinations.

Time series	STC	MTC	NTC	ATC
Individual series				
2–8-year	79	85	84	79
8–16 year	39	37	24	41
16–32-year	25	18	16	24
Two series				
2–8-year + 8–16-year	85	92	89	88
2–8-year + 16–32-year	93	96	95	94
8–16-year + 16–32-year	41	37	26	42
All three series				
2–8-year + 8–16-year + 16–32-year	93	97	95	95

It is also obvious from Figure 2(b) that whether the actual number of landfalling TCs in this part of Asia is above or below normal very closely follows the 2–8 year curve, which suggests that the variation in STC number mainly occurs on the inter-annual time scale. In fact, the 2–8-year curve alone explains 79% of the total variance of the actual number (Table I). The 8–16- and the 16–32-year oscillations explain 39 and 25% of the total variance respectively. Combining the 2–8- and 8–16-year oscillations adds only 6% more, but combining the 2–8- and 16–32-year series together explain 93% of the variance, an addition of 14%, which is the same if all the three series are included, which suggests that the 8–16-year oscillation is likely insignificant. In other words, the variations of landfall in southern Asia (the Philippines, Vietnam and southern China) appear to be on time scales of 2–8 and 16–32 years, respectively.

3.2. MTC series

As in the STC series, the wavelet analyses of the MTC series suggests that oscillations on inter-annual time scales (2–8 years) are significant throughout much of the time period (Figure 3(a)). On the other hand, the amplitudes of oscillations on the 8–16- and 16–32-year periods become weaker after the mid-1990s. As in STC, the inter-annual time-scale oscillation also appears to

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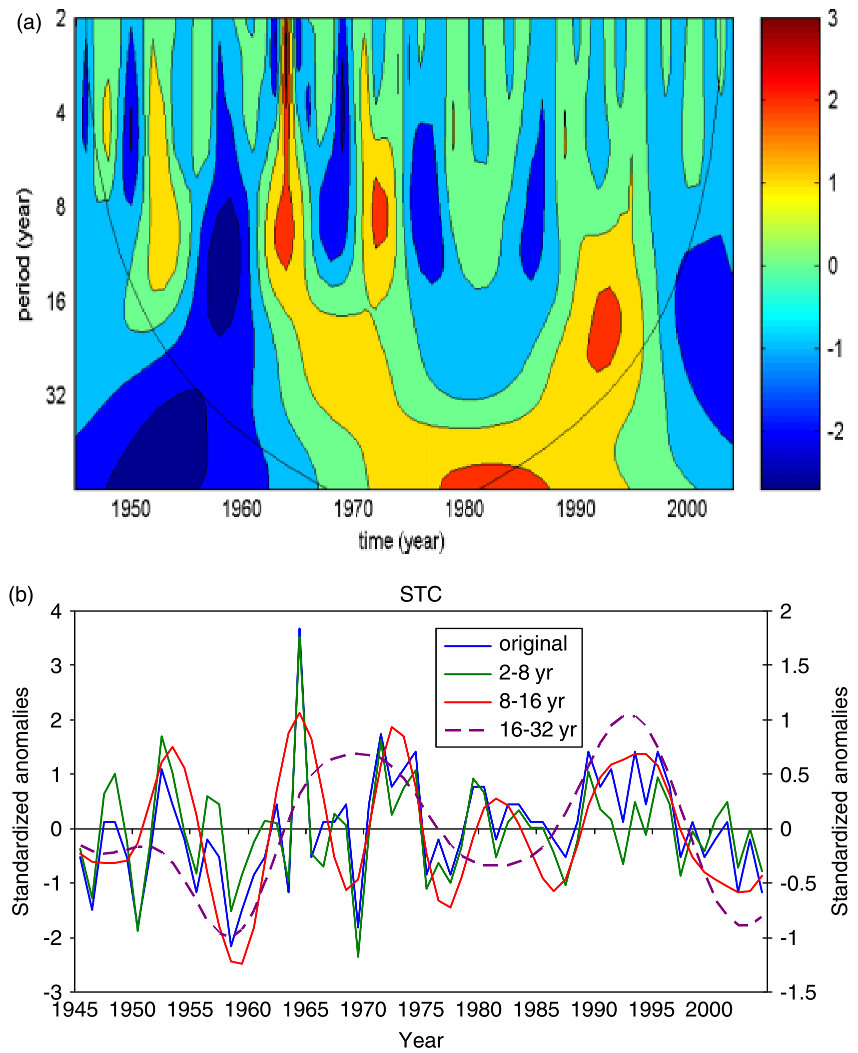

Figure 2. (a) Wavelet analysis of the standardized STC series, and (b) reconstruction of the STC series for periods 2–8 years (green), 8–16 years (red, values multiplied by 5) and 16–32 years (blue dashed, values multiplied by 10), all using scale on the right axis. The original series is also plotted (blue, scale on left axis). The black curve in (a) indicates the cone of influence. This figure is available in colour online at www.interscience.wiley.com/ijoc

be dominant (Figure 3(b)), explaining 85% of the variance of the actual MTC series (Table I). The intermediate time-scale (8–16 year) oscillation appears to have a variation similar to that of the multi-decadal oscillation (16–32 years). This latter low-frequency oscillation shows two above- and below-normal eras. Although this multi-decadal oscillation only explains 18% of the total variance (Table I), a combination of this and the 2–8-year oscillations together explain 96% of the total variance, while a further inclusion of the 8–16-year oscillation increases the explained variance by only 1%. In other words, it appears that the MTC variations are well explained by the inter-annual (2–8-year) and multi-decadal (16–32-year) oscillations.

3.3. NTC series

The inter-annual oscillation associated with the NTC series is significant throughout much of the data period until the mid 1990s (Figure 4(a)). On the other hand, the intermediate time-scale oscillation of 8–16 years is not active until the 1990s, whereas the multi-decadal oscillation (16–32 years) has an appreciable amplitude from the 1960s. Note that the amplitude of the 2–8-year oscillation is generally larger than the total number of landfalling TCs, especially in the period of 1970–1995 during which the multi-decadal (16–32-year) oscillation appears to be dominant (Figure 4(b)). Nevertheless, the 2–8-year series still explains 84% of the overall variance of the NTC series (Table I). The percent of variance explained by either the 8–16-year or the 16–32-year oscillation is the smallest among the three series STC, MTC and NTC. Note again, that this low-frequency oscillation also goes through two maxima and two minima during the data period. However, the phases of these variations are not the same as those in STC or MTC. More discussion of this point will be given later. Combining the 2–8-year with the 16–32-year series explains 95% of the total variance (Table I).

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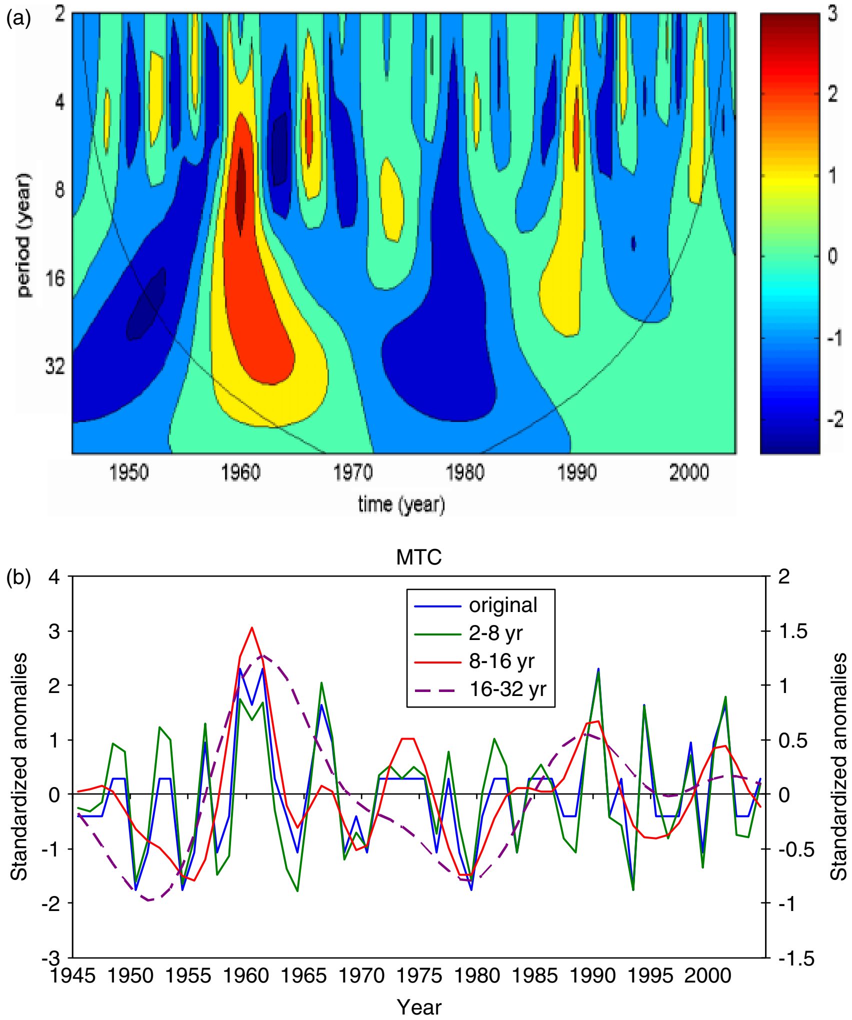

Figure 3. As in Figure 2 except for MTC. This figure is available in colour online at www.interscience.wiley.com/ijoc

3.4. ATC series

Because of the relatively large number of landfalling TCs in south Asia compared with the other two regions, the ATC series is quite similar to the STC series, especially in the inter-annual to intermediate time scales (2–16 years) before 1990 (cf. Figures 5(a) and 2(a)). However, the amplitude of the inter-decadal time-scale (16–32 years) oscillation in the ATC series is larger than that in the STC series. Consistent with these results, the actual variation of the number of landfalling TCs rather closely follows the inter-annual oscillation (Figure 5(b)) before the mid 1980s. After this time, the lower frequency oscillations apparently dominate. Similar to the time series in each of the regions, the 2–8-year oscillation explains the highest percentage of total variance (79%) and a further inclusion of the 16–32-year reconstructed series explains 95% of the ATC variations (Table I). Again, contribution of the intermediate 8–16-year oscillation appears to be insignificant.

Previous studies (e.g. Chan, 1985, 2006) have shown that the total number of TCs (TTC) over the entire WNP also goes through large decadal variations. To see whether the ATC variations are related to TTC, the latter series is also subjected to the same wavelet analysis and the 16-32-year reconstructed. The correlation between the reconstructed TTC and ATC series is 0.93 (Figure 6(b)). Even the raw TTC and ATC series have a correlation coefficient of 0.66 (Figure 6(a)). Both correlations are significant at the 99% level (see Table II). These results give a very important conclusion: if the WNP is active, more TCs can be expected to make landfall somewhere on the Asian coast. This is in contrast with hurricanes in the Atlantic where the frequency of landfall over North America is not well correlated with the number of TCs over the Atlantic (Holland, 2007). A more detailed discussion of this conclusion will be given in Section 4.

3.5. Summary

It is obvious that the frequency of landfall at different locations in Asia varies on many time scales, from inter-annual to multi-decadal. For south Asia and middle Asia, the dominant mode is apparently in the inter-annual time scale, with lower frequency variations simply enhancing the inter-annual signal. On the other hand, a stronger inter-decadal signal exists for TCs making landfall in north Asia (Korean Peninsula and Japan). Thus, different

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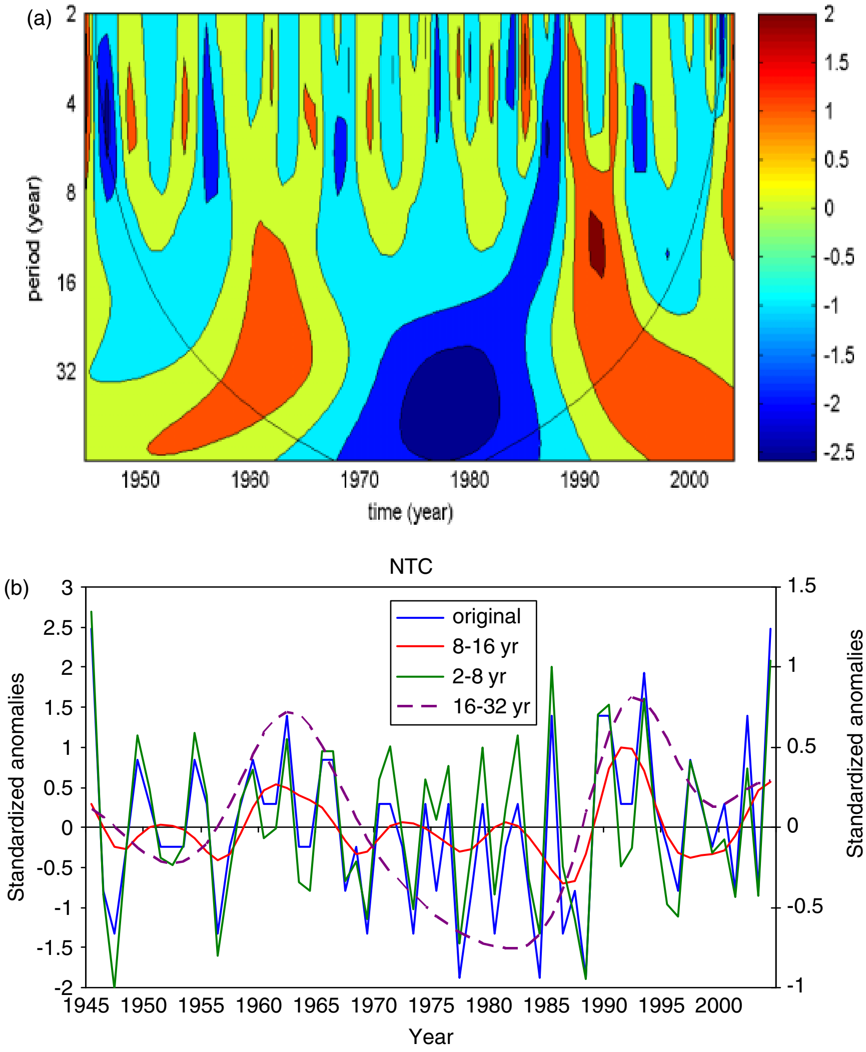

Figure 4. As in Figure 2 except for NTC. This figure is available in colour online at www.interscience.wiley.com/ijoc

factors may be important in making seasonal predictions of the number of landfalling TCs in different locations in Asia.

It is also of interest to note that on all time scales, the three series (STC, MTC and NTC) are not significantly correlated (Table II) except for that between MTC and NTC on the 16–32-year time scale. In other words, in most cases, more TCs making landfall in one area does not necessarily imply either more or less TCs making landfall in other areas. The significant correlation between MTC and NTC at the multi-decadal time scale suggests that at this time scale, if the large-scale conditions are favourable for landfall in east China, they are also likely to result in more landfall events in Korea and Japan. This situation appears to be the case during the last few years (see Figures 3(b) and 4(b)). More discussion of these large-scale conditions will be given in Part 2.

The ATC series is also correlated with all the three series except MTC on the 8–16-year time scale (Table II). As might be expected, because of the larger number of landfall events in southern Asia, the strongest correlation is between the STC and ATC series on all

Table II. Correlations among the various TC time series studied in this paper at the various time scales. Correlations significant at the 95% (99%) level based on the estimated effective degrees of freedom are underlined (in bold). For each of the significant correlations, the effective degrees of freedom are included in parentheses next to the correlation coefficient. See text for the calculation of the effective degrees of freedom.

	MTC	NTC	ATC	TTC
2–8 years				
STC	0.12	−0.07	**0.72** (59)	**0.58** (59)
MTC		0.09	**0.50** (59)	0.31 (59)
NTC			**0.51** (59)	0.19
ATC				**0.65** (59)
8–16 years				
STC	−0.28	0.40	**0.83** (21.5)	**0.69** (20)
MTC		0.34	0.19	0.05
NTC			**0.79** (21.1)	**0.59** (19.5)
ATC				**0.80** (19.8)
16–32 years				
STC	0.04	0.23	**0.78** (10.2)	0.65 (10)
MTC		0.73 (9.6)	0.63 (10)	0.71 (9.8)
NTC			0.71 (9.4)	0.68 (9.1)
ATC				**0.93** (9.6)

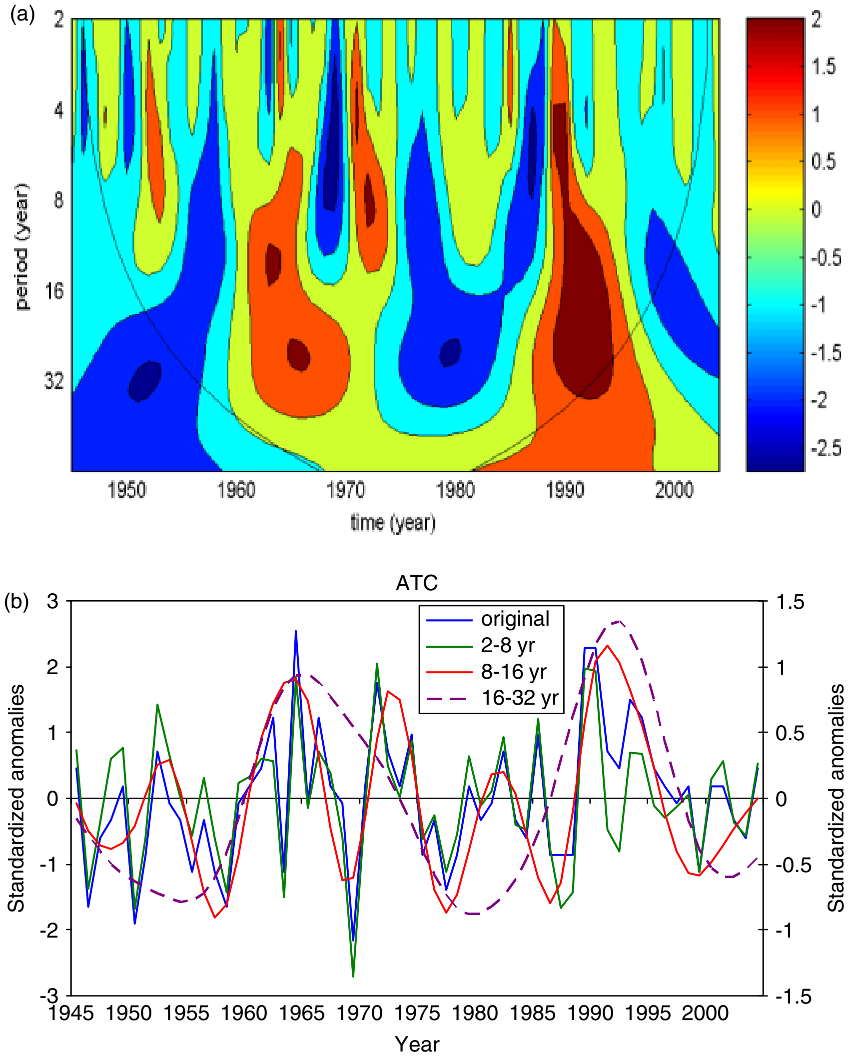

Figure 5. As in Figure 2 except for ATC. This figure is available in colour online at www.interscience.wiley.com/ijoc

time scales. More discussion of these results in relation to the TTC series will be given in Section 4.

4. Relationship between TC activity in the WNP and landfalling TCs

As mentioned in Section 3.4, both the actual number of landfalling TCs and the 16–32-year reconstructed ATC series correlate well with their respective series of the number of TCs in the entire WNP. In this section, this relationship is explored further.

To investigate how each of the four TC series may be related to the TTC series, correlations are made between each of the reconstructed series and the same reconstructed TTC series (Table II). On the inter-annual (2–8-year) time scale, the number of landfalling TCs in south Asia correlates well with that of TTC, which suggests that if more TCs are present in the WNP, more landfalling TCs in southern Asia might be expected. This, however, is not necessarily the case for middle or north Asia. On the 8–16-year time scale, both the STC and NTC series correlate well with the TTC series. The most important result is the one for the 16–32-year period in which all the three time series are significantly correlated with the TTC series. This appears to suggest that if more TCs are expected over the WNP on this time scale, it is likely that more landfalls can be expected in all regions of Asia.

This last result appears to be a contradiction to that discussed in Section 3.5 in which no correlation exists between STC and the other two series on this multi-decadal time scale. An examination of the five series (Figure 7) shows that while they generally vary in tandem, the phases can be quite different among the series. In some cases, the series have the same sign (before 1956, 1964–1969, 1977–1985, and 1989–1998) but in others, the sign of STC is opposite to that of MTC and NTC (which generally have similar temporal variations) (1957–1963, 1970–1976 and from 1999 onward). Thus, even when all the three series are in different phases, a deficit in the STC is ‘compensated’ by an increase in the numbers in the MTC and STC, so that the sum of these three series, which approximates that of ATC (minus one or two from multiple landfalls), correlates exceptionally

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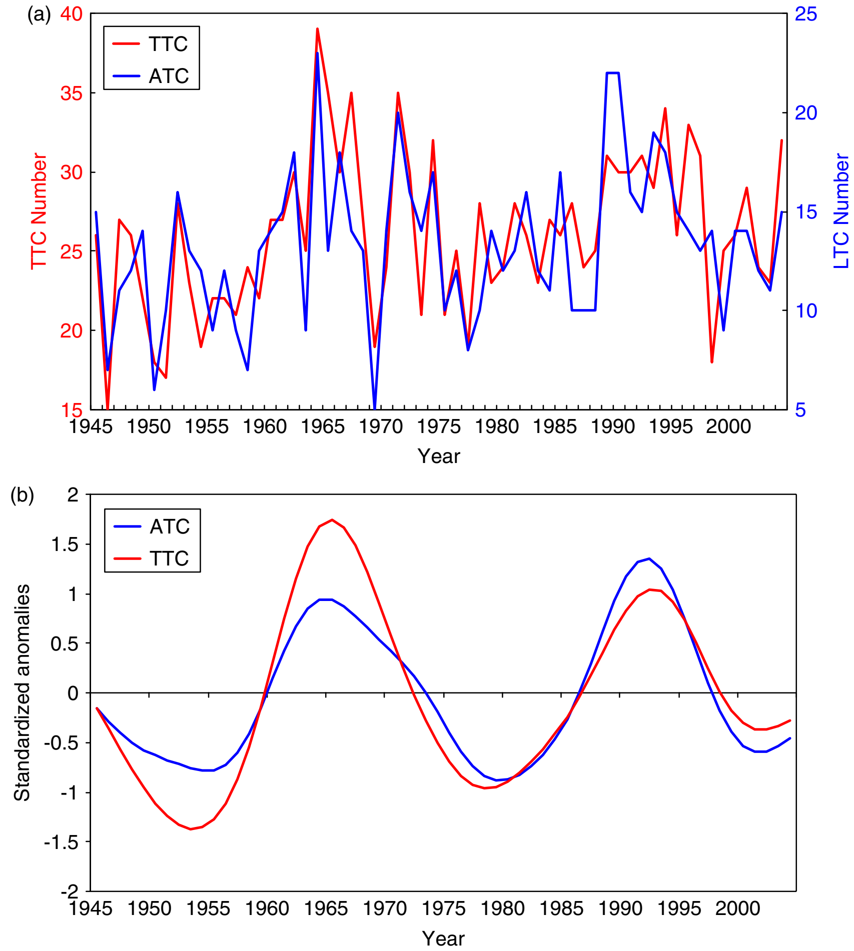

Figure 6. (a) Time series of TTC and ATC. (b) 16–32-year reconstructed TTC and ATC series. This figure is available in colour online at www.interscience.wiley.com/ijoc

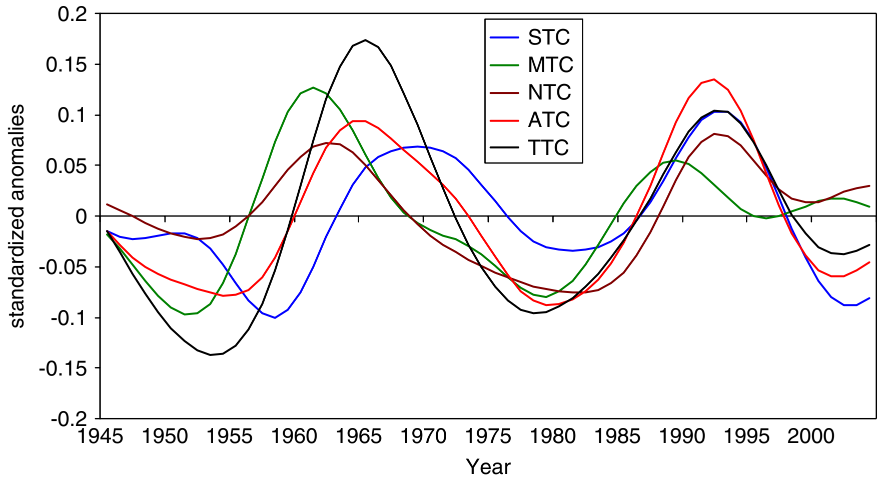

Figure 7. 16–32-year reconstructed series of STC, MTC, NTC, ATC and TTC. This figure is available in colour online at www.interscience.wiley.com/ijoc

well with TTC. Note also from Figure 7, that the significant correlations between ATC and each of the three regional series shown in Table II do not necessarily imply that they always vary in phase.

Thus, interpretation of the correlation between TTC and each of the three series has to be made with caution, in that an increase in TTC does not necessarily imply more landfall events everywhere, an example of which is in the last few years when TTC is negative but more TCs made landfall in east China and north Asia. Only the conclusion that ATC varies very well with TTC on this time scale can be drawn. Nevertheless, this conclusion is very important as it implies that if TC activity over the WNP can be predicted, an estimate of the total landfall in Asia could be made although it might not be as easy for each of the regions. This is in contrast with the result for the Atlantic where more TC activity does not necessarily translate to a higher landfall frequency in the USA (Holland, 2007).

5. Summary and conclusions

This is the first of a two-part series that examines the inter-annual and inter-decadal variations in the number of landfalling TCs in various parts of the western North Pacific, and the possible reasons for such variations. Based on the frequency of tropical cyclone occurrences, the landfalling activity is divided into three regions: South (south China, Vietnam and the Philippines), Middle (east China) and North (Korean Peninsula and Japan). The time series of the annual number of landfalling TCs in each region is then examined.

An important finding in this part of the study is that none of the time series shows a significant linear temporal trend, which suggests that global warming has not led to more landfalls in any of the regions in Asia. Rather, wavelet analyses of each time series show that the landfalling frequencies go through large inter-annual (2–8 years), inter-decadal (8–16 years) and even multi-decadal (16–32 years) variations, with the inter-annual being the most dominant, and the multi-decadal explaining most of the rest of the variance. It is the superposition of these two oscillations that leads to the observed variations in the number of landfalling TCs. In some periods, this number varies in unison among all regions of Asia. In others, one region might have an above-normal number of landfalling TCs while the other regions have below-normal numbers.

In general, at multi-decadal time scales, the number of TC landfalls in each region is well correlated with that of the total number of TCs over the western North Pacific, which suggests that in periods of active tropical cyclone activity, one can expect more landfalls in Asia. At shorter time scales, some regions have better correlations with the TC activity than others.

In Part 2, possible reasons for such variations are explored by examining variations of atmospheric and oceanographic variables on similar time scales. Correlations between these variations are then calculated among the time series. Physical hypotheses are advanced to explain the significant correlations.

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