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AN EMPIRICAL STUDY OF TROPICAL CYCLONE ACTIVITY IN THE ATLANTIC AND PACIFIC OCEANS: 1851–2005

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The trends and intrinsic frequencies in the time series of the number of Tropical Cyclones (TCs), hurricanes and typhoons, and Categories 4 and 5 hurricanes and typhoons in the Atlantic and Pacific Ocean domains, and the yearly integral of hurricane wind energy, represented by the Power Density Index (PDI), in the Atlantic and Eastern North Pacific Ocean domains are studied. The results show that the Empirical Modal Decomposition (EMD) method [Huang *et al.* (1998)] successfully reveals that there are intrinsic modes of variations that are controlled by climate systems such as the Quasi-Biennial Oscillation (QBO), the El Nino Southern Oscillation (ENSO), and the Atlantic and Pacific Multi-Decadal Oscillations (AMO and PDO), along with the Meridional Overturning Circulation (MOC). It also reveals some oscillation modes whose controlling factors are not yet identified. In both the Atlantic and Pacific Ocean domains, the frequencies of TCs, hurricane/typhoon-strength TCs and the strongest (Saffir-Simpson Categories 4 and 5) TCs have slowly rising trends. In the Atlantic Ocean, our study indicates that since the mid-1970s, the observed rise in the number of the strongest (Cats. 4 and 5) TCs as discussed previously by Webster *et al.* [2005] and the rise in the measure of destructiveness, the Power Density Index (PDI), developed by Emanuel [2005], were not the cause of rising trends, but instead, they are the result of the combination of positive phases of several intrinsic frequency modes. In the Pacific Ocean, the rising trends have larger amplitudes than those in the Atlantic Ocean, but the higher frequency modes appear to play a more important role in deciding the year-to-year Pacific TC, hurricane/typhoon and Cats. 4 and 5 TC activity levels.

Keywords: Tropical cyclone activity; Atlantic Ocean; Pacific Ocean.

1. Introduction

The increased Atlantic hurricane activity over the past decade and a half has caused significant death, damage and destruction in coastal and inland areas of the United States and Eastern Asia, that it has received commensurate attention from the public, the U.S. Congress and the international scientific community. Since 1995 the Atlantic Ocean domain, which we take to include the ocean east of the eastern seaboard of the U.S. and the Gulf of Mexico and Caribbean, has experienced above-normal TC activity in general and more specifically, hurricane activity as well. The year 2004 experienced three Saffir-Simpson Category-4 and one category-5 hurricanes, and the state of Florida experienced landfall from four major hurricanes (Charley, Frances, Ivan and Jeanne) in less than two months. In 2005 hurricanes Katrina, Rita and Wilma were amongst the strongest hurricanes ever recorded in the Atlantic Ocean. The scientific community is divided as to the reason for the recent increase in TC and hurricane (Saffir-Simpson Category 1 and higher TC) activity. Some scientists blame human-caused global warming for the increased TC and hurricane activity, while others attribute the increased activity to natural multi-decadal cycles that they claim are naturally occurring and would occur even without the purported anthropogenically induced rise in temperatures of the global ocean surface and waters down to 3000 meters [Pielke *et al.* (2005)].

Emanuel [2005] defined and computed the Power Dissipation Index (PDI), an indicator of hurricane destructiveness, using Atlantic and East Pacific TC observational data from the 1949. His results show that TC destructiveness bears a close relationship with tropical sea surface temperatures, and both have increased markedly since the mid-1970s. Webster *et al.* [2005] found that the number and proportion of the strongest hurricanes and typhoons (Saffir-Simpson Categories 4 and 5) in the Atlantic and Pacific Ocean domains nearly doubled in the time frame from 1990 to 2004, compared to the time window of 1975 to 1989, while the total number of hurricanes and typhoons experienced little change other than natural oscillations, except for the North Atlantic, where the total number of hurricanes and typhoons (Saffir-Simpson Categories 1–5) displayed an upward trend. This pair of papers received enormous media attention and Discover magazine named the issue of Climate Change and Hurricane activity as the science story of the year.

Critics have argued that the aforementioned findings were the results of inaccurate and or incomplete data and faulty data processing methods. They have suggested that recent several decade TC activity variations were caused by natural climate oscillations such as the El Nino Southern Oscillation (ENSO), the Quasi-biennial Oscillation (QBO) and the Atlantic Multi-decadal Oscillation (AMO), as well as others. The variations in TC activity contained multi-temporal modes that have different intrinsic frequencies associated with different climate oscillations. The trends, if any, might be intertwined together with the natural oscillations and become very complex, and therefore, difficult to ascertain. A cold or warm phase of a low-frequency oscillation may be confused for a trend if observed within a shorter time frame and an established trend may be reduced or exaggerated by natural oscillations if observed visually. This complexity is one of the main reasons causing the debate. Unfortunately, in the aforementioned studies, the different temporal modes contained in the time series of the TC activity and climate oscillations were presented together without being differentiated.

In this paper, the empirical mode decomposition (EMD) method will be employed to investigate the different intrinsic frequencies in the time series of both the number and power dissipation index (PDI) of TCs, hurricane/typhoons-strength TCs and strongest (Saffir-Simpson Categories 4 and 5) TCs in Atlantic and Pacific Oceans. The correlation between the variations in TC activity and in Sea Surface Temperature (SST) is studied. And the possibility of using EMD as a forecasting tool to predict future TC activity is addressed. The paper is organized as follows: the EMD method is described in Sec. 2; study results are presented in Sec 3; and a summary is given in Sec. 4.

2. Method

A method, developed by Huang *et al.* [1998], called Empirical Mode Decomposition (EMD) has been shown effective in analyzing nonlinear and non-stationary signal time series. The EMD method is different from Fourier and wavelet transforms because it handles nonlinear and non-stationary signals. The Fourier transform (FFT) is designed to work with linear and stationary signals. The wavelet transform, on the other hand, is well suited to handle non-stationary data but poor at processing nonlinear data. Since the variations in climate and TC activity are complex non-linear and non-stationary in nature, FFT and wavelet are not suited in their analysis.

The EMD is an adaptive decomposition technique that can decompose nonlinear and non-stationary complicated signal time series into a definite number of components with different frequencies by a method introduced by Huang [1998] called sifting. These components are called intrinsic mode functions (IMF). The IMFs have well-behaved Hilbert–Huang transforms and from which the instantaneous frequencies can be calculated. The essential procedure of EMD is to locally identify the most rapid oscillations in the signal, defined as a waveform interpolating interwoven local maxima and minima. To do so, the local maxima/minima points are interpolated with a cubic spline, to determine the upper/lower envelope. The mean envelope is then subtracted from the initial signal, and the same interpolation scheme is repeated for the remainder of the signal. The sifting ends when the mean envelope is reasonably zero everywhere, and the resultant signal is designated as the first IMF. The higher order IMFs are iteratively extracted, applying the same procedure for the initial signal, after removing the previous IMFs. In the original definition of IMF, to be an IMF a signal must satisfy two criteria, the first one being that the number of local maxima and the number of local minima must differ by at most one and the second that the mean of its upper and lower envelopes must equal zero [Huang *et al.* (1998)]. Therefore, a one-dimensional discrete signal time series S_T, after being decomposed by EMD method, can be represented with the following form:

$$S_T = \sum_{n=1}^{N} \mathrm{IMF}(n, T) + \mathrm{residual}(T) \tag{1}$$

where IMF is the N_{th} mode of the signal time series, and *residual* is the residual trend.

3. Results and Discussions

3.1. *Variations in the frequencies of TC activity*

3.1.1. *Tropical cyclones*

Figure 1 shows the Atlantic Ocean TC time series (1851–2005) and its temporal components. There is an upward trend (R in Fig. 1), rising from about eight TCs per year in 1850 to 12 TCs per year in 2005. This trend may be associated with the increasing global sea surface temperature or with better detection of the storms via aircraft reconnaissance following WWII and over the past four decades, by satellite. In addition to the trend, the gravest mode, the EMD method revealed that there are five additional intrinsic frequencies in Atlantic TC variations (C1–C5). C1 has a period ranging from 1 to 3 years, with a central period of 30–31 months. Mode C1 appears to be associated with the quasi-biennial oscillation (QBO), a quasi-periodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 30 months. The QBO affects Atlantic TC activity by changing the strength of vertical wind shear over the region of TC genesis. The amplitude of C1 ranges from 1 to 10 per year, the largest range of all intrinsic modes.

The 2$^{\mathrm{nd}}$ mode, C2, has a period ranging from 2 to 7 years, with an average period of 5.7 years. The amplitude of this component ranges from 1 to 5 TCs per year. Figure 2 shows the EMD components for the Japan Meteorological Agency (JMA) SST ENSO index [Trenberth (1997); Hanley *et al.* (2003)] from March 1868 to November 2005. Gray [1984] showed that during the ENSO warm phase, the anomalously strong upper level westerly winds increase the vertical wind shear and therefore hinder TC development over the Caribbean and Eastern Atlantic Basin. During the ENSO cold phases the upper winds tend to be mainly easterly and therefore favor Atlantic hurricane development. In Figs. 1 and 2 it is shown that the C2 mode negative phases occurred in 2002, 1997, 1991, 1987, 1982, 1976, 1965, 1962, 1957, 1951, 1939, 1918, 1912, 1905, 1902, 1896, 1890, 1883, 1874, 1868, and 1857, corresponding well to the warm phases of the ENSO oscillation (especially

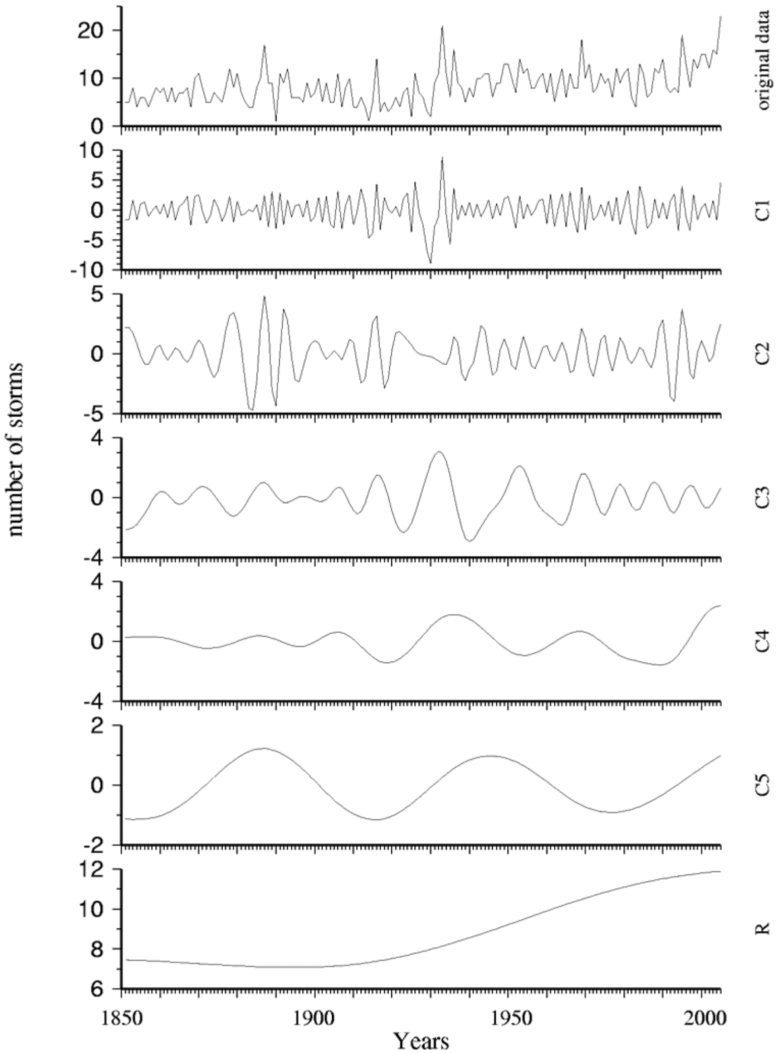

Fig. 1. EMD Components for Atlantic TCs per year (1851–2005).

after 1939, when due to aircraft reconnaissance during and following World War II, synoptic data was collected more routinely and became more accurate), which suggested that the C2 mode is primarily regulated by ENSO. It appears that the 1930 Atlantic TC activity decrease, evident in the first QBO-controlled mode C1, should be attributed to the 1930 ENSO warm phase.

In addition to the QBO and ENSO, another well established factor regulating TC activity is the Atlantic Multi-decadal Oscillation (the AMO), with a period ranging from 40 to 70 years. The AMO affects Atlantic TC activity by changing SST and upper air wind shear. The Atlantic Ocean generally experiences more active TC actively during the AMO positive phase and less active TC activity

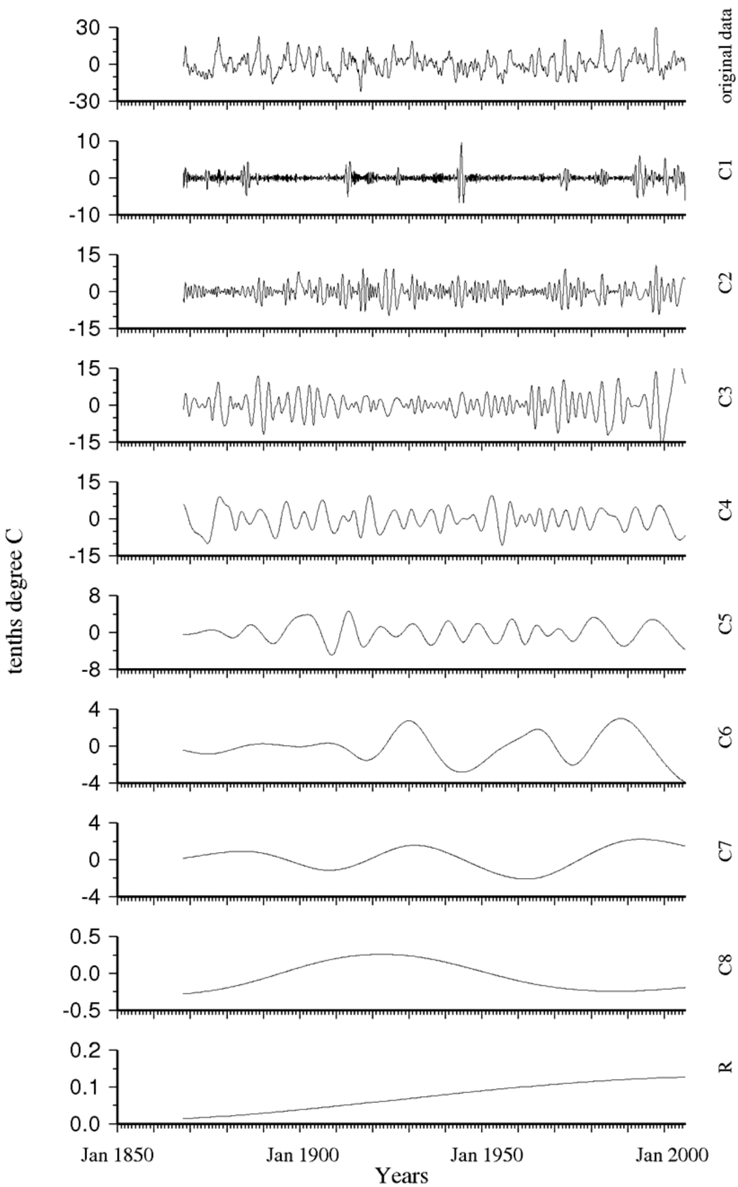

Fig. 2. EMD Components for JMA/SST ENSO Index March 1868-November 2005.

during the AMO negative phase [Goldenberg *et al.* (2001)]. In Fig. 1, Mode C5, with a period of $\sim$ 60–75 years, shows that this TC activity variation correlates very well with the well-known period range of the AMO and of the possible Meridional Overturning Circulation (MOC) period. Mode C5 entered a negative phase in the beginning of the 1960s and remained negative until the mid-1990s, then transitioned to a positive phase, indicating increased Atlantic TC activity. The amplitude and frequency of the AMO and MOC controlled C5 mode are rather steady (Fig. 1, C5).

In addition to the upward trend, the QBO-mode, the ENSO-mode and the AMO-mode, EMD reveals two other intrinsic modes: one is a quasi-multi decadal mode (C3) and the other is a multi-decadal mode (C4). The C3 mode has amplitude ranging from 1 to 4 per year, and an average period of 13 years. The C4 mode has amplitude ranging from 1 to 3 per year, and an average period of 26 years. These two intrinsic TC activity frequencies may be associated with climate oscillations whose relationships with Atlantic TC activity have not been well identified. Mode C3 appears to be associated with the North Atlantic Oscillation (NAO) index Walker [1924], which Rogers [1984] showed to be well correlated with the Southern Oscillation (SO). The C4 mode may be associated with the Pacific Decadal Oscillation (PDO) index [Mantua *et al.* (1997)]. Further work is needed to identify and fully understand the roles of these two intrinsic modes (C3 and C4 in Fig. 1) in affecting Atlantic TC activity.

From the mid-1990s to the mid 2000s, the Atlantic Ocean has experienced above-average TC activity. From Fig. 1 we see that within the time window from 1995 to 2005, Modes C4 and C5 were both in their positive phase and near their relative peaks. The residual trend R (Fig. 1) was rising but the rate of rising was decelerating. So the combination of the trend, plus Modes C4 and C5 may explain the increase in TC activities which occurred in the Atlantic Ocean from the mid-1990s to 2005. From 2004 to 2005, the trend and modes mentioned above as well as the modes with higher frequencies, namely, C3, C2 and C1, were all in their positive phase, which explains the dramatic increase in the Atlantic TC activity in 2004 and 2005. It appears that the C4 and C5 modes approached their peaks and will likely remain in their positive phases for another 15 to 20 years (for Mode C4) and for 35 to 40 years (for Mode C5). The level of Atlantic TC activities is determined largely by the combination of five intrinsic frequency modes. And since the C4 and C5 modes have relatively steady and predictable amplitudes and frequencies, it appears that the prediction of Atlantic TC activities depends critically on the accurate predictions of the C1 and C2 modes, which in turn, are associated with the predictions of the QBO and ENSO oscillations. Modes C1 and C2 also have amplitudes larger than those of Modes C4 and C5, and therefore play a more important role in year-to-year Atlantic TC activity predictions. However, Mode C5 can strongly modulate overall activity for multiple decades, either enhancing or suppressing TC activity.

Figure 3 shows the EMD components for Pacific TCs per year from 1949 to 2004. There is a gravest mode or residue trend (Fig. 3) rising from 37 to 53 per year during the period 1949–2004. In addition to the trend, there are three intrinsic frequency modes shown in Fig. 3. Mode C1 mode is associated with ENSO, with an average period of 3 years and amplitudes ranging from 5 to 10 per year. In ENSO warm phase years, TC activity in the Pacific tends to intensify, while in ENSO cold phase years TC activity tends to be reduced. Mode C2 displays an average period

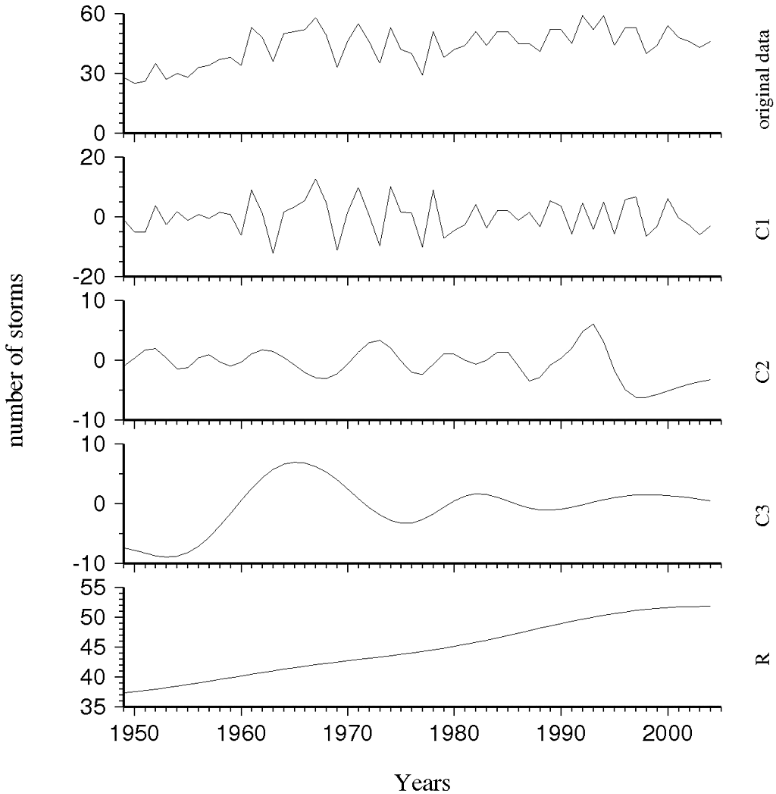

Fig. 3. EMD Components for Pacific Ocean TCs per Year (1949–2004).

of 7 years, with amplitude up to 7 per year. Mode C3 appears to be associated with the PDO, with an average period of 20 years and amplitude as large as 10 per year. It is of note that year to year TC activity in the Pacific varied by 10–20% annually and bi-annually following the early 1960s, superimposed on the rising trend. This is because of the effects of Modes C2, C3 and C4. Mode C2 decreased from 1990 and entered a negative phase in the mid 1990s and remained negative. Mode C3, with amplitude decreasing with time, has oscillated about its average value. The QBO appears to have no significant influence on Pacific TC activity. Given the 56 year time series considered, the level of TC activity in the Pacific is determined by the combination short period intrinsic modes superimposed on the trend. Arguably, the five decade time series of data is relatively short and thus conclusive information is lacking, such as the possible relationship with the AMO and or the MOC.

3.1.2. *Hurricanes and typhoons*

In keeping with the Saffir-Simpson Scale, a hurricane (typhoon) is a TC that forms in the North Atlantic Ocean or the Eastern (Western) Pacific Ocean and reaches

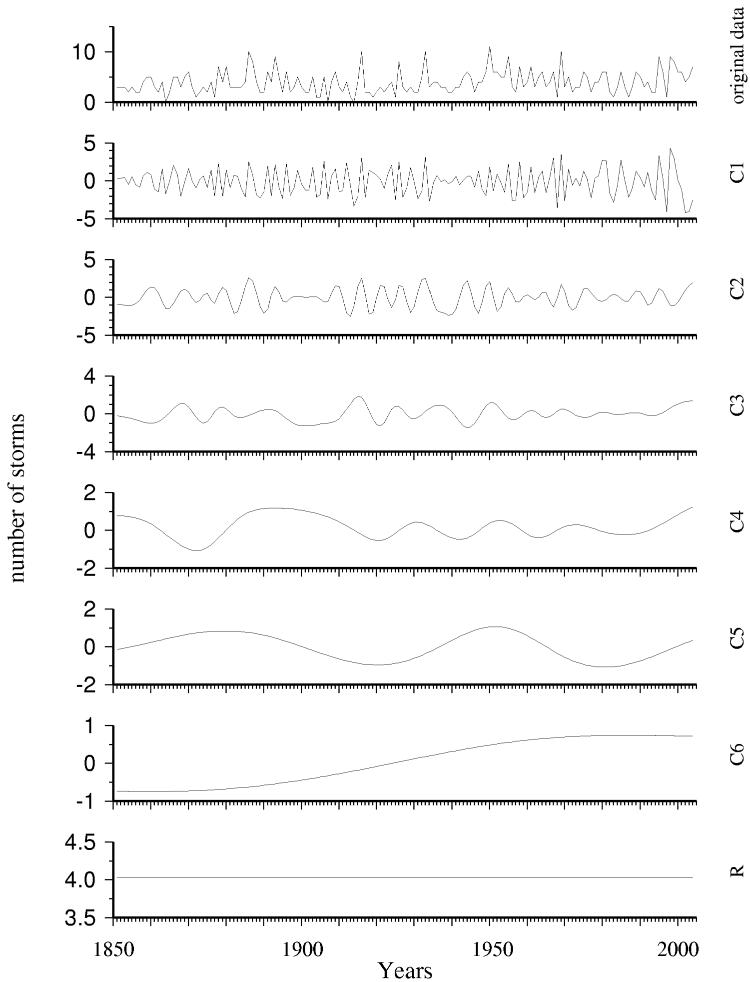

Fig. 4. EMD Components for Atlantic Ocean Hurricanes per Year (1851–2004).

sustained wind speeds of 74 mph or greater. There is a tacit assumption that more TC activity translates to more hurricanes (typhoons). Figure 4 shows the EMD components for Atlantic Hurricanes per year from 1851 through 2004. There are seven intrinsic frequencies in the time series. Similar to the EMD components for the Atlantic TC time series (Fig. 1), the modes C1, C2 and C5 are variability controlled by the QBO, ENSO, AMO, and perhaps the period of the MOC (which is not yet determined but believed to be of order 50–80 years), respectively. In addition to the three well-documented intrinsic frequency modes, there are three additional intrinsic frequency modes C3, C4 and C6 plus the gravest mode, the trend. Mode C3 has amplitudes ranging from 1 to 2 per year, and a period of 13 years, alike that of the TC-C3 mode as shown in Fig. 1, and also suggesting that the hurricane C3 mode may be associated with the NAO. The C4 mode of Atlantic hurricanes has amplitude between 0 and 1 per year, and a period of 25 years, similar to that of the C4 mode of Atlantic TCs (Fig. 1), meaning that it may be related to the PDO. Mode C5 has a period of order 60–80 years and amplitude up to 2 per year. Mode C6 has amplitude of up to 1 per year and a period of about 150 years or just shorter then record length. There is an essentially flat gravest mode or trend over the time frame of 1851–2004. So the overall average of the number of Atlantic hurricanes per year has held constant at ~ 4 and is modulated by a very long, near record length cycle. C6 and the trend, taken together, constitute an overall rise of 2 hurricanes per year from the beginning of the 154 year time series. Note that the C6 mode appears to be rising monotonically over the time frame 1851–2004, but it is a very long period oscillation. The C6 mode has an amplitude small compared with the other modes, and therefore does not have a significant influence on overall Atlantic hurricane activity and also has had no noticeable change from 1974 to 2004. The increased hurricane activity in the Atlantic Ocean Basin since the mid-1990s is the result of the combination of the positive phases of modes C3, C4 and C5 and to a lesser degree C6. It seems that the increase in global sea surface temperature has had an influence on overall Atlantic TC activity but has had little effect on Atlantic hurricane activity.

Figure 5 shows the EMD components for Pacific hurricanes and typhoons per year from 1949 to 2004. The time series has a gravest mode or trend rising from 22 in 1949 to 28 in 2004. In addition to the trend, there are also four intrinsic frequencies. The C1 mode is apparently controlled by ENSO, and C4 appears to be controlled by the PDO. The C2 and C3 modes, having central periods of 6 and 11 years respectively, are controlled by climate variations such as ENSO and perhaps the Solar Sunspot Cycle, but that is only conjecture. The increase (from 25 to 28 per year) in the trend during 1974–2005 was offset by the negative phases in the C3 and C4 modes, which both have declined since 1990 and entered negative phases in the mid-1990s. As a result, in recent years Pacific Ocean hurricane and typhoon activity showed a slight decline. Thus, even with the well documented slow rise in global SST, and a tacit assumption that such a rise would have a positive influence on Pacific hurricane and typhoon activity, its influence appears small compared with the other intrinsic frequency modes and the combination of the phases of different intrinsic frequency modes.

3.1.3. *Saffir-Simpson categories 4 and 5 hurricanes and typhoons*

Figure 6 shows the EMD components for Categories 4 and 5 North Atlantic TCs per year from 1851–2004. Evident is a trend rising from 0.5 per year in 1851 to 1.25 per year by 2004, a 0.005 event/year slope. This slow trend may be associated with the rise in global SST or perhaps detection methodologies. Beside this basic trend, there are other five intrinsic frequency modes. The C1, C2 and C4 modes correspond to the controlling climate variations QBO, ENSO and AMO, respectively. The C3 mode has an average period of 13 and 14 years and amplitudes ranging from 0 to 1 per year. The climate oscillation that controls the C3 mode is not identified

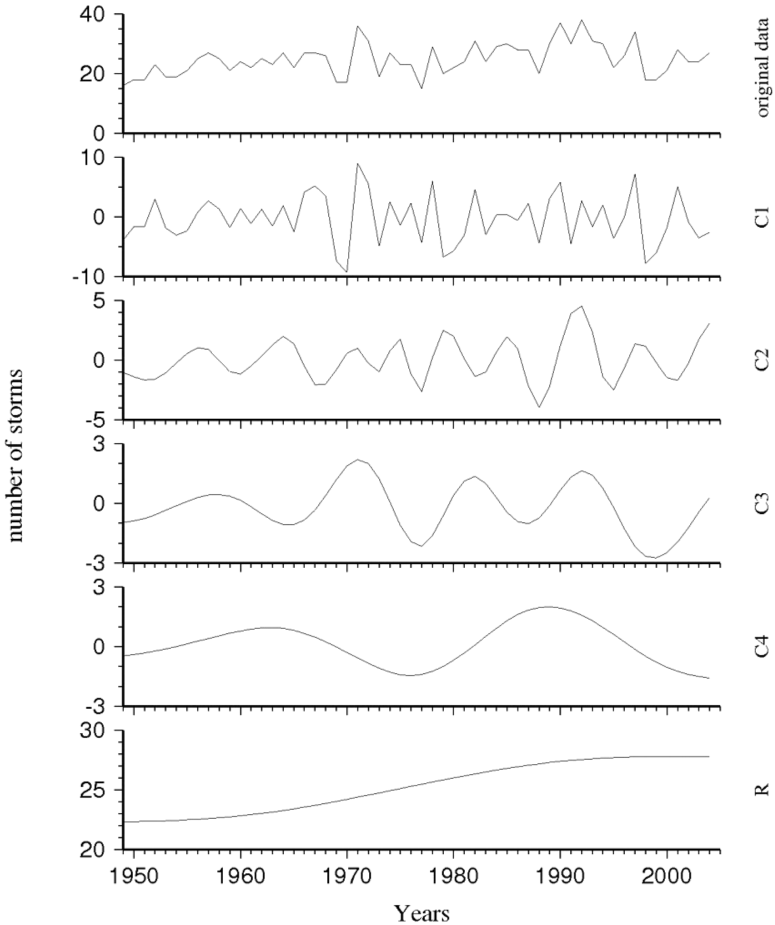

Fig. 5. EMD Components for Pacific Ocean Hurricanes and Typhoons per Year (1949–2004).

and needs further study. The C5 mode, with a 150+ year period, appears to be an outcome of the fact that during the early years of the TC activity records, some Categories 4 and 5 TCs were not recorded or may have been recorded as weaker TCs due to the limited observation techniques. Webster [2005] showed that Categories 4 and 5 TCs increased significantly over the time frames of 1974–1990 and 1990–2004, and suggested that those increases might be associated with anthropogenic global warming.

From Fig. 6 it is evident that over the period 1974–2005 the residue trend was almost constant with only a slight rise. The dramatic rise in Categories 4 and 5 TCs from 1974–1990 and 1990–2005 was the result of the combination of the changes in phases in the C3 and C4 modes. From 1974 to 1990 the C3 mode was largely negative. In 1990 this condition reversed and in the mid-1990s the C3 mode phase became positive. From 1974–1990 the C4 mode was rising but still in a negative phase. In 1990 the C4 mode's phase became positive. Therefore it appears that

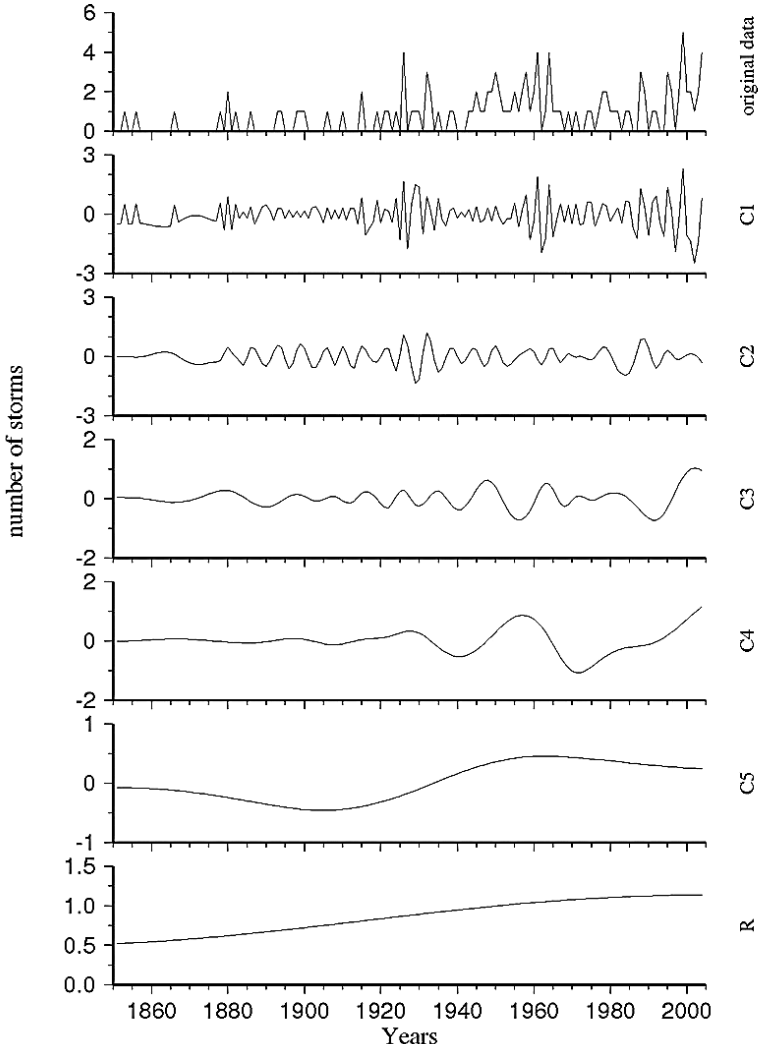

Fig. 6. EMD Components for Saffir-Simpson Categories 4 and 5 North Atlantic TCs per Year (1851–2004).

although global warming might increase the frequency of occurrence of the strongest (Categories 4 and 5) TCs in the Atlantic Ocean, the influence was small and not responsible for the increase in Categories 4 and 5 TCs from the mid-1990s to the mid–2000s. Instead, the increase in Categories 4 and 5 TC might be attributed to the combination of the phases of several multi-decadal intrinsic mode. Moreover, it appears that Modes C3 and C4 will retain positive phases for another 10–15 years or until 2015–2020.

Figure 7 shows the overall time series and the EMD components for Categories 4 and 5 Pacific TCs per year (1945–2004). The time series begins with frequency

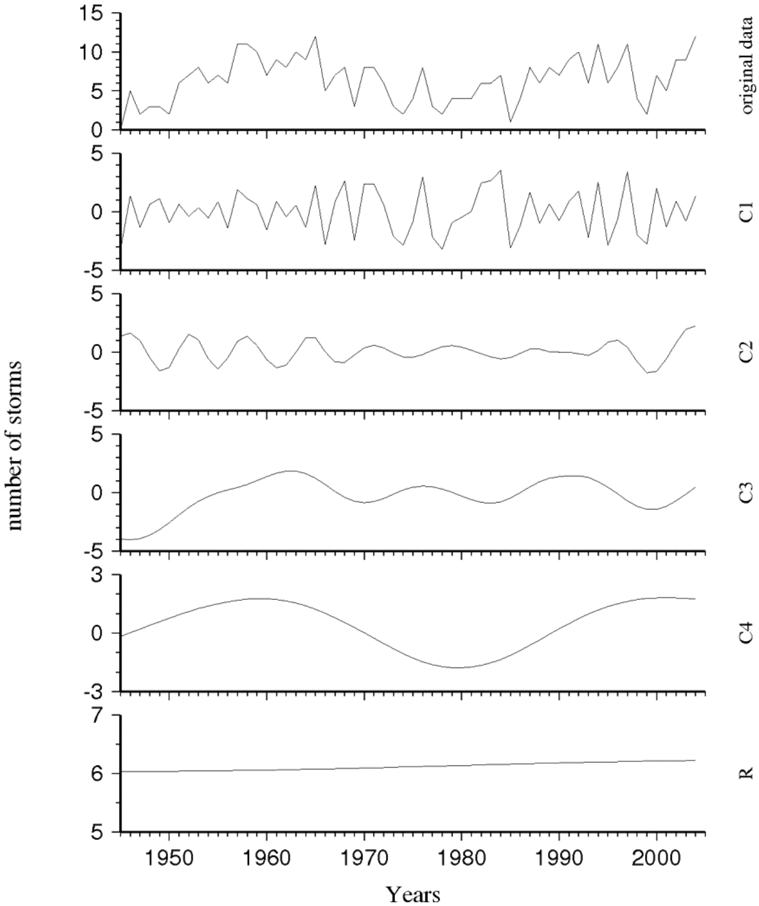

Fig. 7. EMD Components for Saffir-Simpson Categories 4 and 5 Pacific Ocean TCs per Year (1945–2004).

of occurrence of 1 to 5 per year in the early 1950s, rises to 10–15 in the late 1950s to mid-1960s, drops and then rises to 10–15 per year from the mid-1990s to 2004. Similar to the EMD components for the Pacific TCs (Fig. 3), there is a slowly rising trend, going from 6 per year in 1949 to 6.5 per year by 2004 (a slope of ~ 0.008 event/year), and three intrinsic frequency modes, C1, C2 and C3. Mode C1, with amplitude up to 5/year, is associated with ENSO and Mode C3, with amplitude up to 3/year, appears to be associated with the PDO. Mode C3 was negative in 1979–1986 and 1996–2003 and positive from 1987–1995, and in 2004. Mode C4 with period of order 45 years and amplitude up to 3/year, was negative from 1970 to 1989 and positive from 1989 and thereafter. Therefore it appears that the rise in categories 4 and 5 Pacific TCs over the period 1990–2005 which was studied by [Webster *et al.* (2005)] was the combination of the rising trend and the phase change of the C4 mode.

3.2. *Variations in the yearly integral of TC wind energy*

Figure 8 shows the EMD components for the yearly integral of wind energy for Atlantic hurricanes over the period 1851–2004. The wind energy is represented by the power dissipation index (PDI) as presented by Emmanuel [2005] and ranges from 0 (1925) to $30\text{m}^3/\text{s}^2 10^{12}$. There are five intrinsic modes plus the gravest mode, the trend, which is flat at $\sim 10.35\text{m}^3/\text{s}^2 10^{12}$. Mode C1 is controlled by the QBO, C2 by ENSO, C3 by the AMO and C4 by the AMO and the MOC. Amplitudes are

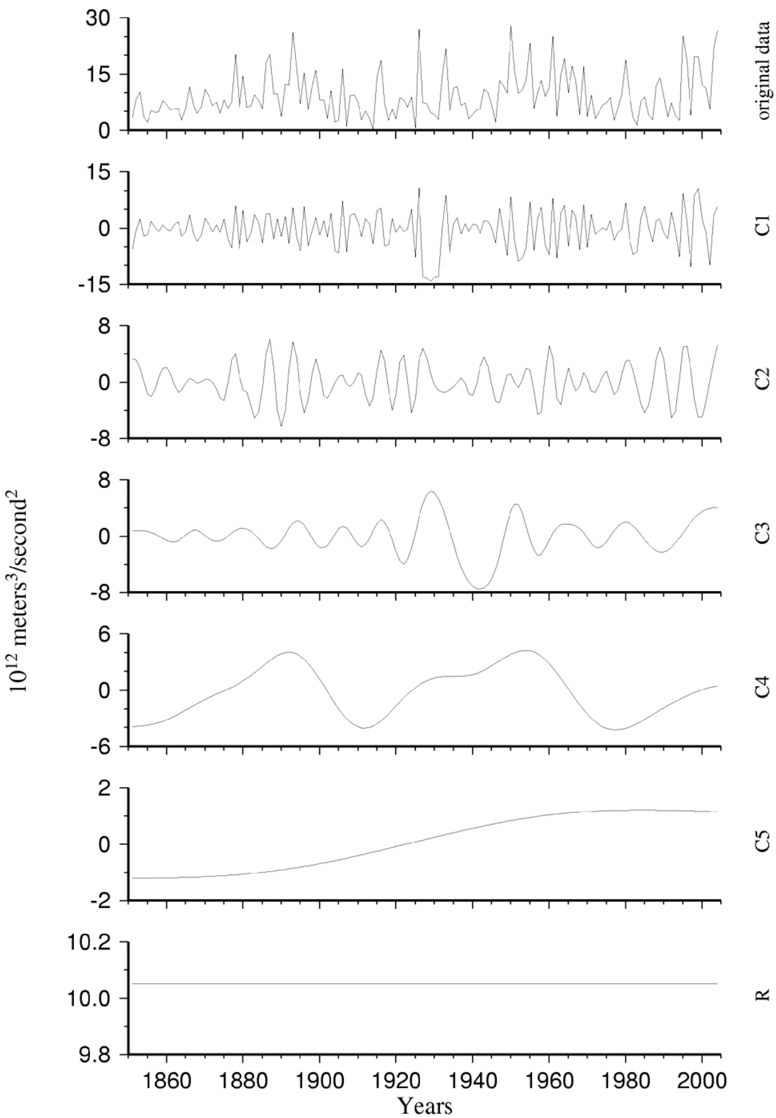

Fig. 8. EMD Components for the Yearly Integral of Wind Energy for Atlantic TCs (1851–2004).

C1 up to $15m^3/s^2 10^{12}$, C2 up to $8m^3/s^2 10^{12}$, Mode C3 up to $8m^3/s^2 10^{12}$, C4 up to $6m^3/s^2 10^{12}$and C5 up to $2m^3/s^2 10^{12}$. Mode C5 has a period of ∼150 years. Emanuel found that since mid-1970s the hurricane destructiveness (indicted by the PDI) had a rising trend. Figure 8 shows that the rise in PDI since the 1970s was principally associated with the positive phase of the C4 mode, an oscillation controlled by the AMO and the MOC. In recent years, especially in 2004 and 2005, the Atlantic Ocean has experienced significant above-normal TC activity. From Fig. 8 it is apparent that this above-normal TC activity seen in recent years, and the destructiveness associated with it, is due to the combination of the positive and rising phases of all the intrinsic frequency modes, namely C1–C4. Although the rise in global SST undoubtedly affected the number of TCs, hurricanes and the strongest hurricanes (Figs. 1–7), it may have had little influence on TC destructiveness.

Figure 9 shows the EMD components for the yearly integral of wind energy, indicted by PDI, for Eastern North Pacific hurricanes over 1949–2004. The residue trend rose from $7m^3/s^2 10^{12}$ in 1949 to $16m^3/s^2 10^{12}$ by the mid-1990s and remained

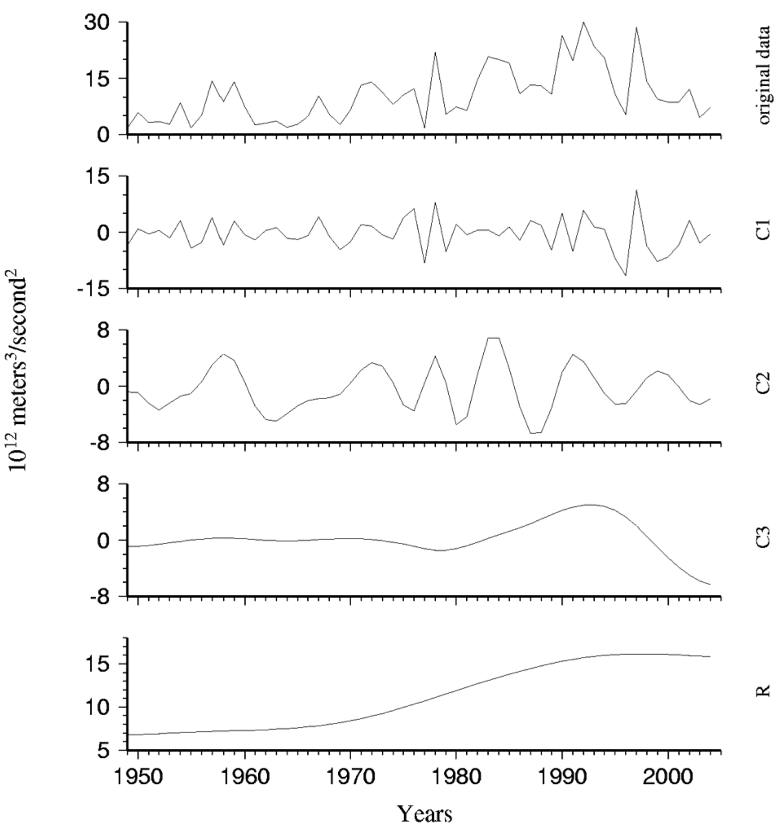

Fig. 9. EMD Components for the Yearly Integral of Wind Energy Eastern North Pacific TCs (1949–2004).

constant thereafter. In addition to the trend, there are three modes, C1, C2 and C3. Mode C1 is controlled by ENSO. Emanuel found that since the mid-1970s, Eastern North Pacific hurricane destructiveness has increased significantly. From Fig. 9 it can be seen that there is indeed a rising trend that might be responsible for the rising hurricane destructiveness, and this rising trend could be related to the globally rising SST, although it cannot be determined conclusively, due to the relatively short record length (1949–2004).

4. Conclusions

(1) The EMD method successfully decomposed the time series of the number of TCs, hurricane/typhoon level TCs and the strongest (Categories 4 and 5) TCs in both Atlantic Ocean and Pacific Ocean. The well-established climate oscillations that control the TC activity, such as QBO, ENSO, AMO, PDO and likely the MOC, etc. were all evident in the EMD components.
(2) The EMD method revealed several intrinsic oscillation frequencies whose controlling climate factors are not identified or understood.
(3) The number of TCs, hurricane/typhoon level TCs, and strongest (Categories 4 and 5) TCs all had rising trends in both Atlantic and Pacific Oceans.
(4) The observed above-normal TC activity in Atlantic Ocean since the mid-1990s should not be attributed to the slowly rising trends. The above normal activity is the result of the combination of several positive phases of one or more dominant intrinsic frequency modes.
(5) In the Pacific Ocean Basin, the amplitude of the frequency of occurrence, rising gravest frequency intrinsic mode or trend, was larger than that in the Atlantic Ocean Basin. However, the rising trends still played less important roles in determining overall frequency of occurrence than the higher frequency multi-year to multi-decadal intrinsic modes.
(6) Year-to-year variability in TC activity is principally determined by the phasing combination of the different intrinsic frequency modes. The lower-frequency modes appeared to have relatively steady and predictable amplitudes and periods. Therefore, with the improvement of the higher-frequency QBO and ENSO forecasts, the EMD method might prove to be a valuable tool to predict TC activity several years in advance in both ocean basins.

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References

Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**: 686–688.

Goldenberg, S. B., Landsea, C. W., Mestas-Nunez, A. M. and Gray, W. M. (2001). The recent increase in atlantic hurricane activity: Causes and implications. *Science*, **293**: 474–479.

Gray, W. (1984). Atlantic seasonal hurricane frequency. Part i: El niño and the 30 mb quasi-biennial oscillation influences. *Monthly Weather Review*, **112**: 1649–1668.

Hanley, D. E., Bourassa, M. A., O'Brien, J. J., Smith, S. R. and Spade, E. R. (2003). A quantitative evaluation of enso indices. *Journal of Climate*, **16**(8): 12490131258.

Huang, N. E., Shen, Z., Long, S. R., Wu, M. L., Shih, H. H., Zheng, Q., Yen, N. C., Tung, C. C. and Liu, H. H. (1998). The empirical mode decompostion and hilbert spectrum for nonlinear and nonstationary time series analysis. *Proc. R. Soc. London A*, **454**: 903–995.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. and Francis, R. C. (1997). A pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, **78**: 1069–1079.

Pielke, R. A. Jr., Landsea, C., Mayfield, M., Laver, J. and Pasch, R. (2005). Hurricanes and global warming. *Bull. Amer. Meteor. Soc.*, **86**: 1571–1575.

Rogers, J. C. (1984). The association between the north atlantic oscillation and the southern oscillation in the northern hemisphere. *Monthly Weather Review*, **112**: 1999–2015.

Trenberth, K. (1997). The definition of el niño. *Bulletin of the American Meteorological Society*, **78**: 2771–2777.

Walker, G. (1924). Correlations in seasonal variations of weather. *Mem. Ind. Meteor. Dept.*, **24**: 275–332.

Webster, P., H. G. J., Curry J. and Chang, H. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, **309**(5742): 1844–1846.