A New Insight into the Contribution of Environmental Conditions to Tropical Cyclone Activities

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ABSTRACT

The changes of tropical cyclone (TC) activities in response to influencing environmental conditions have been paid more and more attention to in recent years. The potential contributions of single and multivariate environmental variables to annual TC frequency and intensity from 1970 to 2009 are investigated in this study. Instead of using correlation coefficient that assumes a set of samples satisfying the normal distribution, a quantitative measurement is formulated based on the information theory. The results show that dynamic environmental variables play an important role in variations of TC activities over the western North Pacific, North Atlantic, and eastern Pacific. These dynamic factors include wind shear between 850 and 200 hPa and 850-hPa relative vorticity. However, the effects of thermal factors on TC activities are distinct over different basins. The thermal environmental variables only have significant contributions to TC frequency and intensity over the eastern Pacific as well as to TC frequency over the North Atlantic. It is found that the primary factors influencing TC activities are indeed not the same over different basins because of the differences in atmospheric conditions and their changes across different areas. The effects of dynamic variables should be considered more in the regions such as the western North Pacific where the thermal conditions are always satisfied.

Key words: tropical cyclone, information theory, entropy

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1. Introduction

Tropical cyclones (TCs) are one of the most violent natural disasters over the world, which often cause severe economic and human losses. It is of high priority to understand the mechanisms of their genesis and development, as well as the changes of their activities. As far as the latter is concerned, a number of studies have investigated TC activities on interannual and decadal timescales and their long-term trends. In recent years, the possible changes of TC activities due to global warming are intensively discussed (e.g., Emanuel, 2005; Trenberth, 2005; Pielke et al., 2005; Anthes et al., 2006; Hoyos et al., 2006; Holland and Webster, 2007; Vecchi and Knutson, 2008), but this remains a challenging problem.

Several environmental conditions have been recognized as favorable for the formation and evolution of TCs, which include a warm ocean layer of sufficient depth, above-normal mid-tropospheric relative humidity, greater than normal low-level relative vorticity, weaker vertical wind shear, etc. (e.g., Gray, 1968, 1988; Merrill, 1988; De Maria, 1996; Emanuel, 1999). In most publications on changes of TC activities, the effect of sea surface temperature (SST) receives more attention than other factors (e.g., Bengtsson et al., 1996; Knutson et al., 2001; Webster et al., 2005; Emanuel, 2005; Trenberth, 2005). Furthermore, Hoyos et al. (2006) discussed potential linkages between global TC intensity and four environmental

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variables, i.e., SST, specific humidity, wind shear, and stretching deformation. Their results indicated that the trend of increasing number of categories 4 and 5 hurricanes for the period 1970–2004 is directly related to the SST trend, while the other three factors influence the short-term variability of categories 4 and 5 hurricanes.

However, three questions remain open after the publication of Hoyos et al. (2006). Firstly, Hoyos et al. (2006) only linked the change of TC intensity to environmental conditions, but they did not consider the variation of TC annual number (frequency). Frank (1988) indicated that the two phases of TC development, namely, its genesis and intensification, are dominated by different dynamical and physical processes. Thus, how do these variables influence the genesis and frequency of TCs?

Secondly, TCs over some basins are considered as a whole in Hoyos et al. (2006). The atmospheric conditions are not the same over different basins. Gray (1968) found that TC activities in different areas have different characteristics. It is quite possible that the contribution of any environmental variable to TC activities in one area is different from that in another area. How is the change of TC activities linked to the environmental factors over individual basins?

Finally, the contributions of environmental variables to the variation of TC frequency and intensity are considered separately in previous studies (e.g., Emanuel, 2005; Hoyos et al., 2006). The behaviors of TCs are hardly determined by only one factor. Both formation and evolution of TCs are influenced by two or more external factors (Gray, 1975; Merrill, 1988). What is the combined effect on the change of TC activities of two or many environmental variables?

The above questions are investigated in this paper in order to increase the understanding of possible linkages between variation of TC activities and change of environmental conditions. The data and methodology are described briefly in Section 2. Section 3 discusses the application of correlation coefficient as a traditional analysis tool. Some results obtained from analyses based on the information theory are provided in Section 4. Finally, the concluding remarks are given in Section 5.

2. Data and methodology

2.1 Data

The 1970–2009 TC-related data used in this study are from the best track datasets provided by the National Hurricane Center (NHC) and the U.S. Joint Typhoon Warning Center (JTWC). The data include location of storm center and 1-min averaged maximum sustained wind ($V_{\max}$) for each cyclone. The TC activities incorporate two distinct phases, i.e., frequency and intensity. The frequency refers to the annual number of TCs with $V_{\max}$ exceeding 34 kt once or more in their lifetimes, while the threshold of $V_{\max}$ for TC intensity is 114 kt.

The environmental variables are derived from the monthly HadISST sea surface temperature with a horizontal resolution of $1^\circ\times1^\circ$ (Rayner et al., 2003) and monthly NCEP/NCAR reanalysis data with a horizontal resolution of $2.5^\circ\times2.5^\circ$ (Kalnay et al., 1996). Referring to some former publications (Gray, 1968; Royer et al., 1998; De Maria et al., 2001; Emanuel and Nolan, 2004; Hoyos et al., 2006), the time series of such variables are analyzed as SST, specific humidity in the layer between 925 and 500 hPa, temperature difference or instability from the surface to 500 hPa, wind shear between 850 and 200 hPa, 850-hPa zonal stretching deformation, and 850-hPa relative vorticity. The first three variables are thermal variables, and the rest are dynamic variables. The 1970–2009 annual values of these variables are computed over seasons and spatially averaged over three basins, i.e., the western North Pacific (WNP; 5°–20°N, 120°E–180°) during May–December, North Atlantic (NA; 5°–25°N, 90°–20°W) during June–October, and eastern Pacific (EPA; 5°–25°N, 120°–90°W) during June–October.

2.2 Some measurements from the information theory

The information theory introduced by Shannon (1948, 1950) is employed to investigate relationships between TC activities (A) and environmental factors (F) in this work. This approach has already been applied in the atmospheric sciences (e.g., Leung and North, 1990; Roulston and Smith, 2002; DelSole, 2004, 2005; Abramov et al., 2005; Balling and Roy, 2004; Hoyos et al., 2006; Naumann and Vargas, 2009). Let A be a discrete variable that may take $i = 1, \ldots, m$ possible values, while F_k may take possible values of $j = 1, \ldots, n_k$ (k represents the kth factor). Then, the entropy (H) of individual variables is calculated as follows:

$$H(A) = -\sum_{i=1}^{m} p_i(A) \log_2 p_i(A), \tag{1}$$

$$H(F_k) = -\sum_{j=1}^{n_k} p_j(F_k) \log_2 p_j(F_k), \tag{2}$$

where $p_i(A)$ refers to the probability of A taking the value of i, and $p_j(F_k)$ represents the probability of F_k taking the value of j. The entropy is used to measure the amount of uncertainty in A (F_k). A greater value of entropy means a more unpredictable A (F_k). Furthermore, the joint entropy, which measures the uncertainty associated with a set of variables, is formulated as:

$$H(A, F_{k_1}, \ldots, F_{k_i}) = -\sum_{i}\sum_{j_1}\cdots\sum_{j_l} p_{i,j_1,\ldots,j_l} (A, F_{k_1}, \ldots, F_{k_l}) \log_2 p_{i,j_1,\ldots,j_l}(A, F_{k_1}, \ldots, F_{k_l}), \tag{3}$$

where, $p_{i,j_1,\ldots,j_l}(A, F_{k_1}, \ldots, F_{k_l})$ is the probability of these (l+1) variables taking values of i, k_1, …, and k_l, respectively.

Besides the entropy, another important index given in the information theory is called mutual information (MI), which serves as a quantity that measures the mutual dependence of two variables. Formally, the MI of A and F_k can be defined as:

$$I(A, F_k) = H(A) + H(F_k) - H(A, F_k), \tag{4}$$

where the three terms at the right hand side are computed from Eqs. (1)–(3). The value of $I(A, F_k)$ in unit of bit measures how much knowing F_k reduces the uncertainty about A. If A and F_k are independent, knowing F_k does not provide any information about A, so $I(A, F_k)$ is zero. By contrast, if A and F_k are identical, knowing F_k determines the value of A, and equals the uncertainty of A ($H(A)$). The greater the $I(A, F_k)$, the closer the relationship between A and F_k. Furthermore, serving as a broader generation of MI, the interaction information is proposed by McGill (1954) to represent the dependence of a set of variables more than two. The interaction information is computed as:

$$I(A, F_{k_1}, \ldots, F_{k_l}) = \sum_{p=1}^{l+1} \Big[(-1)^{p+1} \cdot \sum_{q} H(X_1, X_2, \ldots, X_p)\Big], \tag{5}$$

where $X_1, X_2, \ldots, X_p$ refer to any p variables of A, F_{k_1}, …, and F_{k_l}, and q equals the number of the whole possible combinations while selecting p variables from a set of (l+1) variables. Finally, some quantities such as entropy, MI, and interaction information are illustrated in Fig. 1 for cases of two as well as three variables.

2.3 Classification of variables

As mentioned above, the quantity of entropy, joint entropy, MI, and interaction information is computed for discrete variables. On the one hand, although the annual TC frequency and intensity over individual basins are discrete, some of them include too many categories if one number is considered as a group. Thus, an optimal number of groups, i.e., 6 ($\approx 40^{1/2}$), is chosen based on the law of square-root choice. Then, these 40-yr samples are categorized into 6 equidistant groups.

On the other hand, time series of the six environmental factors are all continuous variables. These environmental variables should be discretized individually before the computations. It is customary to use the histogram for this goal. Neighboring values of one variable are often grouped together in a so-called bin to reduce noise effects. The number of bins is also chosen as 6 and each variable is categorized into a rounder linear fashion to the bins of the histogram.

2.4 Significance test of information

When the information is estimated, it is still unclear whether there exists a significant relationship among the set of variables. Therefore, a significance

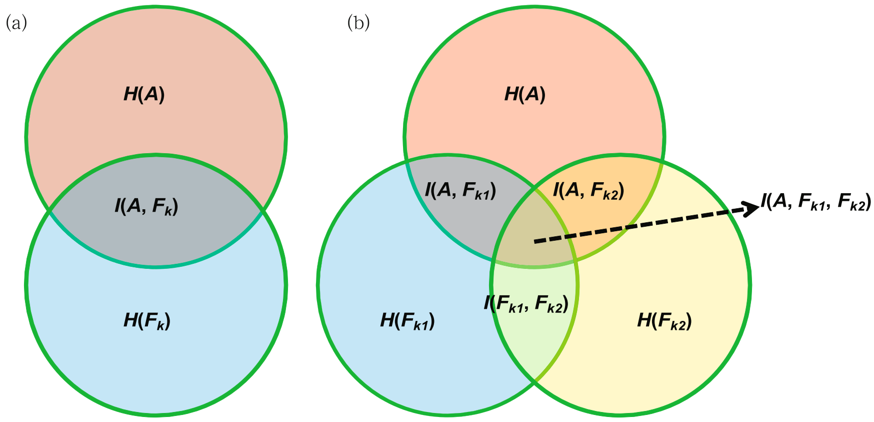

Fig. 1. Information diagrams for (a) two variables A and F_k and (b) three variables A, F_{k_1}, and F_{k_2}.

test needs to be done in order to determine if the calculated information is statistically significant from zero. In this paper, a method applying Monte Carlo techniques proposed by Pegion et al. (2008) is used to estimate the significance level. The information is recalculated between the annual frequency (intensity) of TC and time series of environmental variables by taking a different and random year for the TC index. Then, this computation is applied ten-thousand times and the values are ordered. When the value for the original information exceeds the 95th percentile, it is statistically significant from zero, and a notable relationship exists.

3. Distribution of tropical cyclone activities

When the potential relationship between annual TC activities and time series of environmental variables is investigated, the correlation coefficient is often calculated (e.g., Emanuel, 2005; Hoyos et al., 2006). However, the correlation coefficient only indicates the strength of a linear relationship between two variables. Meanwhile, an important assumption made in the framework of correlation coefficient is that the two variables form a bivariate normal distribution population (Anscombe, 1948).

Figure 2 displays the probability distributions of annual TC frequency and intensity over three basins, while probabilities estimated under the assumptions of normal distribution and Poisson distribution are also given. A nonparametric distribution testing method proposed by Kilic (2005) is used here to evaluate the quality of distribution estimate. Kilic (2005) indicated that testing the distribution of a variable could be considered as a goodness-of-fit problem. Although the two curves in each panel of Fig. 1 seem to be similar, the fitting errors are different. Generally speaking, the fitting errors with Poisson distribution are smaller than those with normal distribution. This indicates that the annual frequency and intensity of TC are more appropriate to be depicted by Poisson distribution. Previous studies also proposed that some activities of TC were Poisson distributed (Solow and Nicholls, 1990; Elsner and Schmertmann, 1993; McDonnell and Holbrook, 2004). Note that the annual intensities of TCs over the NA and EPA are not normal distributed and the fitting errors (Table 1) are 3.06% and 0.96%, respectively. Since the assumption of normal distribution is not met, the application of correlation coefficient fails to describe the relationship between TC intensity over the NA or EPA and environmental conditions.

Besides this, the correlation coefficient cannot be used to estimate the relationships in the set of three variables or more. By contrast, the interaction information has the ability to measure the dependence of any amount of variables. As a result, the MI and interaction information are employed to find potential relationships among any amount of variables instead of correlation coefficient.

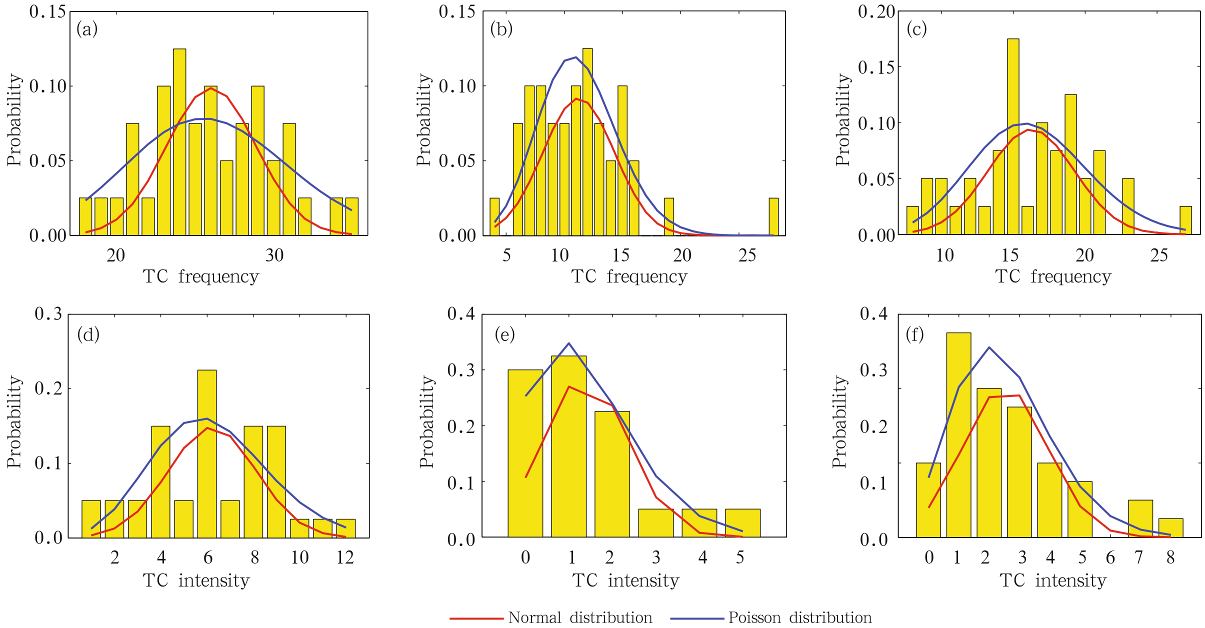

Fig. 2. Probability histogram of annual tropical cyclone activities in the period of 1970–2009 over the western North Pacific (a, d), North Atlantic (b, e), and eastern Pacific (c, f). The upper and bottom panels refer to tropical cyclone frequency and intensity, respectively. Red solid lines represent the estimated probabilities with normal distribution, while blue solid lines refer to the estimated probabilities with Poisson distribution.

Table 1. Probability fitting error (%) of tropical cyclone frequency and intensity associated with normal distribution and Poisson distribution over the western North Pacific, North Atlantic, and eastern Pacific

	Frequency			Intensity		
	WNP	NA	EPA	WNP	NA	EPA
Normal distribution	0.37*	0.30*	0.36*	0.74*	3.06	0.96
Poisson distribution	0.03*	0.26*	0.23*	0.60*	0.75*	0.32*

Superscript "*" refers to values significant at the 95% level based on the test proposed by Kilic (2005).

Table 2. Mutual information (bit) for individual ocean basins between 1970–2009 annual tropical cyclone activities and time series of environmental variables, including SST, specific humidity between 925 and 500 hPa (SHUM), temperature difference from the surface to 500 hPa (INS), wind shear between 850 and 200 hPa (SHR), 850-hPa zonal stretching deformation (SDEF), and 850-hPa relative vorticity (VOR)

		SST	SHUM	INS	SHR	SDEF	VOR
Frequency	WNP	0.47	0.43	0.47	0.55	0.58	0.53
	NA	0.59*	0.39	0.23	0.55*	0.35	0.47
	EPA	0.62*	0.34	0.49	0.53*	0.35	0.39
Intensity	WNP	0.56	0.57	0.64	0.51	0.35	0.49
	NA	0.57	0.54	0.58	0.87*	0.47	0.72*
	EPA	0.48	0.32	0.53	0.40	0.31	0.47

Superscript "*" represents values significant at the 95% level.

4. Results

4.1 Information provided by single environmental variable

The relationships between annual TC activities and individual environmental variables are discussed firstly, and quantitatively estimated by the MI. Table 2 shows that only a few values of information are significant at the 95% level. Over the NA, either SST or wind shear provides significant information on TC frequency, while TC intensity is significantly dependent on wind shear as well as relative vorticity. Over the EPA, both SST and wind shear give significant information on TC frequency. Other environmental variables fail to describe TC activities since they give much smaller values of information.

Both increasing of SST and decreasing of wind shear are favorable for the genesis of TCs over the NA (Fig. 3) and EPA (Fig. 4), and the relationships between any of these two variables and TC frequency are nearly linear. The annual variations of TC frequency over these two basins are primarily determined by SST or wind shear. Furthermore, the information value provided by SST is a bit greater than that given by wind shear. Thus, the annual TC frequency is more dependent on SST than wind shear. This indicates that the influence of SST should be considered in the first place, and warm water is needed to fuel the heat engine of TCs. Because of the positive relation between TC frequency and SST, it is deduced that the TC frequency over the NA and EPA maybe increase if SST increases. This deduction is consistent with the result of Webster et al. (2005).

However, we find no environmental variable providing significant information on the occurrence of TCs over the WNP (see also Table 1). This may sug-

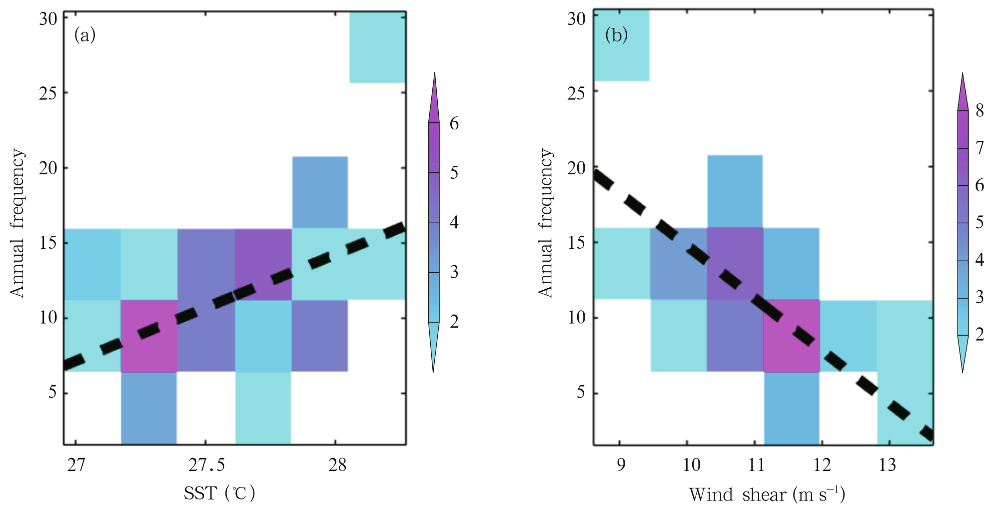

Fig. 3. Binned distributions of 1970–2009 annual tropical cyclone frequency over the North Atlantic versus time series of (a) SST and (b) wind shear between 850 and 200 hPa. Black dashed lines are fitted by the least-square method.

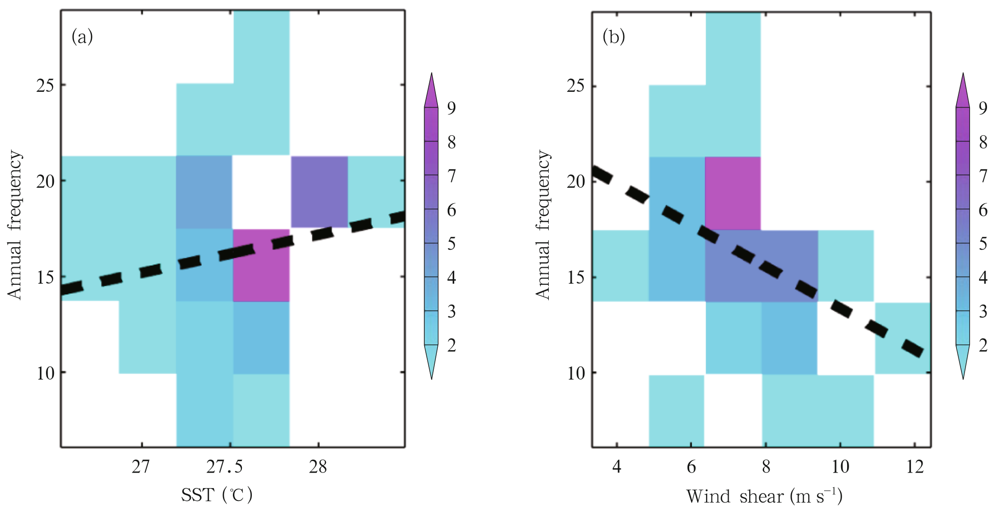

Fig. 4. As in Fig. 3, but for the eastern Pacific.

gest that the influence of a single factor is not sufficient enough to contribute to the annual variation of TC frequency. The atmospheric and oceanic conditions over the WNP have distinctive characteristics. The WNP contains a large area of water warmer than 26.5°C (threshold value for cyclogenesis), called the western Pacific warm pool. The large-scale atmospheric circulation over the WNP is often determined by the monsoon system. Therefore, there are still some arguments on which is the primary factor influencing the genesis of TCs over this area. Some researchers considered thermal factors as the most important (Sugi et al., 2002; McDonald et al., 2005; Chauvin et al., 2006; Liu et al., 2010) while others thought dynamic variables or large-scale circulations played the greatest role (Chan, 2005; Yokoi et al., 2009). In this study, however, we find that neither thermal nor dynamic variable alone is notably related to the TC genesis over the WNP.

Webster et al. (2005) presented that the long-term upward trend of TC intensity is associated with increasing SSTs. The result of this study does not support this statement. It can be seen from Table 2 that the information provided by SST on TC intensity is not significant over all three basins. Even for the WNP and EPA, no single environmental variable contributes notably to TC intensity. Although some studies pointed out that some favorable atmospheric conditions may lead to a larger number of intense TCs over the WNP (Chan, 2008) and EPA (Lupo et al., 2008), there is no environmental variable by itself that guarantees an active season of intense TC.

Nonetheless, there do exist two atmospheric variables contributing significantly to TC intensity over the NA: wind shear and relative vorticity (Fig. 5 and Table 2). Their values of information (above 0.70 bit) are much larger than those of other factors (below 0.60 bit). This suggests that the number of intense TCs over the NA is primarily controlled by the dynamic variable but not the thermal variable. It is supposed that when a storm is formed, the influences of thermal variables become a bit smaller, while the effects of dynamic variables are dominant during its intensification. When the atmospheric background provides smaller wind shear and/or larger relative vorticity, more intense TCs are expected over the NA.

4.2 Information supplied by double environmental variables

Unlike the correlation coefficient, a method from the information theory can be used to evaluate the combined effect of two or more variables on the object variable. For example, the joint information (I_2) of

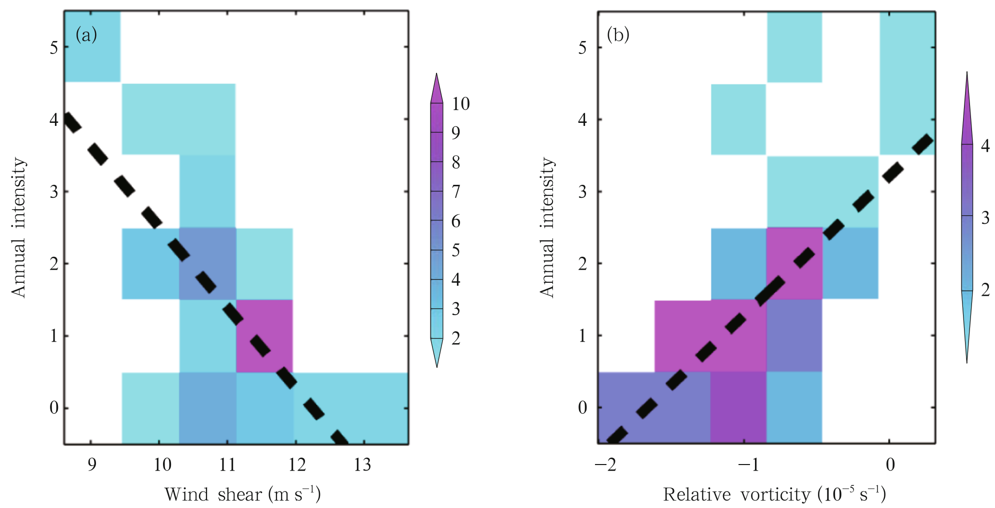

Fig. 5. Binned distribution of 1970–2009 annual tropical cyclone intensity over the North Atlantic versus time series of (a) wind shear between 850 and 200 hPa and (b) 850-hPa relative vorticity. Black dashed lines are fitted by least-square method.

two factors (F_{k_1} and F_{k_2}) with A is defined by Eqs. (4)–(5) and illustrated in Fig. 1 as:

$$I_2(A, F_{k_1}, F_{k_2}) = I(A, F_{k_1}) + I(A, F_{k_2}) - I(A, F_{k_1}, F_{k_2}), \quad (6)$$

where $I(A, F_{k_1})$ and $I(A, F_{k_2})$ are the MI of two variables defined in Eq. (4), while $I(A, F_{k_1}, F_{k_2})$ is the interaction information of three factors formulated in Eq. (5). The larger the value of I_2, the greater the combined influence of F_{k_1} and F_{k_2}.

Tables 3, 4, and 5 give the joint information provided by any two environmental variables over different basins. It is interesting that there exists no relationship between the value of information and its significance level. This is the result of employing Monte Carlo experiments to conduct the significance test, where the significance level is correlated with the distribution of tested variables.

For the NA, since there are some single variables contributing significantly to TC activities, the joint information of these variables is thus significant. This is confirmed by the notable relations between TC frequency and SST plus wind shear, as well as between TC intensity and wind shear plus relative vorticity. It is thus assumed that all the values of joint information including any one of these factors are ought to be notable. However, only a few of them are significant in Table 3. Concretely speaking, the TC frequency is only significantly dependent on the joint influences of SST plus specific humidity, wind shear plus stretching deformation, and wind shear plus relative vorticity, while the TC intensity is only notably correlated with the joint effects of specific humidity plus wind shear, instability plus wind shear, and wind shear plus stretching deformation. This means that the contribution of one indistinctively related factor plus one notably related factor is not often significant. This is possibly because of the former destroying the original connection between the latter and TC activities, but not enhancing the relation. Note that the annual variation of TC intensity is remarkably related to the joint contribution of SST plus instability (Table 3), which indicates that although the contributions of factors themselves are small, the merged effect can be significantly large.

The above deduction is also applicable to the TC frequency over the EPA, which is significantly related to the joint influences of SST plus specific humidity, SST plus wind shear, SST plus relative vorticity, and instability plus relative vorticity (Table 4). By contrast, the TC intensity over the EPA is only dependent on the joint effect of instability plus relative vorticity, which gives a value of information of 1.41 bit, much greater than others. This implies that the intensification of TC over the EPA is influenced by these two factors. When the low-level troposphere is instable (large lapse rate) and associated with positive relative vorticity, a storm tends to intensify and the number of intense TCs also increases.

Table 3. Joint information (bit) of any two environmental (row and column) variables influencing annual tropical cyclone frequency (upper right of the diagonal) and intensity (lower left the diagonal) from 1970 to 2009 over the North Atlantic. The abbreviations of atmospheric factors are the same as in Table 2

	SST	SHUM	INS	SHR	SDEF	VOR
SST	—	1.26*	1.13	1.20*	1.08	1.17
SHUM	1.38	—	0.95	1.00	0.95	1.13
INS	1.59*	1.37	—	0.97	0.75	0.85
SHR	1.35	1.49*	1.43*	—	0.90*	1.04*
SDEF	1.15	1.22	1.12	1.25*	—	0.94
VOR	1.44	1.44	1.28	1.50*	1.11	—

Superscript "*" represents values significant at the 95% level.

Finally, the TC frequency over the WNP is notably influenced by wind shear plus stretching deformation, or wind shear plus relative vorticity (Table 5). It is inferred that the cyclogenesis over the WNP is primarily determined by dynamic variables but not thermal variables such as SST. This is different from the other two basins. Since a warmer atmosphere usu-

Table 4. As in Table 3, but for the eastern Pacific

	SST	SHUM	INS	SHR	SDEF	VOR
SST	—	1.19*	1.24	1.39*	1.24	1.39*
SHUM	0.84	—	1.05	1.01	0.98	1.08
INS	1.01	1.18	—	1.08	1.13	1.46*
SHR	0.97	0.86	1.06	—	0.94	1.16
SDEF	1.07	1.17	1.23	0.95	—	1.15
VOR	1.20	1.02	1.41*	1.20	1.13	—

Table 5. As in Table 3, but for the western North Pacific

	SST	SHUM	INS	SHR	SDEF	VOR
SST	—	1.55	1.69	1.26	1.54	0.48
SHUM	1.51	—	1.49	1.35	1.49	1.48
INS	1.84	1.55	—	1.40	1.69	1.62
SHR	1.41	1.55	1.50	—	1.70*	1.30
SDEF	1.44	1.49	1.72	1.26	—	1.89*
VOR	1.74	1.55	1.43	1.47*	1.67	—

ally holds more moisture, the thermal conditions for the genesis of TCs are often satisfied. Therefore, dynamic variables play a more important role over this basin. Similar to TC frequency, the TC intensity is also dominated by the joint contribution of dynamic variables. They are wind shear and relative vorticity. The number of intense TCs increases in an atmosphere with lower wind shear and larger relative vorticity.

4.3 Information offered by three or more environmental variables

To further discuss the influences of thermal and dynamic variables on TC activities over different basins, the joint information (I_3) of three contributing variables is formulated as:

$$I_3(A, F_{k_1}, F_{k_2}, F_{k_3}) = I(A, F_{k_1}) + I(A, F_{k_2}) + I(A, F_{k_3}) - I(A, F_{k_1}, F_{k_2}) - I(A, F_{k_1}, F_{k_3}) - I(A, F_{k_3}, F_{k_1}) + I(A, F_{k_1}, F_{k_2}, F_{k_3}), \quad (7)$$

where $I(A, F_{k_1}, F_{k_2}, F_{k_3})$ is the interaction information of four variables, and others are the same as in Eq. (6). Here, F_{k_1}, F_{k_2}, and F_{k_3} refer to the three thermal variables or the three dynamic variables introduced in Section 2.

It is displayed in Table 6 that the contributions of thermal and dynamic variables are generally the same over the NA and EPA, except for TC intensity over the NA where dynamic variables dominate. The values of joint information are similar. This suggests that TC activities over these two basins are determined by not only thermal conditions but also dynamic circumstances. By contrast, the joint information of dynamic variables is larger than that of thermal variables over the WNP, indicating that TC activities over the WNP are primarily determined by dynamic conditions.

Furthermore, the joint information of all the six variables influencing TC activities is calculated over the three basins (Table 7). The equation can be derived from Eqs. (6) and (7) and is not given here. It can be seen that the joint information given by all the variables is the same as the entropy of TC activity, except for TC intensity over the EPA. This seems to indicate that annual TC activities can be fully described if time series of all the environmental variables

Table 6. Joint information (bit) of thermal and dynamic variables influencing annual tropical cyclone frequency and intensity from 1970 to 2009 over the WNP, NA, and EPA

	TC frequency			TC intensity		
	WNP	NA	EPA	WNP	NA	EPA
Thermal	2.18	1.64	1.50	2.11	1.74	1.58
Dynamic	2.23	1.66	1.53	2.18	1.93	1.60

Table 7. Joint information (bit) of all the environmental variables affecting annual tropical cyclone frequency and intensity from 1970 to 2009 over the WNP, NA, and EPA, in association with entropies of tropical cyclone activities

	TC frequency			TC intensity		
	WNP	NA	EPA	WNP	NA	EPA
Information	2.33	1.79	2.10	2.43	2.18	2.02
Entropy	2.33	1.79	2.10	2.43	2.18	2.07

are already known. However, this statement is questionable, and reasons are given below. The number of conditions considering different combinations of six variables is 6^6, which far outweighs the number of samples (40). Samples are mapped in only a few of groups, so the information becomes large. Thus, six environmental variables are not enough to describe the uncertainties of TC activities.

5. Conclusions

The topic of changed TC activities under global warming has drawn more and more attention. Not only variations of TC activities themselves but also possible factors influencing them are explored in many publications (e.g., Gray, 1968, 1988; Merrill, 1988; De Maria, 1996; Emanuel, 1999, 2005; Trenberth, 2005; Pielke et al., 2005; Anthes et al., 2006; Hoyos et al., 2006; Holland and Webster, 2007; Vecchi and Knutson, 2008). This study aims at the latter aspect, and quantitatively estimates the contribution of environmental variables to TC frequency and intensity, which are defined as the numbers of tropical storms and categories 4–5 TCs in Saffir-Simpson scale, over the western North Pacific, North Atlantic, and eastern Pacific basins. These environmental factors include three thermal variables, i.e., SST, specific humidity between 925 and 500 hPa, and temperature difference or instability from the surface to 500 hPa; and three dynamic variables, i.e., wind shear between 850 and 200 hPa, 850-hPa zonal stretching deformation, and 850-hPa relative vorticity.

Unlike other studies, since the annual variations of TC activities are better fitted by Poisson distribution rather than normal distribution, the methods from the information theory (Shannon, 1948, 1950) are used to investigate the potential relationships between TC activities and environmental conditions, instead of correlation coefficient. Based on the information theory, not only the influence of single variable but also the joint effect of multivariate factors are considered and then quantitatively estimated in this paper.

The results show that the annual variations of TC frequency are correlated with both thermal variables and dynamic factors over the NA and EPA. Single variables such as SST and wind shear provide significant information to the genesis of TCs, so does combination of the two. The contribution of thermal variables is considered as large as that of dynamic variables. However, the effect of dynamic variables plays a more important role over the WNP. The combined influence of wind shear and stretching deformation determines the change of cyclogenesis.

Furthermore, the TC intensity is influenced by thermal and dynamic variables together over the EP, which includes SST and wind shear. By contrast, the numbers of intense TCs are primarily determined by dynamic variables over the WNP and NA. The contributions of single variables, e.g., wind shear and relative vorticity, as well as the combination of them are significant over the NA. The annual variation of TC intensity over the WNP is primarily explained by the joint effect of wind shear and relative vorticity.

In a word, the main factors influencing either TC frequency or TC intensity are indeed distinct over different basins. It can be more possibly explained by the differences of atmospheric conditions and their changes in different areas. The influence of dynamic variables should be paid more attention to in the areas such as the WNP, where the thermal conditions are always satisfied. Although the quantitative estimates of environmental contributions are given in this study, the physical mechanism of these variables affecting TC activities still needs to be further investigated in future studies.

REFERENCES

Abramov, R., A. Majda, and R. Kleeman, 2005: Information theory and predictability for low-frequency variability. *J. Atmos. Sci.*, **62**(1), 65–87.

Anscombe, F. J., 1948: The validity of comparative experiments. *J. Roy. Stat. Soc. (Ser. A)*, **111**(3), 181–211.

Anthes, R. A., R. W. Corell, G. Holland, et al., 2006: Hurricanes and global warming–potential linkages and consequences. *Bull. Amer. Meteor. Soc.*, **87**(5), 623–628.

Balling, R. C. Jr., and S. S. Roy, 2004: A spatial entropy analysis of temperature trends in the United States. *Geophys. Res. Lett.*, **31**, L09201, doi: 10.1029/2004GL019630.

Bengtsson, L., M. Botzet, and M. Esch, 1996: Will greenhouse-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? *Tellus (Ser. A)*, **48**, 57–73.

Chan, J. C. L., 2005: Interannual and interdecadal variations of tropical cyclone activity over the western North Pacific. *Meteor. Atmos. Phys.*, **89**(1–4), 143–152.

——, 2008: Decadal variations of intense typhoon occurrence in the western North Pacific. *Proc. Roy. Soc. A*, **464**(2089), 249–272.

Chauvin, F., J. F. Royer, and M. Déqué, 2006: Response of hurricane-type vortices to global warming as simulated by ARPEGE-Climat at high resolution. *Climate Dyn.*, **27**(4), 377–399.

De Maria, M., 1996: The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci.*, **53**(14), 2076–2087.

——, J. A. Knaff, and B. H. Connell, 2001: A tropical cyclone genesis parameter for the tropical Atlantic. *Wea. Forecasting*, **16**(2), 219–233.

DelSole, T., 2004: Predictability and information theory. Part I: Measures of predictability. *J. Atmos. Sci.*, **61**(20), 2425–2440.

——, 2005: Predictability and information theory. Part II: Imperfect forecasts. *J. Atmos. Sci.*, **62**(9), 3368–3381.

Elsner, J. B., and C. P. Schmertmann, 1993: Improving extended-range seasonal predictions of intense Atlantic hurricane activity. *Wea. Forecasting*, **8**(3), 345–351.

Emanuel, K., 1999: Thermodynamic control of hurricane intensity. *Nature*, **401**(6754), 665–669.

——, 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**(7051), 686–688.

——, and D. Nolan, 2004: Tropical cyclone activity and global climate. 26th Conference on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc., Miami, FL, 240–241.

Frank, W., 1988: Tropical cyclone formation. *A Global View of Tropical Cyclones*. R. Elsberry, Ed., Office of Naval Research, 53–90.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**(10), 669–700.

——, 1975: *Tropical Cyclone Genesis*. Dept. of Atmos. Sci. Pap. 232, Colorado State Univ., 121 pp.

——, 1988: Environmental influences on tropical cyclones. *Aust. Meteor. Mag.*, **36**, 127–139.

Holland, G. J., and P. J. Webster, 2007: Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend? *Philos. Transact. A Math. Phys. Eng. Sci.*, **365**(1860), 2695–2716.

Hoyos, C. D., P. A. Agudelo, P. J. Webster, et al., 2006: Deconvolution of the factors contributing to the increase in global hurricane intensity. *Science*, **312**(5770), 94–97.

Kalnay, E., M. Kanamitsu, R. Kistler, et al., 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**(3), 437–471.

Kilic, E., 2005: A nonparametric way of distribution testing. *Econometrics*, 0510006, EconWPA.

Knutson, T. R., R. E. Tuleya, W. X. Shen, et al., 2001: Impact of CO_2-induced warming on hurricane intensities simulated in a hurricane model with ocean coupling. *J. Climate*, **14**(11), 2458–2468.

Leung, L. Y., and G. R. North, 1990: Information theory and climate prediction. *J. Climate*, **3**(1), 5–14.

Liu, C. J., L. P. Ma, Y. Liu, et al., 2010: Linking tropical cyclone number over the western North Pacific with sea surface temperatures. *Hurricanes and Climate Change*. J. Elsner, et al., Eds., Springer, 205–215.

Lupo, A. R., T. K. Latham, T. H. Magill, et al., 2008: The interannual variability of hurricane activity in the Atlantic and East Pacific regions. *Natl. Wea. Dig.*, **32**, 11–33.

McDonald, R. E., D. G. Bleaken, D. R. Creswell, et al., 2005: Tropical storms: Representation and diagnosis in climate models and the impacts of climate change. *Climate Dyn.*, **25**(1), 19–36.

McDonnell, K. A., and N. J. Holbrook, 2004: A Poisson regression model of tropical cyclogenesis for the

Australian–Southwest Pacific ocean region. *Wea. Forecasting*, **19**(2), 440–455.

McGill, W. J., 1954: Multivariate information transmission. *Psychometrika*, **19**(2), 97–116.

Merrill, R. T., 1988: Environmental influences on hurricane intensification. *J. Atmos. Sci.*, **45**(11), 1678–1687.

Naumann, G., and W. M. Vargas, 2009: Changes in the predictability of the daily thermal structure in southern South America using information theory. *Geophys. Res. Lett.*, **36**, L09704, doi: 10.1029/2009GL037576.

Pegion, K., P. Pegion, T. Selsole, et al., 2008: Subseasonal variability of hurricane activity. *Climate Test Bed Joint Seminar Series*. NCEP, Camp Springs, Maryland, December 10, 2008.

Pielke, R. A. Jr., C. Landsea, M. Mayfield, et al., 2005: Hurricanes and global warming. *Bull. Amer. Meteor. Soc.*, **86**(11), 1571–1575, doi: 10.1175/BAMS-86-11-1571.

Rayner, N. A., D. E. Parker, E. B. Horton, et al., 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**(D14), 4407, doi: 10.1029/2002JD002670.

Roulston, M. S., and L. A. Smith, 2002: Evaluating probabilistic forecasts using information theory. *Mon. Wea. Rev.*, **130**(6), 1653–1660.

Royer, J. F., F. Chauvin, B. Timbal, et al., 1998: A GCM study of the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclones. *Climatic Change*, **38**(3), 307–343.

Shannon, C. E., 1948: A mathematical theory of communication. *Bell Syst. Tech. J.*, **27**, 379–423, 623–656.

——, 1950: Prediction and entropy of printed English. *Bell Syst. Tech. J.*, **30**, 50–64.

Solow, A., and N. Nicholls, 1990: The relationship between the southern oscillation and tropical cyclone frequency in the Australian region. *J. Climate*, **3**(10), 1097–1101.

Sugi, M., A. Noda, and N. Sato, 2002: Influence of the global warming on tropical cyclone climatology: An experiment with the JMA global model. *J. Meteor. Soc. Japan*, **80**(2), 249–272.

Trenberth, K., 2005: Uncertainty in hurricanes and global warming. *Science*, **308**(5729), 1753–1754.

Vecchi, G. A., and T. R. Knutson, 2008: On estimates of historical North Atlantic tropical cyclone activity. *J. Climate*, **21**(14), 3580–3600.

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

Yokoi, S., Y. N. Takayabu, and J. C. L. Chan, 2009: Tropical cyclone genesis frequency over the western North Pacific simulated in medium-resolution coupled general circulation models. *Climate Dyn.*, **33**(5), 665–683.