INTRODUCTION AND APPLICATION OF A NEW COMPREHENSIVE ASSESSMENT INDEX FOR DAMAGE CAUSED BY TROPICAL CYCLONES

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ABSTRACT

Using principal component analysis, a new comprehensive assessment index for damage caused by tropical cyclones in mainland China is developed based on data from 1984 to 2008. It is a weighted average of four kinds of damage data: including the deaths and missing, affected crop area, destroyed houses, and rate of direct economic loss. The weighting coefficients are set by principal component analysis. Two indices are derived, which differ in the importance of the deaths and missing in severity assessment according to the sign of the second principal component of damage data. Trends in the damage caused by individual tropical cyclones and in the annual frequencies of the various levels of severity of damage caused by tropical cyclones are analyzed. No clear trend in damage from individual tropical cyclones is found. The annual frequency of tropical cyclones causing heavy and catastrophic damage shows a clear decrease from 1984 to 2008 with no trend in the total number of damaging tropical cyclones.

Keywords: tropical cyclone, damage assessment, principal component analysis

1. Introduction

Tropical cyclones (TC) are one of the main causes of natural disasters in China, inflicting huge losses on coastal regions. Four of the worst 10 natural disasters in mainland China in 2006 were caused by TCs; the worst two disasters were caused by the super typhoon "Saomai" and the severe tropical storm "Bilis" (The National Disaster Reduction Committee Office 2007). There were one or two TCs in the list of the worst 10 natural disasters in China every year from 2007 to 2012 (The National Disaster Reduction Committee Office 2007, 2008, 2009, 2010, 2011, 2012, 2013). Recently, researchers and forecasters have made encouraging progress in the forecasting of TC track and intensity. Tropical cyclone disaster research has also covered destructive power (Zhang et al. 2010), the distribution of risk and the nature of damage (Lei et al. 2009; Li and Duan 2010; Yang et al. 2010), and damage assessment models or systems (Watson and Johnson 2004; Chen et al. 2009; Liu et al. 2010). The damage varies with the distribution of wind or rain, the building quality, rescue and relief procedures, and so on. It is useful to investigate objective and quantitative methods to describe the severity of damage caused by TCs. There is no recognized method for assessing the severity of TC damage. The direct economic losses or casualties are often analyzed as a single index of damage (Pielke and Landsea 1998; Watson and Johnson 2004; Zhang et al. 2009). The single index is simple and convenient, and it is applied to most TCs with direct economic losses in direct proportion to casualties. However, for many TCs there is a large gap between the ranking of damage based on direct economic losses and that based on casualties. For example, the severe typhoon "Hagupit" in 2008 is ranked more severely based on direct economic losses (0.3214% of the current year's Gross Domestic Production (GDP) in mainland China) than on casualties (47). Therefore some researchers have tried to construct indices that provide a comprehensive assessment of damage. These include indices using damage data normalized by a logarithmic function (Lu 1995; Qian et al. 2001; Lei et al. 2009), damage indices of landfall TCs based on fuzzy mathematics (Liang et al. 1999; Ma et al. 2008), and the typhoon general disaster grade division model that uses the theory of grey association analysis (Wang et al. 2010). Although these indices are based on statistical theory, they still have shortcomings. The main problem arises from the methods of determining

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weighting coefficients, which are not completely objective. Original damage data are nondimensionalized to values 10,000 or 1000 times smaller in the index developed by Lu (1995). Expert evaluation is used in processing damage indices with fuzzy mathematics. The method used to classify the grade of transfer function is subjective in the grey association analysis model. Thus, the indices are subjective to a greater or lesser extent. Another shortcoming is that some indices do not cope well with missing damage data. In summary, it is necessary to develop a representative, objective, practically applicable damage index to assess the severity of TC disasters.

The remainder of the manuscript is organized as follows. The data are introduced in Section 2. Sections 3 and 4 describe the development of a comprehensive assessment index of TC damage based on principal component analysis (PCA), and the severity grade classification standards. The annual trends of damage from single TCs and of frequency of TCs with all severity grades of disaster are introduced in Sections 4 and 5. Finally, Section 6 contains the conclusions and discussion.

2. Data

Damage data, such as number of casualties, affected crop area, number of destroyed and damaged houses, and direct economic losses, have often been used in damage assessment models (Lu 1995; Qian et al. 2001). However, in recent years, difficulties in collecting data on casualties and damaged houses meant that these data were often missing. To ensure comparability of data and interoperability of models, these items should be adjusted. In recent decades, the main types of data that have been always available are the deaths and missing, affected crop area, number of houses destroyed, and direct economic losses. The first three items describe the extent of damage to life, agriculture, and housing, respectively. Direct economic losses also describe the extent of economic damage to other sectors, such as the direct losses in power systems, transport systems, aquaculture, and so on (Lu et al. 2002). Therefore, in this paper the Deaths and Missing (DM; unit: person), Affected Crop Area(ACA; unit: thousand hectare), Number of Destroyed Houses (NDH; unit: room), and Direct Economic Losses (DEL; unit: billion RMB)(RMB is Renminbi) are selected as measures of the severity of TC damage. Damage data for all TC events during 1984–2008 were collected by the Shanghai Typhoon Institute of the China Meteorological Administration (CMA) and the National Climate Center, supported by a national ‘85’ project and a CMA project to disseminate new technology.

To produce a robust dependence on DM, ACA, NDH and DEL, these data must be validated and calibrated to ensure model objectivity and stability. The extent of damage is determined not only by the severity of the disaster but also by the level of social development. This explains the higher value of damage data in recent years than earlier, especially in DEL data (Xu 1994; Pielke and Landsea 1998; Chen et al. 2009; Zhang et al. 2009). The Rate of Direct Economic Losses is defined as follows:

$$RDEL = \frac{DEL}{GDP} \times 10000, \qquad (1)$$

Here, GDP is the current yearly gross domestic production in mainland China in units of billion RMB. As there is a considerable difference in magnitude between DEL and GDP, the unit of RDEL is 0.01%. There was no clear trend in RDEL from 1983 to 2006, although DEL had a clear upward trend (Zhang et al. 2009).

Tropical cyclones that cause damage measured by at least one of the four damage data types (DM, ACA, NDH, and DEL) are referred to as TCs causing damage (DTCs). There were 187 DTCs in 24 provinces of mainland China during 1984–2008. Guangdong province suffered the most (98 DTCs), followed by Fujian and Zhejiang provinces. Guangxi and Hainan suffered more than 50 DTCs. Three provinces (Jiangsu, Shanghai, and Jiangxi) suffered more than 20 DTCs.

3. Comprehensive assessment index for damage caused by tropical cyclones

Principal component analysis (PCA) is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. A comprehensive assessment index based on a weighted linear function of multiple indices (factors) can be deduced from the principal components. The weighting coefficients are determined from the variance contribution of the principal components. This removes the impact of subjective factors in deriving weighting coefficients and ensures objective ordering (Yu 1993; Ye 2004; Hou 2006).

To eliminate the effect of data dimensionality, the data need to be nondimensionalized before applying PCA. A number of methods can be used, including min-max normalization, range analysis, the proportion method, Z-score, and mean value analysis (Ding et al. 2001; Han 2008). The most popular method is standard deviation normalization. However, this assumes that the data have a Gaussian distribution, which is not the case for TC damage data. Mean value analysis is often used in comprehensive evaluations by PCA (Fu et al. 2001; Ye 2001; Ye 2004), as it preserves the correlativity and deformation in the original data, but it can be easily affected by a few extreme values (Gao et al. 2011). Median normalization has the two main advantages of mean value analysis, but is not so strongly affected by extremes. A comparison of mean value analysis and median normalization based on the criteria for nondimensionalization methods introduced in Bai et al. (1995), shows that median normalization is more appropriate for this topic.

Median normalization is applied here, and eigenvalues and eigenvectors are deduced from the PCA covariance matrix (Gao et al. 2011). The median normalization equation is as follows:

$$x_{ij}^{*} = \frac{x_{ij}}{xm_j} \qquad i = 1,\ldots,n;\ j = 1,\ldots,p. \tag{2}$$

Here, p is the damage assessment factor, n is the number of DTCs, and xm_j is the median of the j th damage assessment factor.

The eigenvectors of the first and second principal components are shown in Fig. 1. Their variance contributions are 72.51% and 8.84%, respectively, and their accumulated variance contribution is 91.34%. DM makes the maximum contribution and ACA the minimum contribution to the first principal component. The consistency in factors is shown by the uniformly positive values. (The first principal component is effectively the average of the four factors.) DM has the opposite sign to the others in the second principal component. This results from the great effort of government and the public toward preventing and reducing the effects of natural disasters. Many people living in high-risk regions suffered in the past as a result of extreme weather caused by TCs, but are now evacuated during such events, thereby reducing the number of casualties.

In PCA, the leading principal components with accumulated variance contribution larger than 85% are usually selected. The weighting coefficients are calculated using their variance contributions (Yu 1993; Fu 2001; Gao et al. 2011). The signs of the eigenvector values of most principal components (except for the first) are different. The eigenvector signs (positive or negative) will influence the resulting sort order of the weighting coefficients. This procedure was discussed and analyzed by Fu (2002) and Liu et al. (2009). They proposed that the variance contributions of principal components should be constrained follows:

$$\sum_{k=1}^{p} w_k t_k b_{jk} \geq 0, \qquad j = 1,2,\ldots,p \tag{3}$$

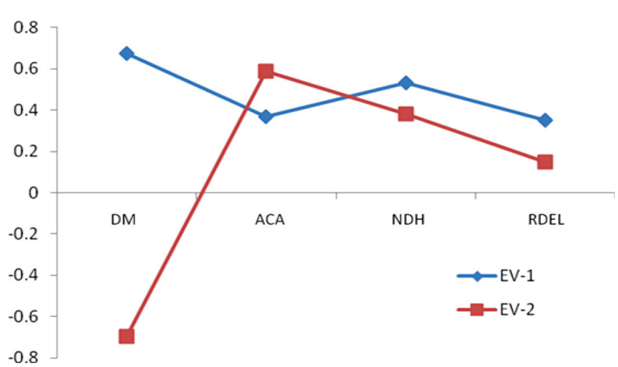

FIG. 1. WRF domains used for all ensemble simulations of Hurricane Ernesto.

Here, w_k is the variance contribution of the k^{th} principal component and t_k can take the values –1, 0, 1 corresponding to negative, zero or positive contribution of the eigenvector of the principal component. (Note that not all the t_k can be zero.) and b_{jk} is the projection of the principal component.

The accumulated contribution of the first two principal components of TC damage data is 91.34%, thus satisfying the 85% condition. The constrained condition described in equation (3) also satisfying with all t_2 value. So the comprehensive evaluation of TC damage is based on a weighted sum of the first and second principal components. For positive values of the first principal component, t_1 is 1, while t_3 and t_4 are 0. The comprehensive evaluation index of TC damage is defined as follows:

$$TDP_i^{*} = \sum_{k=1}^{2}\sum_{j=1}^{4} t_k w_k e_{kj} x_{ij}^{*} . \tag{4}$$

Here, TDP is the comprehensive evaluation index for TC damage, and e_{kj} is the eigenvector value of the j^{th} assessment factor in the k^{th} principal component. For a linear relationship between $t_1 w_1 e_{1j}$ and $t_2 w_2 e_{2j}$, equation (4) can be simplified to

$$TDP_i^{*} = \sum_{j=1}^{4} w_j^{*} \frac{x_{ij}}{xm_j} , \tag{5}$$

where

$$w_j^{*} = \sum_{k=1}^{2} t_k w_k e_{kj} . \tag{6}$$

To remove the inconvenience of a very small index in applications, equation (5) is transformed to

$$TDP_i = \sqrt{\sum_{j=1}^{4} w_j^{*} \frac{x_{ij}}{xm_j}} . \tag{7}$$

There are two groups of w_j^{*} for positive and minus signs of t_2 (Table 1) for the damage data of TCs from 1984 to 2008. Two comprehensive assessment indices for damage are obtained when median values of DM, ACA, NDH, and RDEL (21.50 persons, 163.47 thousand hectares, 1.34 ten thousand rooms, 2.9453 × .01%, respectively) are substituted into equation (7). The index with t_2 = 1 is named TDPr and the index with t_2 = −1 is named TDPd. The weighting coefficient of DM is largest in the formula of TDPd and it means that TDPd mostly reflects DM. In the formula for TDPr, the weighting coefficients of ACA, NDH, and RDEL are larger than that of DM. This means that TDPr represents economic losses caused by TCs. Compared with economic losses, DM appears more random, and is more closely related to government action and public awareness of damage. Recently, the Chinese Government has devised

TABLE 1. Weighting coefficients for damage assessment factors in TDP.

	DM (person) (w_1^*)	ACA (thousand hectare) (w_2^*)	NDH (ten thousand rooms) (w_3^*)	RDEL (0.01%) (w_4^*)
TDPr ($t_2 = 1$)	0.3586	0.3775	0.4581	0.2831
TDPd ($t_2 = -1$)	0.6217	0.1567	0.3139	0.2272

TABLE 2. Classification standards for TC damage.

	Grade			
	Mild disaster	Medium disaster	Severe disaster	Catastrophe
TDPr	<0.90	0.90 ≤ TDPr < 2.00	2.0 ≤ TDPr < 3.0	≥3.0
TDPd	<0.90	0.90 ≤ TDPd < 1.95	1.95 ≤ TDPd < 2.9	≥2.9

many prediction schemes to ensure personal security. Most people living in high-risk regions affected by TCs are now evacuated by the government during severe events, thereby reducing casualties (Lei et al. 2009).

The above analysis shows that the two comprehensive assessment indices for damage caused by TCs, TDPr and TDPd, have clear connotations and can be used where appropriate for different applications/requirements.

4. Grade of damage caused by TCs

The China Meteorological Administration (CMA) issued a document entitled "Trial Regulations about Meteorological Damage Data Collection, Investigation, and Assessment" (document number [2005](96)) in May 2005. In this file, disasters are classified into five grades, but just four grades are used in the file named 'Regulations about Meteorological Damage Data Collection, Investigation, and Assessment', an update of the document released after 2005. These four are analogous to those described in Qian et al. (2001) and Lei et al. (2009), and in this paper TC damage is classified into four grades following Lei et al. (2009). They are level 1: mild disaster; level 2: medium disaster; level 3: severe disaster; and level 4: catastrophe.

A combination of percentile and clustering methods gives the definitions of the grades of TC damage shown in Table 2. There are 23 (25) catastrophe DTCs, with TDPr (TDPd) more than or equal to 3.0 (2.9), representing 12.3% (13.4%) of all DTCs during 1984–2008. The percentage of severe, medium, and mild disaster DTCs in all is 20.3% (17.1%), 30.5% (30.5%), and 36.9% (39.0%), respectively.

The average damage caused by TCs for all four damage grades during 1984–2008 is shown in Table 3 for TDPd, and in Table 4 for TDPr. The average DM of TCs classified by TDPd (TDPr) as catastrophe, and as severe, medium, and mild disasters is 362.64 (343.96), 96.34 (104.32), 30.91 (34.58), and 2.55 (3.64), respectively. The corresponding average RDEL value in units of 0.01% is 24.34 (26.18), 10.62 (10.02), 4.06 (3.75), and 0.73 (0.53), respectively. Comparing the average damage of every grade classified by TDPr and TDPd, only the average DM of catastrophe TCs

TABLE 3. The average damage caused by TCs from 1984 to 2008 for each grade of damage (classified by TDPr).

Damage grade	DM (persons)	ACA (thousand hectares)	NDH (ten thousand rooms)	RDEL (0.01%)	Sample size
Level 4	343.96	1702.32	18.72	26.18	23
Level 3	104.32	548.88	6.57	10.02	38
Level 2	34.58	265.05	1.85	3.75	57
Level 1	3.64	39.54	0.17	0.53	69

TABLE 4. The average damage caused by TCs from 1984 to 2008 for each grade of damage (classified by TDPd).

Damage grade	DM (persons)	ACA (thousand hectars)	NDH (ten thousand rooms)	RDEL (0.01%)	Sample size
Level 4	362.64	1408.20	17.31	24.34	25
Level 3	96.34	663.20	6.60	10.62	32
Level 2	30.91	307.97	2.40	4.06	57
Level 1	2.55	52.96	0.23	0.73	73

classified by TDPd is greater than that classified by TDPr. The averages of ACA, NDH, and RDEL of catastrophe TCs classified by TDPd are all smaller in contrast.

The 11 most severe DTCs for the period 1984–2008 are listed in Table 5. Apart from a slight difference in ranking, the same 11 TCs are picked out by TDPr and TDPd. The first three for TDPd are "Fred" in 1994, "Bilis" in 2006, and "Herb" in 1996, the same as the first three for DM. They rank 4, 5, and 2, respectively, in the TDPr list. The first three TCs in the TDPr list include TC "Winnie" in 1997, with the largest value of ACA, "Herb" in 1996, with the largest value of RDEL, and NDH "Tim" in 1994 with the largest value of NDH. They rank 5, 3, and 4 in the TDPd list, respectively. Five of the 11 most damage TCs occurred during 1994–1997, and the two that occurred after 2000, "Bilis" and "Saomai", were both in 2006.

TABLE 5. The 11 most damaging TCs ranked according to TDPr and TDPd during 1984–2008.

TC name	ID number	TDPd	Rank	TDPr	Rank
Fred	9417	7.1129	1	6.0886	4
Bilis	0604	6.5529	2	6.0728	5
Herb	9608	6.4640	3	6.5221	2
Tim	9406	5.6884	4	6.4724	3
Winnie	9711	5.4904	5	6.5673	1
Saomei	0608	4.6359	6	4.0368	9
Mimie	8509	4.5263	7	4.8064	6
Sally	9615	4.4805	8	4.6748	7
Nelson	8510	4.0306	9	3.6668	11
Polly	9216	3.6322	10	3.7862	10
Abe	9015	3.6151	11	4.1654	8

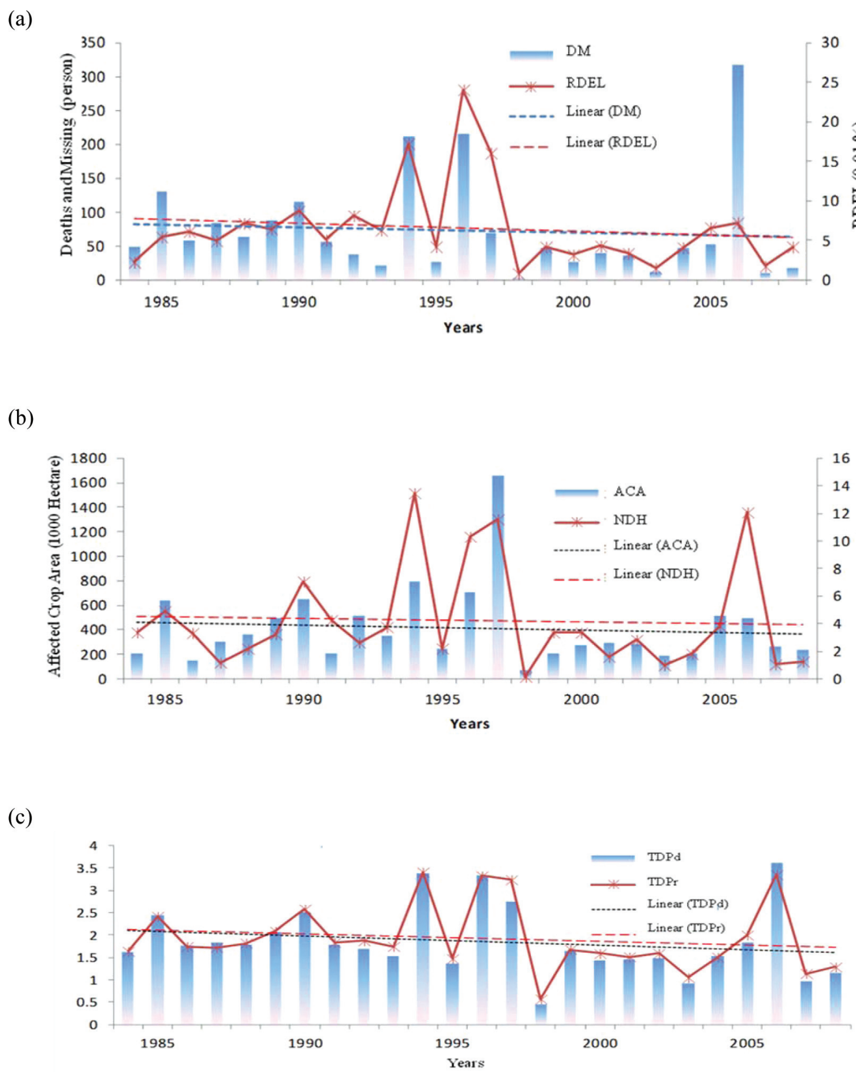

FIG. 2. Average annual TC damage for 1984–2008.

The Advanced Typhoon Damage Index (ATDI) described by Lei et al. (2009) is deduced by a standardization method. In the ATDI list, the top three are "Herb" in 1996, "Winnie" in 1997, and "Tim" in 1994. A comparison of the ATDI list with those of TDPr and TDPd, shows that rank in the ATDI list is closer to that in TDPr than that in TDPd.

5. Trends of severity of average TC damage and of frequency of DTCs

Over the past 20 years, the casualties, ACA, NDH, and DEL have increased linearly, especially DEL, as opposed to the decreasing tendency of DM caused by TCs (Lei et al. 2009; Zhang et al. 2009). Lei et al. (2009) discussed the characteristics of damage by a single TC. They found that the number of destroyed and damaged houses, ACA, and DEL resulting from a single TC increased linearly from 1980 to 2004. Fig. 2 shows the change in average annual damage of a single TC. The DM, RDEL, ACA, and NDH decrease linearly from 1984 to 2008. However, the significance of these decreases is below the 95% level, and so the decreases are not statistically significant. The average annual TC TDPr and TDPd also decrease linearly, the latter more obviously. Again, these decreases are not statistically significant.

In summary, the average annual TC damage appears to have no statistically significant linear trend during 1984–2008, consistent with the frequency of landfalling TCs (Zhang et al. 2009). Consequently, the seriousness of damage caused by TCs shows no clear trend.

Fig. 3 shows the changes in frequency of levels 1–4 dam-

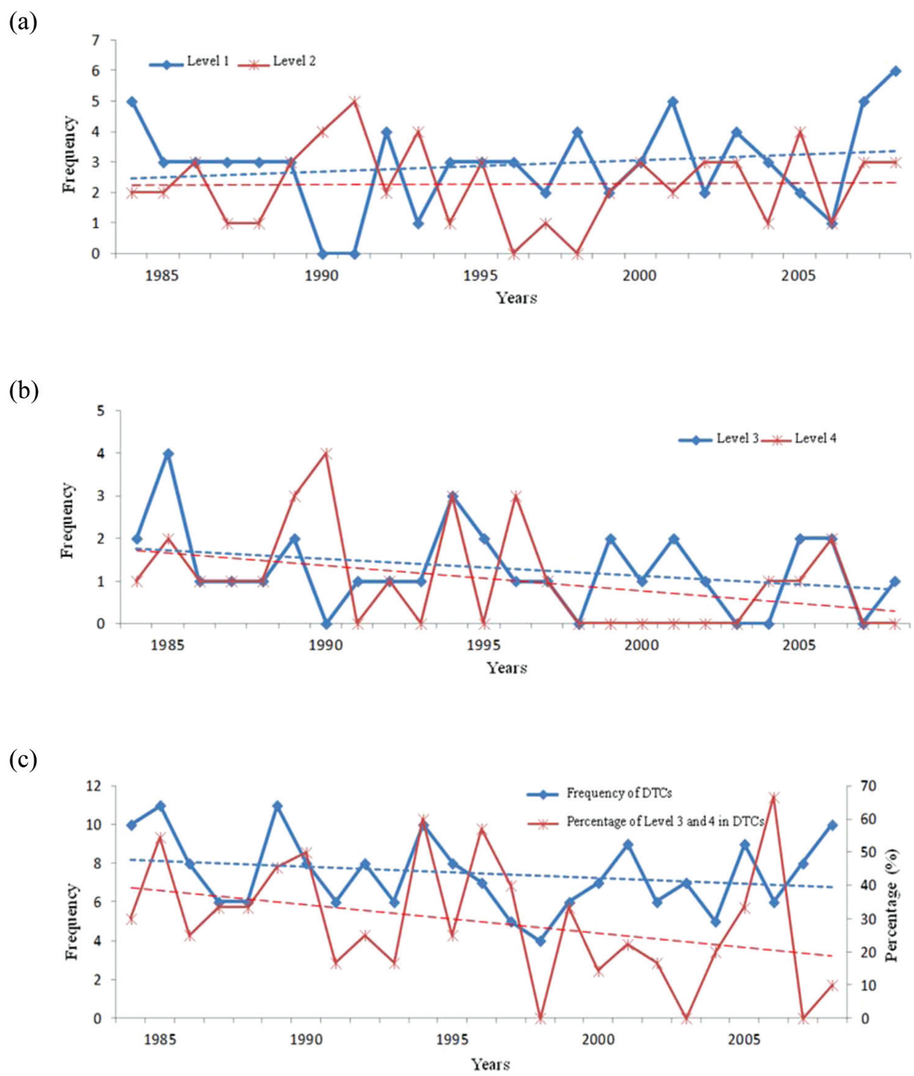

Fig. 3. Annual frequency of damage caused by DTCs for each grade of damage, classified by TDPd. The dashed lines are the linear trends of the respective solid lines.

age grades of DTCs. The total annual frequency of DTCs decreased slowly, but the annual frequency of level 1 and level 2 DTCs increased linearly, with level 1 DTCs increasing more quickly (Fig. 3a). However, the annual frequency of level 3 and level 4 DTCs decreased linearly, with the frequency of level 4 DTCs decreasing more quickly. Only the trend in level 4 DTCs is statistically significant, at the 90% significance level (Fig. 3b). The annual frequency of DTCs and annual percentage of level 3 and 4 DTCs are shown in Fig. 3c. Both of these show significant trends: at the 95% significance level for frequency and 90% significance level for percentage.

This means that the annual frequency of mild disasters (catastrophes) caused by TCs increases (decreases) and the frequency of extraordinary disasters, level 3 and 4, decreases notably. Similar results are obtained for damage classes defined in terms of TDPr.

The severity of damage has a close relationship with not only the destructive force of the TC, but also the accuracy of weather forecasts, the measures for disaster response, and public alerts to the disaster. In recent years, the accuracy of TC track forecasts has improved greatly, the public and government are more alert, and appropriate disaster responses have been implemented. Therefore, the clear decrease in the annual frequency of severe and super disasters caused by TCs does not imply a decrease in the annual frequency of TCs with huge destructive force.

6. Conclusion and discussion

Principal component analysis of DM, ACA, NDH, and RDEL data has been used to develop two comprehensive assessment indices for damage caused by TCs, TDPd and TDPr, based on cases during 1984–2008. The means of TDPd and TDPr are similar. The former pays more attention to casualties, and the latter pays more attention to material damage. They are both suitable for research and operational use. Damage grades of DTCs may be classified in terms of TDPd and TDPr. In addition, the method used to develop TDPd and TDPr ensures that the two indices are objective.

Variations in the severity of annual single tropical cyclone damage and annual frequencies of damage grades are analyzed here. The results show no clear trend in the severity of annual single TC damage. The annual frequency of mild disasters (catastrophes) caused by TCs increases (decreases) slightly, while the frequency of DTCs shows no significant trend. The clear decrease in the annual frequency of severe and super disasters caused by TCs results from improved TC track forecasts, better alerting of the public and government, and improved disaster response, and does not imply a decrease in the annual frequency of TCs with huge destructive force.

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