An Improved Statistical Scheme for the Prediction of Tropical Cyclones Making Landfall in South China

ANDY ZUNG-CHING GOH AND JOHNNY C. L. CHAN

Guy Carpenter Asia-Pacific Climate Impact Centre, School of Energy and Environment, City University of Hong Kong, Hong Kong, China

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ABSTRACT

This study describes an improved statistical scheme for predicting the annual number of tropical cyclones (TCs) making landfall along the coast of south China using data from 1965 to 2005. Based on the factors affecting TC behavior inside the South China Sea (SCS), those responsible for TCs making landfall are identified. Equations are then developed using the coefficients of empirical orthogonal functions of these factors to predict, in April, the number of these TCs in the early (May–August) and late (September–December) seasons, and in June, the number in the period between July to December. The new scheme achieves a forecast skill of 51% over climatology, or an improvement of about 11% compared to previous studies, when predicting landfalling TC for the whole season, and it seems to be able to capture the decrease in their number in the recent years. Analyses of the flow patterns suggest that the conditions inside the SCS are apparently the major factor affecting the number of landfalling TCs. In years in which this number is above normal, conditions inside the SCS are favorable for TC genesis, and vice versa. The strength of the 500-hPa subtropical high also seems to be a factor in determining whether TCs from the western North Pacific (WNP) could enter the SCS and make landfall.

1. Introduction

The heavily populated coastal area of southern China is one of the regions most affected by tropical cyclones (TCs), which are among the deadliest and costliest natural disasters. Understanding the behavior of TCs in the South China Sea (SCS), especially of those storms making landfall, is thus of great importance to the safety and well-being of millions. Unfortunately, this has been a relatively less studied area.

Landfalling TCs have always been a hot topic in TC research. Various studies have been carried out in areas such as convective properties (e.g., Chan et al. 2004), rainfall distribution (e.g., Kimball 2008), and maximum wind speed and decay (e.g., Kaplan and DeMaria 1995) of TCs after landfall. At the same time, despite the daunting nature of the task, much effort has been dedicated to predicting the number of TCs making landfall. However, the focus of most of these works is the Atlantic basin (e.g., Lehmiller et al. 1997; Bove et al. 1998), with relatively few studies concentrating on landfalling TCs in the western North Pacific (WNP) (e.g., Wu et al. 2004), and even fewer studies dedicated solely to the SCS (e.g., Liu and Chan 2003, hereafter LC03).

LC03 provided a statistical scheme for predicting the annual number of TCs making landfall along the coast of south China, and suggested that the number of landfalling TCs depends on the status of the El Niño–Southern Oscillation (ENSO). Using this scheme, they issued real-time predictions for the annual number of TCs making landfall along the south China coast. Although this scheme provides a 40% improvement in forecast skill over climatology, it did not fare well in both 2003 and 2004, when the numbers were overestimated (information online at http://weather.cityu.edu.hk/tc_forecast/forecast.htm). The failure to identify appropriate predictors that could explain the decreasing trend observed in the annual number of TCs moving into the SCS from the WNP has been attributed as a possible reason for this error in the forecast. A possible reason could be the heavy dependence of LC03's scheme on ENSO-related predictors.

The objective of this study is to improve on the LC03 scheme by investigating other factors that could possibly

Corresponding author address: Johnny Chan, School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China.
E-mail: johnny.chan@cityu.edu.hk

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affect TC activity in the SCS. While investigating the interannual and interdecadal variations of SCS TCs, Goh and Chan (2009, hereafter GC09) identified seven factors related to TC behavior in the SCS, which can be divided into two groups: steering (500-hPa geopotential height and zonal wind) and genesis (850-hPa geopotential height and relative vorticity, 200-hPa divergence, 200–850-hPa vertical wind shear, and moist static energy) factors.

In addition, GC09 found that the number of TCs being steered into the SCS from the WNP is affected by both ENSO and the Pacific decadal oscillation (PDO). Their results add to the list of literature that has indicated a link between ENSO, PDO, and TC behavior in the WNP and the SCS (e.g., Li 1988; Chan 1985, 2000; Wang and Chan 2002; Chan 2005; Leung et al. 2005). These results suggest that TCs making landfall along the south China coast should also be related to ENSO and PDO, as they all have traversed the SCS before reaching the coast. This view is further supported by the results of Saunders et al. (2000) and Wu et al. (2004), both indicating that the number of landfalls in southern China is affected by the ENSO. Therefore, the seven factors from GC09, along with the ENSO and PDO indices, will be the basis of investigation for this study.

The data used in this study are listed in section 2 of this paper. Section 3 discusses the trend observed in the data, and the prediction schemes are developed in section 4. Predictions are made using the developed schemes in section 5, and, finally, some discussion and concluding remarks are given in section 6.

2. Data

a. Data

The temporal range of this study is 1965 to 2005. This time period is chosen as some studies (e.g., Song et al. 2002; Wu et al. 2005) have indicated that uncertainties exist in data before 1965. Six-hourly TC positions and atmospheric data are respectively provided by the Hong Kong Observatory and the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis project (Kalnay et al. 1996). ENSO data are available from the Climate Prediction Center of the National Weather Service (information online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml), while PDO data are extracted from the Joint Institute for the Study of the Ocean and Atmosphere Web site (http://jisao.washington.edu/pdo/PDO.latest).

b. Data categorization

The coastline defined as the southern coast of China in this study includes the coast of both Guangdong and Hainan Provinces (Fig. 1). Hainan is also included as no clear separation can be found in landfall frequencies between these two provinces. When a straight line joining two consecutive 6-hourly positions of a TC crosses the defined coastline, that TC would be regarded as having made landfall on the southern coast of China. TCs that made landfall, then moved back onto the ocean, and subsequently made landfall again would only be counted once.

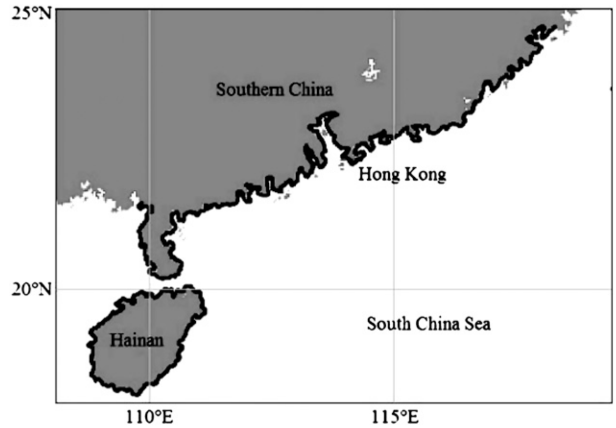

FIG. 1. Map of southern China. Thick black line indicates coastline of south China as defined in this study.

Some studies (e.g., LC03, Wang et al. 2007) divided the active TC season in the SCS, which is between May and November, into an "early" and a "late" season. In this study, the TC season in the SCS is divided into May–August (early season) and September–December (late season). Moreover, for the sake of making a prediction in June, the period from July to December will also be considered separately, and will hereafter be named the JD season. Further, the ENSO index utilized in this study is defined according to Trenberth (1997), while the PDO index is defined according to Mantua (1999).

3. Trend in landfalling TCs

Figure 2 shows the time series for the number of TCs making landfall on the southern China coast in the early (N_E), late (N_L), and JD (N_J) seasons for the period 1965–2005. On the average, the values for N_E, N_L, and N_J are 3.03, 1.55, and 3.93 respectively, over this period. There has been a decreasing trend in landfalling TCs in all seasons over the study period. Specifically, using the method in Santer et al. (2000), the trends in N_E, N_L, and N_J over the study period are calculated to be −2.84, −0.21, and −2.80 (100 yr)$^{-1}$, respectively, although none of the trends is significant at the 95% confidence level.

To further illustrate the decrease in the number of landfalling TCs, especially in the past decade, a change

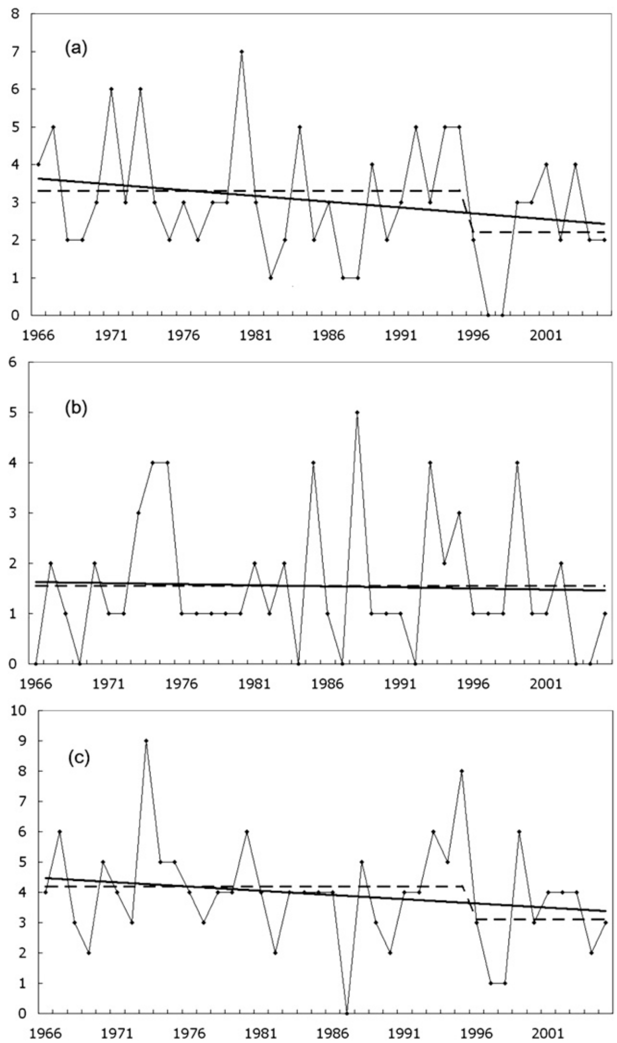

FIG. 2. Number of TCs making landfall along the coast of south China during (a) the early season (N_E), (b) the late season (N_L), and (c) the JD season (N_J). The solid straight line indicates the trend, while the dashed line shows the shift in the number of TCs as derived from the change-point analysis.

point analysis is carried out. Using the algorithm developed by Rodionov (2004), with a confidence level $p = 0.1$ and a cutoff length $l = 20$, during 1996 statistically significant shifts of 95% and 90% are detected in the time series of N_E and N_J, respectively, with the annual average numbers of landfalling TCs decreasing, respectively, from 3.3 and 4.2 before 1996 to 2.2 and 3.1 after. However, this shift is not seen in the N_L time series.

4. The prediction schemes

a. Developing the prediction schemes

As in Chan et al. (1998, 2001), two forecasts are to be made each year: one in April for the early and late seasons, and the other in June for the JD season. As mentioned in section 1, seven factors that affect TC behavior, namely, 500-hPa zonal wind (500U), 200-hPa divergence (DIV), 500-hPa geopotential height (500H), 850-hPa geopotential height (850H), 500–1000-hPa moist static energy (MSE), 200–850-hPa shear (SHR), and 850-hPa vorticity (VOR), are chosen in an attempt to explain the observed behavior of TCs making landfall along the coast of southern China. The monthly anomalies of these factors from September of the previous year to March (for April prediction) or May (for June prediction) of the current year are evaluated over the domain of this study, namely 0°–25°N, 100°–160°E, and are then subjected to an empirical orthogonal function (EOF) analysis, in which the first three EOFs that explain the most variance for each of the factors are identified. This domain is chosen as most TCs are found in this area in this basin.

Those factors that are most related to the behavior of the TCs will be chosen through a forward stepwise regression analysis, in which the above factor EOFs, along with the monthly ENSO and PDO indices, as defined in section 2, from January of the previous year to March (for April prediction) or May (for June prediction) of the current year, are inserted into a regression equation one by one, and the one that contributes the most to increasing the correlation coefficient, R, of the regression equation is kept each time. This process will continue until the increase in R^2 of the regression equation by adding a new factor EOF is less than 0.05, as suggested by Wilks (2006).

The factors thus selected for each season will therefore be the ones having the strongest relationship to the behavior of landfalling TCs during that season, and the final prediction equation for each season will be a weighted linear combination of the respective factors, or the predictors, selected for that season. North et al. (1982)'s method is used to estimate the sampling errors in the EOFs.

b. Assessing the prediction schemes

To assess the robustness of the prediction equations derived from a set of dependent samples, a cross validation will be carried out for each prediction. In their paper, Barnston and van den Dool (1993) provided a general description of the procedure for carrying out the cross validation. Michaelsen (1987) suggested that for small numbers of observations (such as in this study), it is best to omit each observation one at a time, the so-called leave-one-out cross validation. Thus, for each of the predictions in this study, 40 new prediction equations will be derived by omitting one observation at a time, and a new predicted number of TCs will be calculated for each year. These new values will be matched

TABLE 1. Coefficients of the factor EOFs chosen for the prediction equations for the early, late, and JD seasons.

Early		Late		JD	
Factor EOF	Coefficient	Factor EOF	Coefficient	Factor EOF	Coefficient
$500U2_{Mar(0)}$	−0.557	$500U1_{Sep(-1)}$	0.839	$SHR3_{Oct(-1)}$	0.633
$500U3_{Oct(-1)}$	0.558	$500U3_{Sep(-1)}$	0.403	$SHR3_{Apr(0)}$	0.660
$500U3_{Feb(0)}$	−0.412	$500H1_{Oct(-1)}$	0.427	$SHR3_{May(0)}$	−0.478
$500H2_{Oct(-1)}$	−0.735	$850H2_{Nov(-1)}$	−0.595	$DIV1_{Mar(0)}$	−0.580
$MSE1_{Dec(-1)}$	−0.834	$850H3_{Mar(0)}$	0.476	$ENSO_{Apr(-1)}$	1.035
$MSE2_{Jan(0)}$	0.976	$SHR2_{Dec(-1)}$	0.234	$PDO_{Jul(-1)}$	−0.571
$MSE3_{Mar(0)}$	−0.579	$VOR2_{Sep(-1)}$	0.839	Constant	4.084
$SHR1_{Mar(0)}$	0.530	$ENSO_{Apr(-1)}$	0.484		
Constant	3.025	Constant	1.543		

against the observed numbers to determine the performance of the prediction equations. It should be noted that the correlation between the observed values and values from the cross validation would generally be lower than that between the observed and hindcasted values, the latter being the in-sample predicted values calculated by using all 40 yr of data, and calculated using dependent samples (Barnston and van den Dool 1993).

Apart from studying the correlation between the observed values and those from the cross validation, the accuracy of the schemes in predicting the number of landfalling TCs can also be determined by analyzing the correlation between the observed and the hindcasted values, the absolute and root-mean-square errors, and the forecast skill S. The forecast skill is a measurement of the forecasting performance of a scheme over climatology and was defined by Wilks (2006) as

$$S = \left(1 - \frac{\mathrm{RMSE}_{\mathrm{Scheme}}}{\mathrm{RMSE}_{\mathrm{Climatology}}}\right) \times 100\%,$$

where $\mathrm{RMSE}_{\mathrm{Scheme}}$ and $\mathrm{RMSE}_{\mathrm{Climatology}}$ refer to the root-mean-square error of the scheme and of the climatology, respectively.

Finally, a hindcasted or predicted number would be considered acceptable if the value falls within one standard deviation of the observed value during the respective season, which follows from the definition by LC03.

5. Forecasting the number of TCs making landfall in different seasons

In the following sections, the last number in the abbreviations of the factors indicates the EOF—1 for the first EOF, 2 for the second, etc.—whereas (0) and (−1) after the month indicate that the factor is for that month in either the current and or the previous year, respectively. For example, $500U2_{Mar(0)}$ would mean the second EOF of the 500-hPa zonal wind in March of the current year. Further, the respective coefficients for each of the factor EOFs in the prediction equations can be found in Table 1.

a. *Early season*

1) PREDICTORS

The prediction for N_E will be made in April. Eight predictors are included in the prediction scheme, namely, $500U2_{Mar(0)}$, $500U3_{Oct(-1)}$, $500U3_{Feb(0)}$, $500H2_{Oct(-1)}$, $MSE1_{Dec(-1)}$, $MSE2_{Jan(0)}$, $MSE3_{Mar(0)}$, and $SHR1_{Mar(0)}$. Figure 3a is a scatterplot of the hindcasted and cross-validated numbers as calculated by this scheme versus the observed number of TCs. The correlation coefficient between the hindcasted and observed numbers is 0.804, which is statistically significant at the 95% level, and the forecast skill S is 40.5% above the climatological mean. On the other hand, the correlation coefficient for the cross-validation values and the observed values is 0.642, also statistically significant at the 95% level, and S is 21.2%.

2) PREDICTIONS FOR 2006, 2007, AND 2008

Because the scheme was developed based on the data during the period 1965–2005, it is possible to perform independent predictions for the years 2006–08. Using this scheme, the predicted N_E values are 1.71, 3.49, and 1.87 for 2006, 2007, and 2008, respectively, with the observed values being 3, 2, and 3. All of these values fall within the one standard deviation threshold.

b. *Late season*

1) PREDICTORS

The prediction for N_L will also be made in April. Eight predictors are chosen for this scheme: $500U1_{Sep(-1)}$, $500U3_{Sep(-1)}$, $500H1_{Oct(-1)}$, $850H2_{Nov(-1)}$, $850H3_{Mar(0)}$, $SHR2_{Dec(-1)}$, $VOR2_{Sep(-1)}$, and $ENSO_{Apr(-1)}$. The correlation between the hindcasted and observed values is 0.817, significant at the 95% confidence level, with an S of 42.4%. The cross validation gives a 95% significant

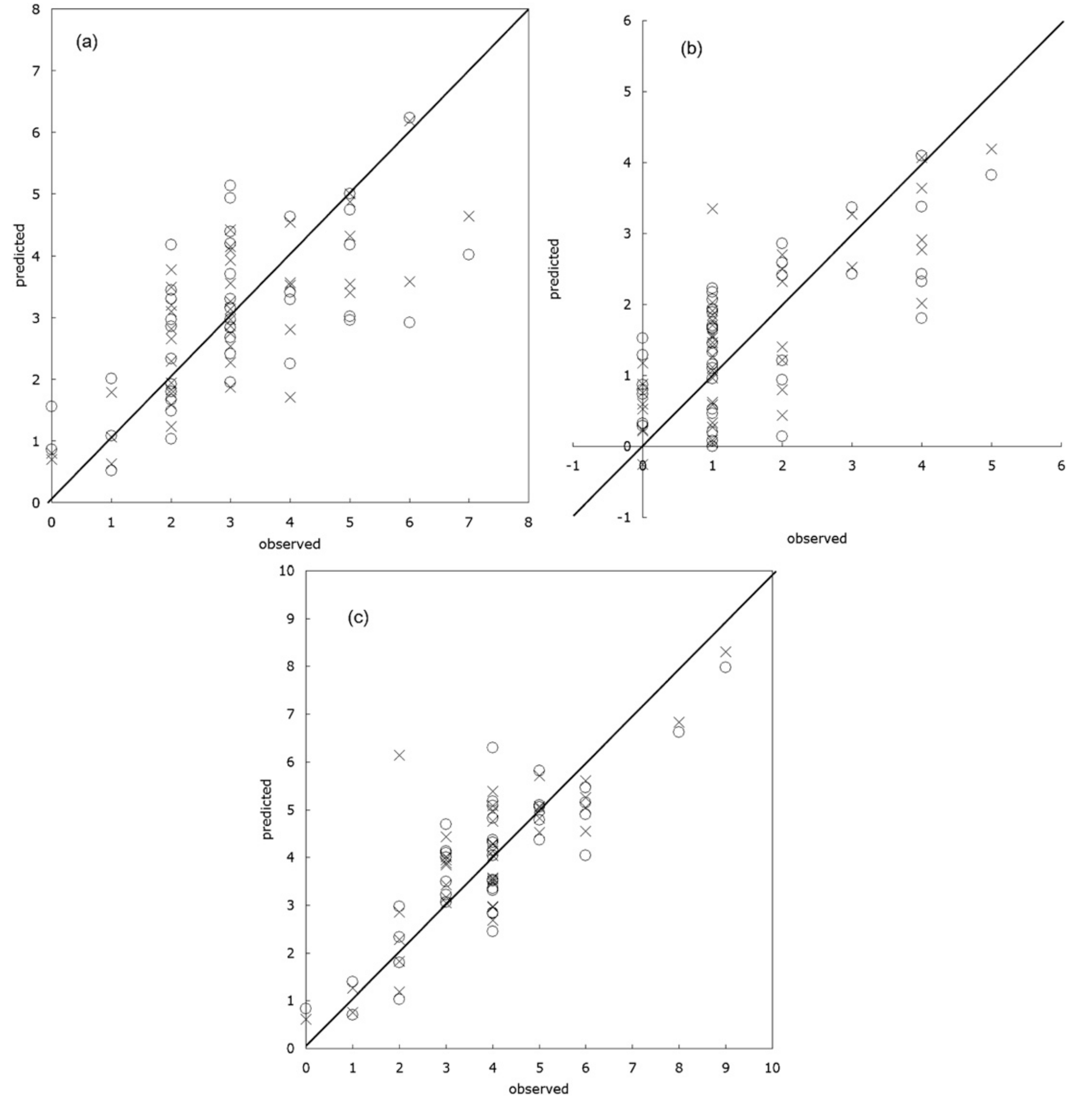

FIG. 3. Scatterplots of the calculated vs observed numbers of landfalling TCs for the April prediction for the (a) early, (b) late, and (c) JD seasons. Crosses indicate values calculated from the prediction equation, while circles are cross-validation values. The thick diagonal straight line is the 45° line indicating a perfect prediction.

correlation of 0.7 with the observed values, and an S of 27.9%. Refer to Fig. 3b for a scatterplot of these values.

2) PREDICTIONS FOR 2006, 2007, AND 2008

The predicted N_L values are −0.25, 3.35, and 0.80 for 2006, 2007, and 2008, respectively, versus the observed values of 0, 1, and 2. Both the predictions for 2006 and 2008 are within one standard deviation of the actual value.

c. JD season

1) PREDICTORS

The six predictors to be used in the prediction scheme for the N_J are $\mathrm{SHR3}_{\mathrm{Oct}(-1)}$, $\mathrm{SHR3}_{\mathrm{Apr}(0)}$, $\mathrm{SHR3}_{\mathrm{May}(0)}$, $\mathrm{DIV1}_{\mathrm{Mar}(0)}$, $\mathrm{ENSO}_{\mathrm{Apr}(-1)}$, and $\mathrm{PDO}_{\mathrm{Jul}(-1)}$. The correlation between the hindcasted values and the observed values is 0.899, significant at the 95% confidence level, and S in the current scheme is 56.3%. On the other hand, the correlation value between the cross-validated values and the observed values and S are 0.842 and 45.7%, respectively, with the former also significant at the 95% confidence level. Refer to Fig. 3c for a scatterplot of this scheme.

2) PREDICTIONS FOR 2006, 2007, AND 2008

This scheme predicts the N_J values in 2006, 2007, and 2008 to be 6.14, 3.95, and 4.29, respectively, compared to the observed numbers of 2, 3, and 4. The values for 2007

TABLE 2. Comparison between the prediction made by LC03's scheme and the current schemes for the annual number of TCs making landfall on the coast of south China for the whole season, which is the sum of the values predicted for the early and late seasons.

Year	Observed	LC03	Whole season (current scheme)
2001	5	3 ± 1	5.47
2002	4	4 ± 1	2.81
2003	4	5 ± 1	4.69
2004	2	5	1.99

TABLE 3. Statistics derived from the current prediction schemes for evaluating their performance in predicting the annual number of TCs making landfall on the coast of south China for the different seasons. The number for the whole season is the sum of the number of landfalling TCs calculated for the early and late seasons, and presented for comparison with the LC03 scheme.

	LC03	Whole	Early	Late	JD
Correlation	0.78	0.871	0.804	0.817	0.899
Absolute error	1.0	0.808	0.721	0.647	0.629
Root-mean-square error	1.2	0.98	0.936	0.761	0.754
Forecast skill (%)	~40	50.9	40.5	42.4	56.3

and 2008 are both within one standard deviation of the observed value.

d. Whole season

As LC03 was derived for the whole season, the statistics for the whole season as calculated by the current scheme is recorded here for reference. The number of TCs making landfall for the whole season is simply the sum of those making landfall in the early and late seasons. The correlation between the hindcasted and observed values is 0.871, which is statistically significant at the 95% level, and S is 50.9%. On the other hand, the correlation between the cross-validated and observed values is 0.784, with a forecast skill of 37.1%.

e. Capturing the decreasing trend

As previously mentioned, one of the problems with LC03's scheme is its failure to capture the decreasing trend of landfalling TCs in the past few years. The current scheme seems to have more skill in predicting this trend. The predicted number of landfalling TCs by the different schemes shows that LC03 could not predict the decreasing TC number, whereas the current scheme seems to be doing better at this (Table 2). However, LC03's scheme was only used from 2001 to 2004, which makes the sample size too small for a solid conclusion to be drawn.

6. Summary and discussion

Prediction schemes have been formulated for predicting the number of TCs making landfall over the coast of south China during the early, late, and JD seasons. Specifically, this study is an attempt to improve the scheme developed by LC03, which is for predicting landfalling TCs along the south China coast over the whole season. Results show that the current scheme provides a highly statistically significant correlation of 0.871 between the hindcasted and observed values, and the corresponding forecast skill is 50.9%, also highly improved over LC03's S of ~40% (Table 3). Another clear improvement of this scheme over LC03 is its ability to capture the decreasing trend of landfalling TCs, which LC03 did not perform well, although this conclusion is based on only 4 yr of comparisons. Moreover, the prediction schemes also suggest that ENSO and PDO are in fact affecting landfalling TCs, as both the ENSO and PDO indices appear in the prediction equations. As for predictions made for 2006, 2007, and 2008, the prediction schemes generally produced acceptable results, as the predicted values mostly fall within or very close to one standard deviation from the observations.

It is not easy to explain physically why the predictors are physically linked to the various predictands. Attempts have been made to correlate the predictors with the same field during the TC season. Although in some cases some statistically significant correlations can be found, it is difficult to establish causality. Nevertheless, the factors identified in section 5 are clearly related to either the genesis conditions or steering directions, which should therefore bear a relationship with the number of landfalling TCs.

In conclusion, this study presents an improved prediction scheme for the number of TCs making landfall on the coast of south China. The schemes for the early, late, and JD seasons all provide reasonable results. Verifications of this scheme from the following few years will be made to determine whether, given a long enough sample, that these schemes can indeed provide better predictions.

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