DOI:10.16555/j.1006-8775.2014.02.002



Article ID: 1006-8775(2014) 02-0103-09

# CLIMATE PREDICTION EXPERIMENT FOR TROPICAL CYCLONE GENESIS FREQUENCY USING THE LARGE-SCALE CIRCULATION FORECAST BY A COUPLED GLOBAL CIRCULATION MODEL

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**Abstract:** Based on an analysis of the relationship between the tropical cyclone genesis frequency and large-scale circulation anomaly in NCEP reanalysis, large-scale atmosphere circulation information forecast by the JAMSTEC SINTEX-F coupled model is used to build a statistical model to predict the cyclogenesis frequency over the South China Sea and the western North Pacific. The SINTEX-F coupled model has relatively good prediction skill for some circulation features associated with the cyclogenesis frequency including sea level pressure, wind vertical shear, Intertropical Convergence Zone and cross-equatorial air flows. Predictors derived from these large-scale circulations have good relationships with the cyclogenesis frequency over the South China Sea and the western North Pacific. A multivariate linear regression (MLR) model is further designed using these predictors. This model shows good prediction skill with the anomaly correlation coefficient reaching, based on the cross validation, 0.71 between the observed and predicted cyclogenesis frequency. However, it also shows relatively large prediction errors in extreme tropical cyclone years (1994 and 1998, for example).

**Key words:** CGCM; large-scale circulation; tropical cyclone; climate prediction

**CLC number:** P435 **Document code:** A

## 1 INTRODUCTION

Being one of the countries most seriously hit by tropical cyclones (TCs), especially landfall TCs, which bring with them abundant amount of rain, China suffers great damages that result in huge economic losses and casualties. As the TCs affecting China are mainly from the western Pacific and South China Sea, predicting the frequency of TCs genesis in the two regions has long been an important operation at National Climate Center of China (NCC). The cyclogenesis, intensity and track of TCs are affected by large-scale atmospheric circulation, which includes tropical sea temperature, atmospheric convection in the tropics, divergence/convergence in the upper and lower atmosphere, and vertical wind shear, which has been much studied at home and abroad[1-11]. In the latest work over the past few years, cyclogenesis in the western Pacific and North Pacific Oscillation[12], the size of sea ice in North Pacific[13], circulation east off Australia[14], and Antarctica Oscillation[15] all are closely related with the issue above. All of the work above has paved solid theoretic basis for predicting the TCs.

Statistical approach has been widely used in predicting the TC season[1, 16-19]. Recently, based on multiple climatological factors, Fan and Wang[20] built a model for statistical predicting the annual genesis of TCs in the northwestern Pacific and with good results. Nicholls[16] used the Southern Oscillation-El Nino index to perform seasonal prediction of the number of TCs in Australia. Klotzbach et al.[18, 19] predicted the frequency of hurricanes in the Atlantic using a statistic prediction model that is based on precursory atmospheric signals. At present, there are only a couple of objective methods based on statistical physics, including the optimized subset and

**Received** 2013-09-11; **Revised** 2014-03-21; **Accepted** 2014-04-15

**Foundation item:** Specialized Science and Technology Project for Public Welfare Industry (GYHY200906015); National Basic Research Program of China (973 Program, 2010CB428606); Key Technologies R&D Program of China (2009BAC51B05)

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mean-generating function methods, at NCC to predict the TC. Statistical physics based prediction cannot take into account the variation of the atmosphere itself in many circumstances while the activity of the TC is closely related with the anomaly of simultaneous atmospheric circulation. Therefore, the anomaly of large-scale tropical atmosphere must be known before the activity pattern of the TC can be predicted and dynamic models have advantages of their own doubtlessly. In 2006, climate models were first put forward to be used in real-time forecasting of the frequency of the TC in western Pacific in the summer of 2006 and the result was consistent with the observation[21]. A nine-layer model from the Atmospheric Physics Institute of Chinese Academy of Sciences was used to study its predictability for large-scale circulation anomaly that was closely related with the TC[22], with the finding that it is capable of performing climatological prediction, with some success, of the TC activity in northwestern Pacific. All of these studies have shown that it is feasible to have observation-based prediction of the TC frequency using dynamic models. Mainly due to relatively weak capabilities of models to predict TC-related circulation anomaly, there has not been any predictive model in the TC forecasting operation of NCC that is based on dynamic models.

The SINTEX-F coupled model has been developed on the basis of SINTEX jointly founded under a Europe-Japan cooperation program[23-26]. As shown in some analyses, the SINTEX-F GCM does well in modeling and predicting the large-scale circulation features of the tropical atmosphere[27]. In view of it, this study attempts to extract a TC-related large-scale circulation field that has high predicting skill as well as observations to set up an objective statistical predictive model of the annual frequency (AF) of the TC in the South China Sea and western Pacific, which is for both forecasting experiment and result verification.

## 2 MODEL, DATA AND METHODS

The atmospheric part of the model is the latest high-resolution version of ECHAM4[28]. It has a horizontal resolution of T106 and 19 vertical layers. The global ocean model is Version 8.2 of Océan Parallélisé that contains the structure of OCRA2[26]. With a horizontal resolution of 2°×2°, the model improves to 0.5° and has 31 vertical layers in areas near the equator. The coupled fields of the model (e.g. sea surface temperature, land surface momentum flux, thermal flux and water vapor flux) are obtained by interpolation and air-sea exchange is executed once every 2 hours through a coupling mechanism that involves the ocean, atmosphere, sea ice and soil[30]. No flux correction is made to the coupled model with only the sea-ice covered area in the OCGCM adjusted towards the observed monthly climatological value. The initial atmospheric condition is determined by integrating for a year under the observed monthly climatological SST. The ensemble forecasting scheme includes nine members that are from three groups of coupled physics (equivalent to three groups of model) and three schemes of initial value formulation. They are combined in pairs of two, totaling at nine groups of forecasting scheme. For detailed introduction to the model, see Roeckner et al.[28], Madec et al.[29] and Valcke et al.[30]. The SINTEX-F model shows high skill in predicting the ENSO, IOD and Asian monsoons[31-36] and does well in the prediction experiments in the past few years[37].

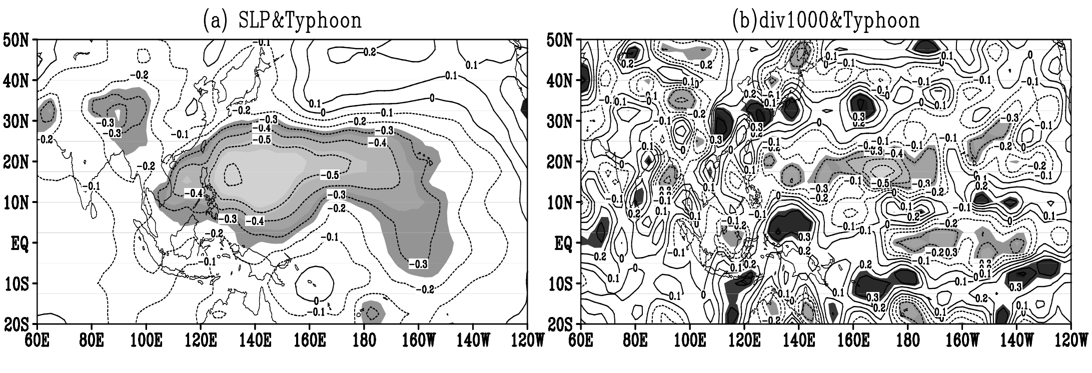
The model data used in this work is the circulation field of May to October from 1982 to 2010 forecast from March 1 by SINTEX-F GCM, which includes the sea level pressure (SLP), zonal winds at 850 and 200 hPa and meridional wind at 850 hPa. The data of TC frequency in northwestern Pacific and South China Sea are all from the *Yearly Book for Typhoons* from China Meteorological Administration. The TCs studied in this work are the ones with near-the-eye wind at Force 8 on the Beaufort scale. The observations used are issued by NCEP/NCAR, which are the monthly mean global reanalysis with the horizontal gridpoint at a resolution of 2.5°×2.5°. The variables include SLP, outgoing longwave radiation (OLR), zonal wind at 1000 and 200 hPa and zonal and meridional wind at 850 hPa.

First, main large-scale circulation conditions are determined that affect the TC activity through the correlation between the annual TC frequency and related NCEP data. Then, correlation analysis is applied to extract information on large-scale circulation field that offers the model with high prediction skill and is closely related with the TC genesis and identify predictors for the key region. And then, large-scale circulation factors forecast with the SINTEX-F model are used to set up a statistical prediction model for the AF of the TC via multivariate regression analysis. The forecast results are cross-verified and experimented through prediction.

## 3 RELATIONSHIP BETWEEN THE TC FREQUENCY AND LARGE-SCALE ATMOSPHERIC CIRCULATION

As the genesis of the TC is closely related with the large-scale circulation, many studies have worked on it. At NCC, the annual typhoon prediction is for the total number of TCs that are formed over the whole year while the TCs in the South China Sea and western Pacific mainly appear from May to October, which take up 80% of the annual cyclogenesis frequency. The series of the TC number from May to

October is correlated with that of the whole year at 0.94 while the monthly frequency of TC genesis from January to April is less than one on a multi-year scale. Therefore, the annual TC frequency and May-to-October circulation are selected to set up a statistical relationship between each other by taking into account the operational need for prediction of annual TC frequency and the relationship presented above between the May-to-October time and the whole year as well as the winter-summer circulation contrast. Fig. 1 gives the correlation between the AF and the large-scale circulation averaged over May to October, which include SLP, divergence at 1000 and 200 hPa, vorticity at 850 hPa, vertical shear of the zonal wind at 200 and 850 hPa and the meridional wind at 850 hPa. Fig. 1 gives the correlation between the AF of the TC and the large-scale circulation averaged over May to October, which includes the divergence at 1000 and 200 hPa, vorticity at 850 hPa, vertical shear of the zonal wind at 200 and 850 hPa (|U200 hPa−U850 hPa|) and the meridional wind at 850 hPa. Fig. 1a shows that the AF is much negatively correlated with the SLP in the South China Sea and western Pacific. In the main area of TC activity, low SLP is accompanied with active TCs and otherwise is true. The physical implication of this link is well-defined. Fig. 1b−1d present the relationship between the Intertropical Convergence Zone (ITCZ) and the AF, which indicates that strong low-level convergence (Fig. 1b), upper-level divergence (Fig. 1c) and 850 hPa vorticity (Fig. 1d) are all conducive to large number of TC genesis, which is also easily understood in physics. Fig. 1e gives the relationship between the genesis frequency of the TC and the wind shear between the upper and lower levels of the troposphere. As shown in a number of studies, the vertical wind shear of the source area of the TC has important effects on the TC genesis; the larger the vertical wind shear, the less likely the TC will be generated. Significantly negative correlation is found over an extensive area of 140°E−160°W, 10°−20°N, which is consistent with previous studies. Besides, it is also noted that a large area of significantly positive correlation also exists to the west of it, constituting a well-defined dipole pattern with the eastern area of negative correlation. Such distribution also reflects the effect of the circulation anomaly of the subtropical monsoon in East Asia on the genesis frequency. As the subtropics from the Indian Ocean to the western Pacific is affected by the monsoon, the lower level is with a westerly and the upper level an easterly and a large wind shear between these levels indicates a strong monsoon circulation and thus a strong monsoon trough, making it more likely for the TC to form. In Sun et al.[14], the anomaly of the equatorial westerly upstream of the western part of the western Pacific (125°−150°E) is also focused for its role in affecting the TC cyclogenesis. Therefore, the positive correlation in the corresponding area of Fig. 1e carries its own physical meaning as well. When a cross-equatorial airflow strengthens near 90°E, the westerly in 125°−150°E and 5°−15°N also enhances, increasing the convection east of the Philippines and frequency of the TC in the western Pacific. It can be seen that the genesis frequency is also well linked with the activity of the cross-equatorial flow near 90°E. It is also shown in the correlation between the genesis frequency and the meridional wind at 850 hPa, as indicated in Fig. 1f, with the maximum exceeding 0.4 (surpassing the 99% confidence level). In view of the possibility that the TC series may be erroneous for the time prior to the mid-1970s, the distribution of the correlation is determined once again using the data in 1975−2008. The result showed that main areas of significant correlation still exist as compared with those determined with the 1951−2008 data (figure omitted), suggesting stable correlation for the analysis above.



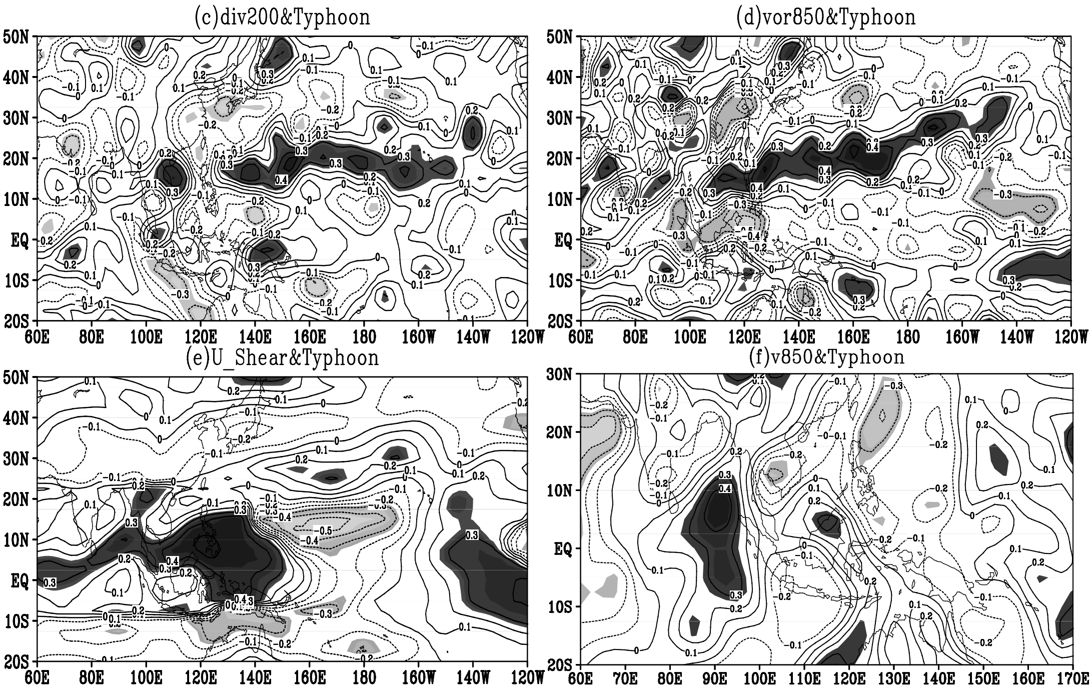



**Figure 1.** Correlation between the AF and large-scale circulation averaged over May to October. Shading indicates areas that pass the 95% confidence test. (a): SLP; (b): divergence at 1000 hPa; (c): divergence at 200 hPa; (d): vorticity at 850 hPa; (e): vertical shear of the zonal wind (|U200 hPa-U850 hPa|); (f): meridional wind at 850 hPa.

Based on the analysis above, six key-region indexes can be constructed as predictors. Table 1 gives the method of calculating the indexes and the area where they distribute. These indexes are good indicators of related features given by Fig. 1. Fig. 2 gives the time series of the six key-area indexes and the genesis frequency. They are correlated at −0.63, −0.65, 0.61, 0.61, 0.57, and 0.38 respectively, all passing the 99.9% test of confidence. If a significant linear trend exists between the two series, their correlation may be caused by the tendency. It is the interannual correlation between series that this work is more concerned about in the prediction of annual TCs. Therefore, the linear trend is removed from the series of the TC and the atmosphere before calculating the correlation again, which are −0.65, −0.64, 0.57, 0.66, 0.54 and 0.33 respectively, suggesting that the high correlation is still there between the two series. It shows that the factors determined for the key region are associated with the TC indeed. The six indexes are then used to set up a multi-variate regression equation for the genesis frequency.

$$y(t) = -0.078 - 0.18\times x_1(t) - 0.47\times x_2(t) + 0.29\times x_3(t) + 0.33\times x_4(t) - 0.57\times x_5(t) + 0.18\times x_6(t)$$

Figure 3 gives the fitting of the series of genesis frequency using the multi-variate regression equation. It shows that the regression equation formulated with the indexes has good fitting of the series and the reconstructed TC series is correlated with the observed ones at a coefficient of 0.73, far surpassing the 99.99% test of confidence and much above the correlation coefficient between each of the index series and TC frequency series. If a circulation model is able to have good prediction of the large-scale environmental field that is closely linked with the TC genesis, the large-scale circulation predicted by models can be used to set up prediction models for the TC frequency. In the next section, on the basis of analyzing the capabilities of the SINTEX-F GCM model in predicting such circulation, model output will be used to set up an objective, statistics-based model to predict the TC frequency over the South China Sea and western Pacific and to run experimental prediction and assessment of the result.

**Table 1.** Computation of the indexes for the key regions of NCEP data.

| Circulation factors | Computation of key regions and indexes |
|---|---|
| SLP | Standardized SLP anomaly averaged over 125°–155°E, 10°–22.5°N |
| Divergence at 1000 hPa (div1000) | standardized divergence anomaly averaged over 160°–180 °E, 15°–22.5°N |
| Divergence anomaly at 200 hPa (div200) | standardized divergence anomaly averaged over 150°–180°E, 17.5°–22.5°N |
| Vorticity at 850 hPa (Vor850) | standardized vorticity anomaly averaged over 140°–170°E, 15°–25°N |
| Zonal wind shear between upper and lower levels (*US*) $US=\|U_{200\ hPa}-U_{850\ hPa}\|$ | standardized US differences between the mean for 117.5°–137.5°E, 5°–15 °N and that of 152.5°–177.5°E, 10°–17.5 °N |
| Cross-equatorial airflow at 850 hPa (*V*850) | standardized 850 hPa meridional wind anomaly averaged over 87.5°–92.5°E, 7.5°S–7.5°N |

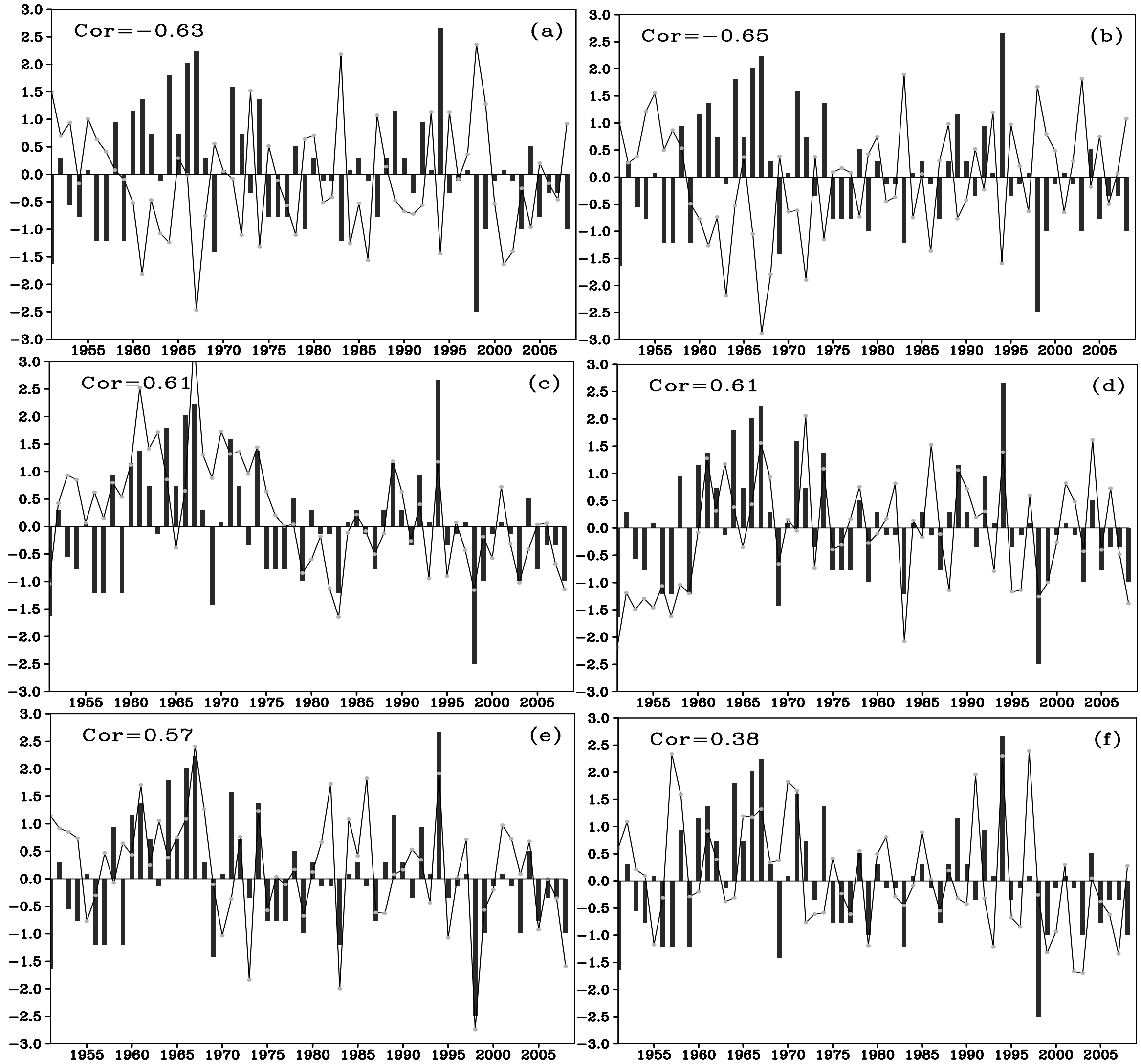



**Figure 2.** Standardized time series of the six key-region indexes (solid curve) and TC frequency (histogram). (The correlation coefficients of the two series are shown in the upper left corner of the curve). (a): SLP; (b): divergence at 1000 hPa; (c): divergence at 200 hPa; (d): vorticity at 850 hPa; (e): vertical shear of zonal wind; (f): meridional wind at 850 hPa. The abscissa is for the year.

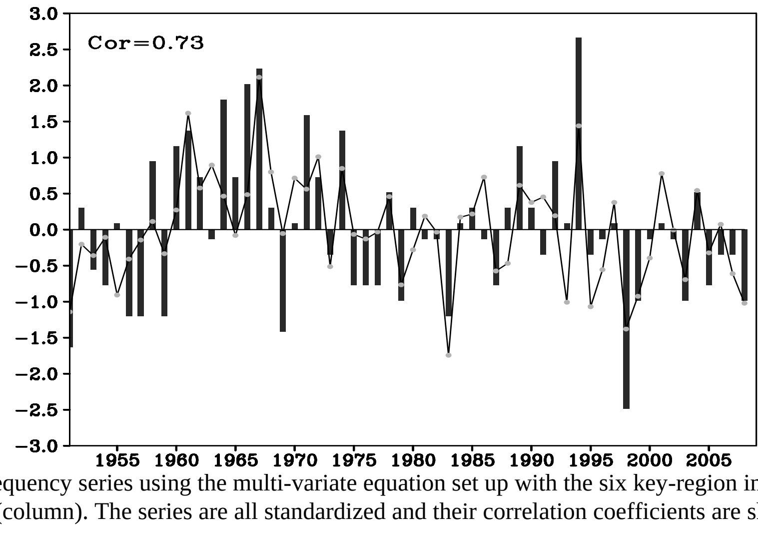



**Figure 3.** Fitting of TC frequency series using the multi-variate equation set up with the six key-region indexes (solid curve) and observations of the series (column). The series are all standardized and their correlation coefficients are shown at the upper left corner.

## 4 PREDICTIVE MODEL BASED ON SINTEX-F AND ITS VERIFICATION

Based on the analysis above on the observations, this work first investigated the capabilities of simulating the correlation between these TC frequencies and the large-scale circulation using the SINTEX-F GCM model. Like the previous section, the correlation is sought between the AF and the May-to-October circulation forecast with the model. As shown in the correlation analysis, the TC frequency's correlation with four of the six large-scale environmental fields presented in the previous sections (including the SLP, vertical wind shear in the troposphere, the cross-equatorial flow at 850 hPa and vorticity at 850 hPa) is well reflected in the model prediction. Fig. 4 gives the correlation between the TC frequency and the four circulations predicted by the model. The model is shown to reproduce main observed patterns of correlation. The correlation between the TC frequency and the predicted SLP is systematically more to the east in distribution as compared to the observation but the overall correlativity is quite significant (Fig. 4a). Consistency and differences both exist between the tropospheric wind shear and the observation as far as the distribution of correlation is concerned, with the simulated correlation for North Pacific and Southern Hemisphere much stronger than the observation (Fig. 4b). Systematic errors are also found between the simulated correlation between the 850 hPa meridional wind (Fig. 4c) and 850 hPa vorticity (Fig. 4d) and the observation, and their main physical characteristics are consistent with it. Based on the distribution of these correlations, the indexes for the four key regions can also be defined following what is presented in the previous text. Table 2 gives the definitions of the indexes. Fig. 5 presents the series of the indexes. They are correlated with the TC frequency by −0.7, 0.79, 0.53, and 0.64 respectively, all passing the test of 99% confidence. With the removal of the linear trend of the series for the TC and the atmosphere, the correlation is 0.65, 0.75, 0.63, and 0.60 respectively, still with significant correlativity.

**Table 2.** Key-region indexes determined with model data.

| Predictors | Key-region indexes determined with model data |
|---|---|
| SLP | Standardized SLP anomaly averaged over 170°E–140°W, 7.5°–22.5°N |
| Zonal wind shear between upper and lower levels (*US*) $US=\|U_{200\ \mathrm{hPa}}-U_{850\ \mathrm{hPa}}\|$ | Standardized wind shear (US) differences between the mean for 110°–140°E, 2.5°–15.0°N and that of 155°–175°E, 2.5°–15.0°N |
| Cross-equatorial flow at 850 hPa (*V*850) | Standardized 850 hPa meridional wind anomaly averaged over 82.5°–90°E, 10.0°S–2.5°N |
| Vorticity at 850 hPa (Vor850) | Standardized 850 hPa vorticity anomaly averaged over 140°–170°E, 10.0°–17.5°N |

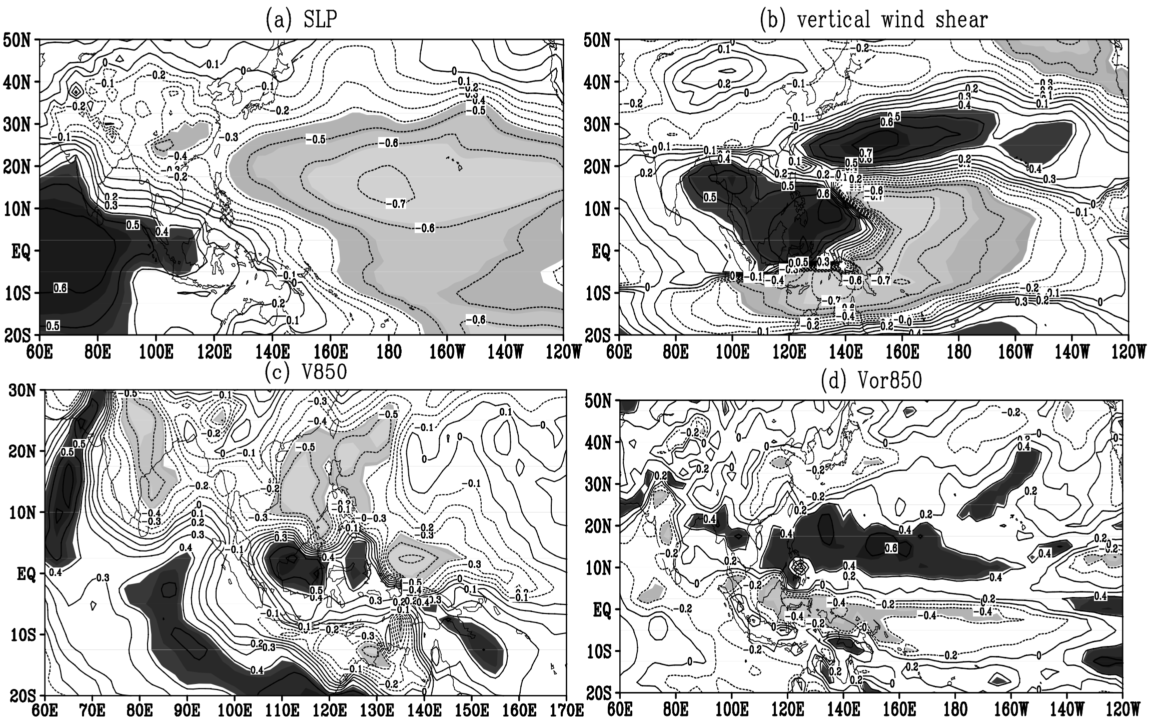



**Figure 4.** Correlation between the AF and model-predicted large-scale circulation. The shading is the area that passes the test of 95% confidence. (a): SLP; (b): vertical shear of meridional wind (|U200 hPa-U850 hPa|); (c): meridional wind at 850 hPa; (d): vorticity at 850 hPa.

The four indexes are used as the predictors to construct a multi-variate regression equation for the AF.

Figure 6 gives the model-fitted and observed anomalies of TC frequency for 1982−2010. They are correlated by a coefficient of 0.8 with a same-sign rate of 86%.

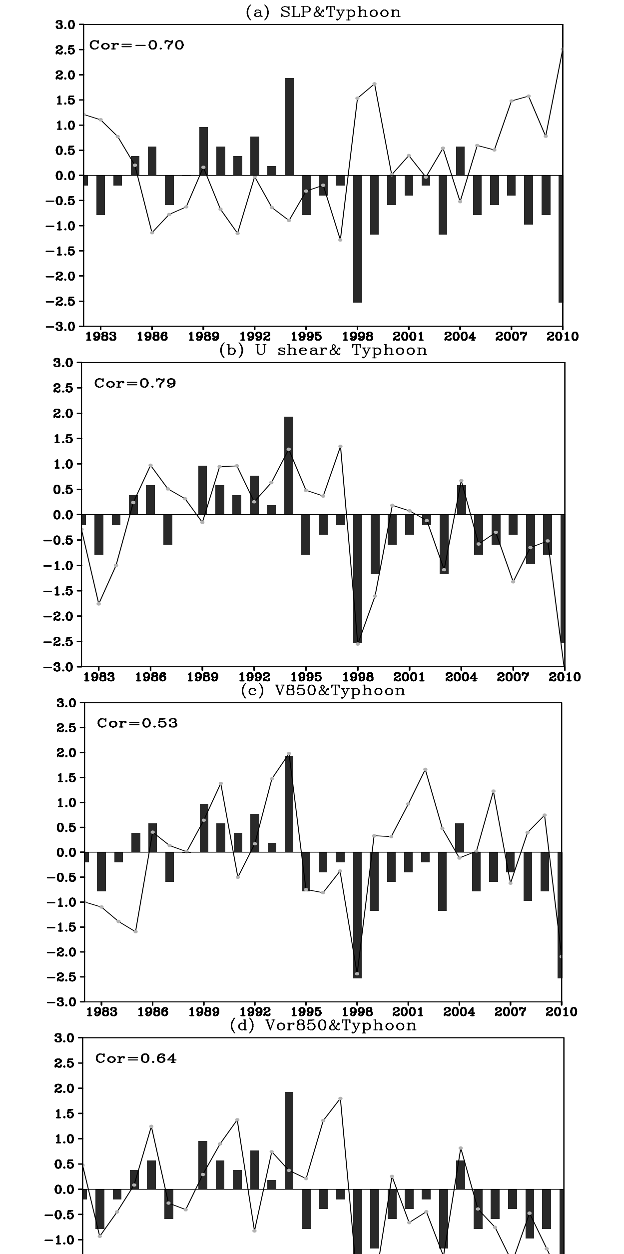



**Figure 5.** Standardized time series of model-predicted indexes of the four key regions (solid curve) and TC frequency (column). The correlation coefficients are shown in the upper left corner of the curve. Other captions are the same as in Fig. 4.

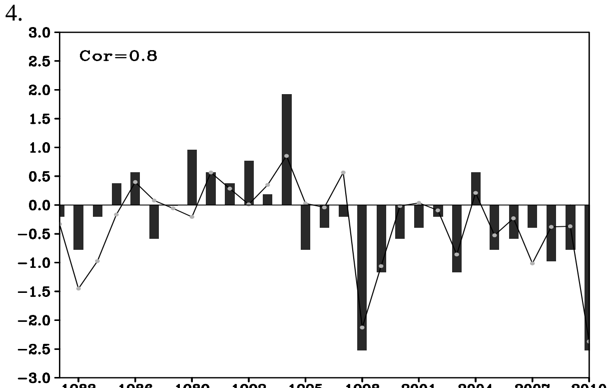



**Figure 6.** Fitting of the TC frequency by the multi-variate regression model set up with the four indexes of model-predicted key regions (curve) and observed series of the TC frequency (column). Both of the series are standardized. Their correlation coefficients are shown at the upper left corner. The abscissa is for the year.

The results of the predictive model are cross-verified as follows. For each of the predictive equations, data from the Mth year (with M taken to be 1, 2, ……, 29) are removed from the set of all available data (for the 29 years from 1982 to 2010). Then, the factors retained for the Mth year are used as the observation in the prediction while what is forecast for the Mth year is used as the observation. Repeat this procedure until M takes all possible values to obtain a series of the predicted value. As the forecast model does not involve predictors for the current year, the forecast so determined is considered one that is based on independent samples. In this way, the verified result of the forecast is close to the real forecast instead of retrospective forecast. Fig. 7 gives a standardized anomaly of the TC frequency derived from the cross verification, which is correlated with the observed frequency by 0.71 and passes the test of 99% confidence. Table 3 gives the TC frequency for each of the years using the cross-verification and the statistics of forecast results over the years. In the result of the cross-verification for the 29 years, the sign of the prediction is the same as that of the observed, or at a rate of 82.8%. There are 16 years for which the absolute forecast error is ±2, taking up 65.5% of the total. 1994 and 1989 are the two years with relatively large forecast errors. The number of TC genesis is anomalously larger, being 37 and 32 respectively, more than any other years since 1951. For the prediction, it is 30 and 25 respectively, or with relative errors at −18.9% and −21.9% respectively. For the years of extremely small frequency (1998 and 2010, both having 14 TCs), the model predicts 17 and 15 TCs respectively, though the relative error is larger for 1998 (21.4%). It is then clear that the forecast error is relatively large for extreme cases. 1994 and 1998 are the years with anomalously more and less TCs, being in extreme situations. For the predictive model that is based on statistical approach, predictive information is mainly from the historical data, which does not predict well if the case is extreme. Extreme events are just the things that cannot be predicted well with the usual statistical methods. In addition, the large-scale circulation field is the main element to build the model with but the large-scale environmental field is just one of the factors affecting the TC genesis. Especially, extreme situations cannot be explained entirely with the large-scale environmental field, which may account for the fact that the model produces large errors in predicting the anomalously more and less TC years.

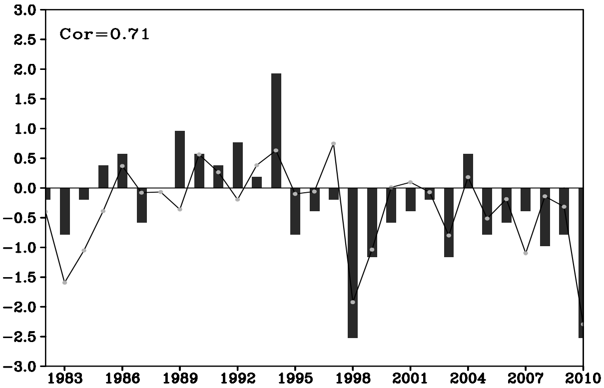



**Figure 7.** Series of TC frequency (results of cross-verification shown in curves) predicted by the multi-variate equation set up with the model-based key-region indexes and that of the observation (column). Both the series are standardized and the correlation coefficients are shown at the upper left corner.

**Table 3.** Cross-verifications of the model prediction of the AF in 1982-2010.

| Year | Observed AF | Predicted AF via Cross-verification | Correct anomaly or not (against a climatological mean of 27 TCs for 1971-2000) | Absolute error of prediction | relative error of prediction/% |
|---|---|---|---|---|---|
| 1982 | 26 | 25 | Y | −1 | −3.8 |
| 1983 | 23 | 19 | Y | −4 | −17.4 |
| 1984 | 26 | 22 | Y | −4 | −15.4 |
| 1985 | 29 | 25 | N | −4 | −13.8 |
| 1986 | 30 | 29 | Y | −1 | −3.3 |
| 1987 | 24 | 27 | Y | 3 | 12.5 |
| 1988 | 27 | 27 | Y | 0 | 0 |
| 1989 | 32 | 25 | N | −7 | −21.9 |
| 1990 | 30 | 30 | Y | 0 | 0 |
| 1991 | 29 | 28 | Y | −1 | −3.4 |
| 1992 | 31 | 26 | N | −5 | −16.1 |
| 1993 | 28 | 29 | Y | 1 | 3.6 |
| 1994 | 37 | 30 | Y | −7 | −18.9 |
| 1995 | 23 | 27 | Y | 4 | 17.4 |
| 1996 | 25 | 27 | Y | 2 | 8.0 |
| 1997 | 26 | 31 | N | 5 | 19.2 |
| 1998 | 14 | 17 | Y | 3 | 21.4 |
| 1999 | 21 | 21 | Y | 0 | 0 |
| 2000 | 24 | 27 | Y | 3 | 12.5 |
| 2001 | 25 | 27 | N | 2 | 8.0 |
| 2002 | 26 | 26 | Y | 0 | 0 |
| 2003 | 21 | 23 | Y | 2 | 9.5 |
| 2004 | 30 | 28 | Y | −2 | −6.7 |
| 2005 | 23 | 24 | Y | 1 | 4.3 |
| 2006 | 24 | 26 | Y | 2 | 8.3 |
| 2007 | 25 | 22 | Y | −3 | −12.0 |
| 2008 | 22 | 26 | Y | 4 | 18.1 |
| 2009 | 23 | 25 | Y | 2 | 8.7 |
| 2010 | 14 | 15 | Y | 1 | 7.1 |

## 5 CONCLUSIONS

Based on analyses of the correlation between the frequency of TC genesis and the large-scale circulation, this work uses the large-scale information from the SINTEX-F air-sea coupled model to extract useful information that is both capable of performing good prediction and closely related with the TC genesis. The results are then used to construct a statistical model for predicting the TC frequency on the basis of dynamic model outputs. Both experiments and verifications were conducted for the prediction.

(1) The genesis of the TC is closely related to the large-scale circulation, which includes the convection in the source area of the TC, wind shear between the upper and lower levels, ITCZ anomaly and the subtropical monsoon upstream of the TC source region and cross-equatorial flows. The predictive model, set up with six key-region factors from the NCEP data, has a fitting rate of 0.73 (correlation coefficient) for the AF of the TC.

(2) The SINTEX-F air-sea coupled model is successful in predicting part of the large-scale circulation patterns closely related to the TC genesis. The patterns include the SLP in the active area of the TC, vertical wind shear in the troposphere, vorticity of the ITCZ and the cross-equatorial flow near 90°E (at 850 hPa for the latter two). The four predictors are well correlated with the TC genesis and the fitting rate of the multi-variate regression model is 0.8 (correlation coefficient, surpassing the test of 99.9% confidence) for the TC genesis.

(3) Cross-verification was conducted of the result of the predictive model set up with the output of the SINTEX-F air-sea coupled model. It is shown that the overall result is good. The cross-verification results are correlated with the real TC frequency at 0.71 (which passes the test of 99% confidence) and the same-sign rate is 82.8%. The predictive model has the largest error for extreme years of the TC. The model's capability can be improved for cases of extremely large or small number of TCs if improvement can be made in introducing factors of extreme conditions in addition to the large-scale circulation.

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**Citation:** JIA Xiao-long, CHEN Li-juan, LUO Jing-jia. Climate prediction experiment for tropical cyclone genesis frequency using the large-scale circulation forecast by a coupled global circulation model. *J. Trop. Meteor.*, 2014, 20(2): 103-111.