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IMPACT OF SUMMER WARMING ON DYNAMICS–STATISTICS–COMBINED METHOD TO PREDICT THE SUMMER TEMPERATURE IN CHINA

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Abstract: Based on NCEP / NCAR daily reanalysis data, climate trend rate and other methods are used to quantitatively analyze the change trend of China's summer observed temperature in 1983—2012. Moreover, a dynamics-statistics-combined seasonal forecast method with optimal multi-factor portfolio is applied to analyze the impact of this trend on summer temperature forecast. The results show that: in the three decades, the summer temperature shows a clear upward trend under the condition of global warming, especially over South China, East China, Northeast China and Xinjiang Region, and the trend rate of national average summer temperature was 0.27℃ per decade. However, it is found that the current business model forecast (Coupled Global Climate Model) of National Climate Centre is unable to forecast summer warming trends in China, so that the post-processing forecast effect of dynamics-statistics-combined method is relatively poor. In this study, observed temperatures are processed first by removing linear fitting trend, and then adding it after forecast to offset the deficiency of model forecast indirectly. After test, ACC average value in the latest decade was 0.44 through dynamics-statistics-combined independent sample return forecast. The temporal correlation (TCC) between forecast and observed temperature was significantly improved compared with direct forecast results in most regions, and effectively improved the skill of the dynamics-statistics-combined forecast method in seasonal temperature forecast.

Key words: dynamics-statistics-combined; global warming; temperature forecast; model error correction
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1 INTRODUCTION

Under global warming in recent years, the summer temperature in China shows a significant rising trend in 1983—2012. Especially in 1993—2012, summer temperature remained high [1-4], and a wide range of sustained high temperature occurred over southern areas of China this summer [5-7]. Global warming undoubtedly makes more negative impacts on human living and brings more uncertainties to summer temperature forecast[8-12].

Currently, short-term climate forecast is still a worldwide difficulty, and a variety of forecast methods have been proposed for China's regional precipitation and temperature [12-16]. In recent years, dynamic model forecast is combined with physical statistics to make full use of historical data for improving forecast results, which has become a much-noted research trend, and certain research results have been achieved [17-20]. Using model error values of available years to estimate the predicting year is the core of the dynamics-statistics combination method [21-26]. However, it is found that independent sample return results in the latest decade were significantly lower than the observed temperature in most years. It is indicated that systematic errors exist in the dynamics-statistics-combined forecast method for summer temperature forecast.

Through analyzing the above problems, the main cause is found for the defect in the model forecast results to simulate the rising trend of observed temperature under global warming, while model forecast is hardly able to forecast trend changes. If adding the rising trend to the model forecast simulation process, it needs to make substantial modification in numerical model framework. Meanwhile, it is rather miscellaneous for assimilation schemes and physical parameters in complex processes. In this study, the rising trend of observed temperature is removed, so as to eliminate the rising trend of model errors in the past years and indirectly compensate the simulation defect of the model. The observed temperature after the removal of the rising trend was combined with model forecast

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results, and the dynamics-statistics-combined forecast method with optimal multi-factor portfolio was used for forecast. Based on the forecast results, the removed rising trend of observed temperatures was added again to the final forecast. The dynamics-statistics-combined model error correction method is used for summer forecast. In this paper we apply this method in summer temperature forecast. The difference of the method applied in different elements from the perspective of model error correction principle is analyzed to put forward the solution of systemic error resulting from global warming. The results show that forecast was greatly improved.

2 DATA AND METHODOLOGY

2.1 *Data sources*

(1) NCEP/NCAR daily average temperature reanalysis data for 1981—2012 were taken as observational data in this study, which were processed into average summer temperature data with a horizontal resolution of 2.5 × 2.5, and the summer average of 1981—2010 was taken as climatological summer temperature[27-30].

(2) The monthly temperature field data since March among historical return products of model forecast by National Climate Center (NCC) seasonal / interannual forecast model (CGCM) for 1983—2012 were taken as model data, which were processed into summer model average temperature data with a horizontal resolution of 2.5×2.5 and a total of 144×73 grids. The data of 375 grids in China were studied herein.

(3) A total of 114 pre-exponential factors were taken from January 1951 to March 2012, including 40 climatic indices provided by U.S. National Oceanic and Atmospheric Administration (NOAA) and 74 circulation eigenvectors offered by Climate Diagnostics and Forecast Division of National Climate Center.

2.2 *Dynamics-statistics-combined model error correction method based on optimal multi-factor portfolio*

Considering that the impact factors are different in different regions, China is divided into eight parts. Fig.1 shows the scope of all regions. We carry out the dynamic statistical combination forecast in each region, and then merge the regional forecast results.

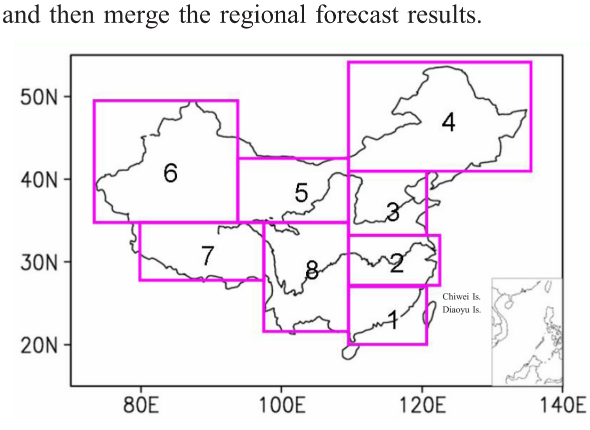

Figure 1. The eight regions of China.

The key of the similarity method on dynamics-statistics error correction method based on optimal multi-factor portfolio is to use the optimal pre-multi-factor portfolio to determine similarity years and conduct model error similarity correction [31-34]. This method was applied to different climatic regions, and then these results were integrated to obtain China's summer forecast results. The following is a brief summary on the objectively quantified dynamics-statistics return forecast method after the removal of trends (see Fig.2).

According to the above steps, the entire forecast method is divided into three stages, i.e., data input, process handling and result output.

Data input: Collecting the observed temperature data and model forecast data as well as 114 × 12 pre-exponential factors in the three decades. The key of this step is to remove the trend of multi-year observed temperature data to get rid of trend changes.

Process handling: Forecasting temperature based on region division. This method is the same for all regions so that single-region temperature forecast is adopted herein. The national forecast results can be obtained by combining those of each region. Step 1: for 114 × 12 pre-exponential factors of the forecast year, the Euclidean distance is taken as a condition to determine four similar years. The average model error of these four similar years is set as that of the forecast year for model error correction. Then, each correction result of 114 × 12 factors can be derived to calculate the ACC value. The cross-examined average ACC in the three decades is regarded as a standard to sort various factors, and the factors with the ACC value greater than 0.1 (the pre-factor set varies in different regions) are taken as the pre-factor set of regional summer temperature. Step 2: two-factor configuration is taken as an example for multi-factor portfolio. The factor with top ACC in Step 1 is taken as the first factor, and the remaining factors in the factor set are combined with the first factor respectively, and then EOF decomposition is carried out on the exponential sequence of each factor combination in the three decades, i.e.,

$$X_{m\times n} = V_{m\times m} T_{m\times n} \quad (1)$$

where m represents sample quantity, and n represents sample length.

The variance contribution of each eigenvector λ_k is calculated, i.e.,

$$R_k = \lambda_k \Big/ \sum_{i=1}^{m} \lambda_i, [k = 1,2,3,\cdots, p(p < m)] \quad (2)$$

Since the variance contributions of the first several principal components already contain most information of the original variable field, the cumulative variance contribution rate (80%) is taken herein, i.e.,

$$G = \sum_{i=1}^{p} \lambda_i \Big/ \sum_{i=1}^{m} \lambda_i > 0.8 \quad (3)$$

In the meantime, the obtained time coefficient of

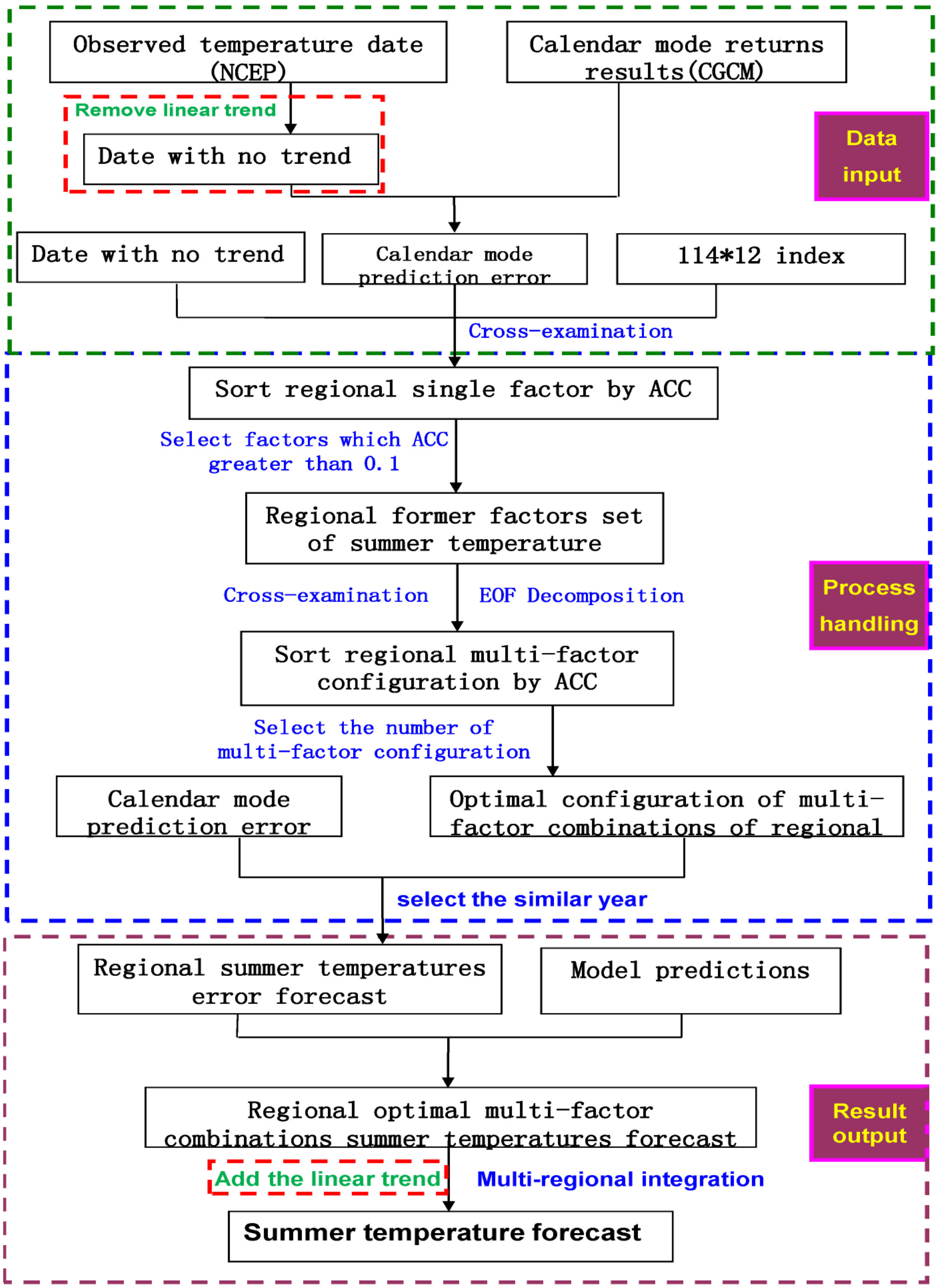

Figure 2. The process of model error correction after removing the linear trend.

main component is taken as the selection basis of similar years so as to get the optimal two-factor combination. In the case of three-factor portfolio, the two obtained optimal factors are taken as the first two factors, and the remaining factors in the pre-factor set are selected with the first two factors to get the three-factor portfolio with the best correction effect by the EOF decomposition method. Through analogy, the optimal multi-factor portfolio is obtained. By testing regions, the correction effect is primarily the best in the selection of optimal 10-factor portfolio.

Result output: EOF decomposition is carried out on the forecast years for configuration in accordance with the above-described optimal factor portfolio, and four similar years are selected on the basis of time coefficient. The model error average of these four similar years is taken as the model error value of the forecast year, combined with model forecast results to obtain the forecast results of the forecast year. The forecast results were added to the previously removed change trend of observed temperature to synthesize China's regional correction results, thus obtaining the final summer temperature forecast results of the forecast year.

3 CHANGE CHARACTERISTICS ANALYSIS AND TREND PROCESSING OF CHINA'S SUMMER TEMPERATURE

3.1 *Change trend analysis of China's summer temperature*

Through the analysis on China's summer temperatures for 1983—2012, it is found that the observed temperature has an increasing trend year by year. Fig.3 shows the distribution of national averages of China's summer observed temperatures and model forecast temperatures in the three decades. It can be seen from the figure that national summer average temperature shows a significant multi-year rising trend. However, the model forecast average summer temperature is about 19.3℃ in the three decades with a small interannual fluctuation, making it difficult to forecast the trend.

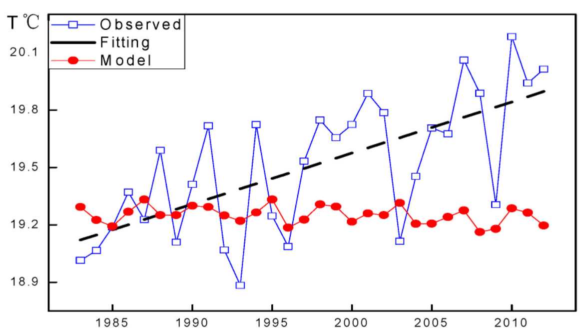

Figure 3. The average temperature of observed and model results for 1983—2012.

In order to quantitatively describe the level of regional warming trend, the climate trend coefficient is r_{xt} calculated, which is defined as the correlation coefficient between element sequence at the n moments (years) and the natural sequence of 1, 2, 3, ……, n.

Through calculating the climate trend coefficients of China's regional summer observed temperature, model forecast and model error temperatures, it is found that the climate trend coefficients of China's summer observed temperatures in most regions are significant at the 0.05 level. Especially in East China, South China, Northeast China and most of the Xinjiang region, the climate trend coefficient is significant at the 0.01 level. It is indicated that the summer temperatures in most China shows a rising trend in the decades, and the warming trend is particularly significant in the above-mentioned areas. Fig.4b shows the distribution of climate trend coefficients of the temperature results forecast by CGCM model of National Climate Center in the decades. The results reveal that the current model forecast temperature results are unable to simulate well the rising trend of China's summer temperature under global warming, and almost no trends exist in the regions. Therefore, it needs to correct the system defect in the post-processing of model forecast results.

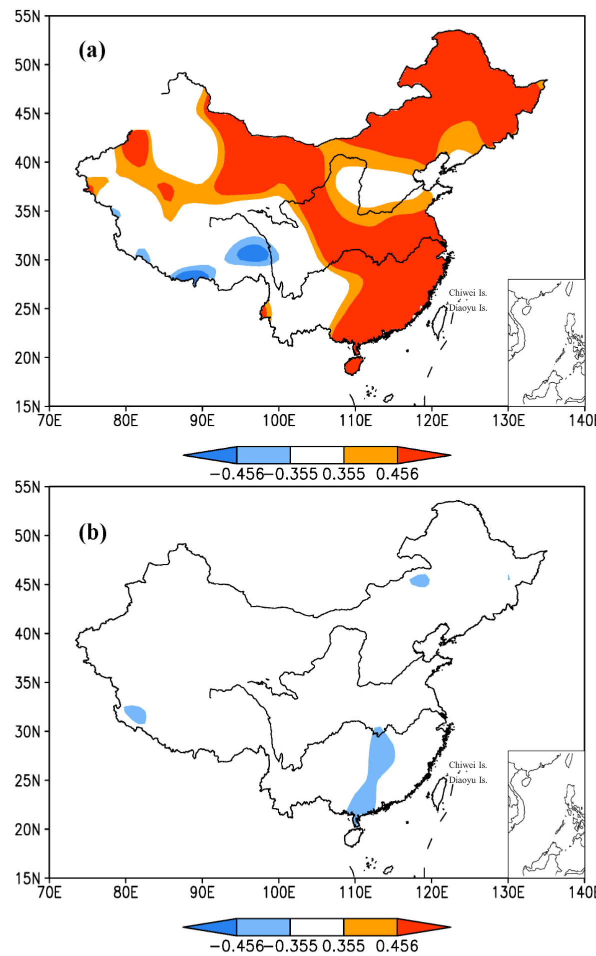

Figure 4. The climate trend coefficient of summer temperature from 1983 to 2012 passing the 0.05 significance test. a: observed; b: model.

3.2 *Linear trend fitting of China's summer temperature*

Through the above research, it is obtained that the observed temperature in 1983—2012 showed a significantly rising trend. In order to understand this trend more intuitively, the climate trend rate was used in this study for fitting analysis on the linear rising trend of observed temperatures in the three decades to quantitatively analyze the warming trend of each region. The climate trend rate is defined as slope a_1 multiplied by 10[35-40]. According to the regression theory,

$$a_1 = r_{xt}\frac{\sigma_x}{\sigma_t} \tag{4}$$

where σ_x is the mean squared error of element x, and σ_t is the mean squared error of the series 1, 2, ⋯, n. Accordingly, the climate trend rate of $a_1 \times 10$ can be obtained from the climate trend coefficient r_{xt}.

Figure 5 shows the national distribution of climate trend rates of observed and model temperatures for 1983—2011. The climate trend rate of observed national summer average temperature was 0.27 ℃ per decade, while that of model forecast was −0.011 ℃ per decade. Both are similar in national distribution pattern and climate trend coefficient. It is found from the observed distribution that most of China shows a positive climate trend, except for a minor part of southwest region with a negative climate trend rate. It is also indicated that the temperatures of the three decades showed a significantly linear rising trend in most of China. However, the climate trend rate of model temperature was very small, equal to 0 ℃/decade, so that its trend change may not be considered.

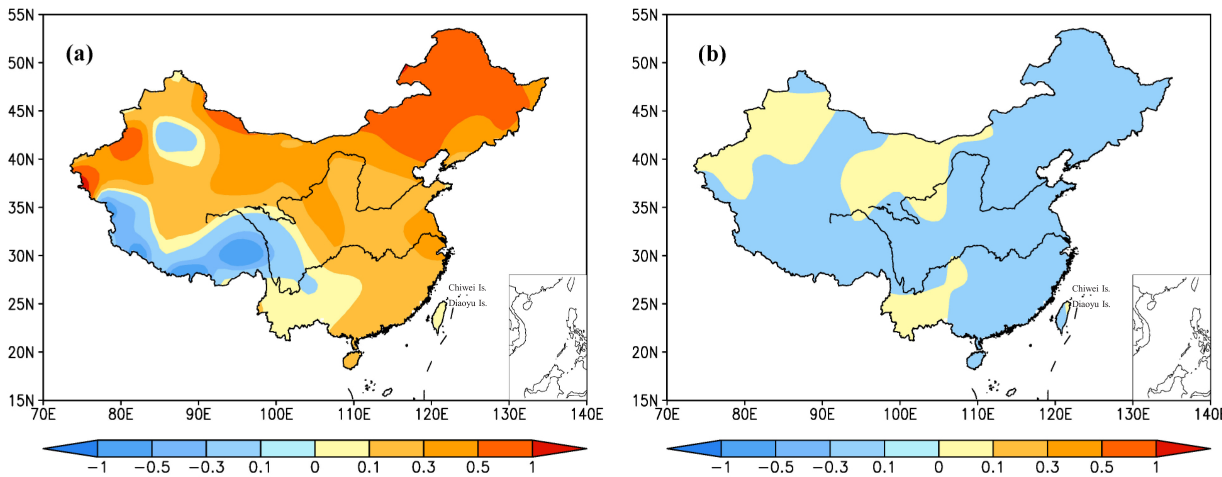

Figure 5. The climate trend rate of summer temperature from 1983 to 2012. a: observed; b: model.

3.3 *Removing and adding method of linear trend prior and posterior to model forecast error correction*

It is proven in the content above that the trend of temperature will affect the correction method of model forecast error. Therefore, it needs to consider the impact of such trend on the correction and modify during error correction of model forecast temperature result.

The approach taken in this study is to first remove such linear warming trend from the observed temperature data. Annual increasing trend term is removed since 1983.

$$X_t=S_t-a_1t \quad t=1, 2, 3, \cdots\cdots, n \text{ (year)} \tag{5}$$

S_t is the observed data in the t-th year, and X_t is the temperature data after removing the trend in the t-th year. For the 375 grids over the China region, the observed temperatures in the past three decades were processed to obtain new temperature data X according to Equation 2.

Removing the trend of observed summer temperatures aims at making the observed temperature more stable and reducing the impact of summer temperature rise. However, such trend of observed temperature exists in fact. After avoiding the effects of linear increasing trend on model forecast error correction, it needs to include the original warming trend based on the corrected results with the linear trend removed so as to obtain the final forecast results. The linear trend can be added according to Equation 3.

$$Z_t=W_t+a_1t \tag{6}$$

W_t is the result of model forecast error correction of the observed data and model data after removing the linear trend, and Z_t is the corrected result of final model forecast error.

4 EFFECT CONTRAST PRIOR AND POSTERIOR TO METHOD IMPROVEMENT

4.1 *Application of removing the linear trend of observed data in the dynamics−statistics correction method with optimal multi−factor portfolio*

It is analyzed above that due to the defect in temperature model results in simulating the trend of global warming, model error correction method has no ideal forecast effect, and a solution is proposed to avoid substantial modification on numerical model framework. In this section, the dynamics-statistics correction method with optimal multi-factor portfolio is used for quantizing independent sample return forecast in 2003—2012 to analyze the impact of global warming on China's summer temperature forecast.

Figure 6a shows the comparison of ACC between direct forecast and the forecast with removal of warming trend. The results reveal that the forecast with the removal of warming trend is significantly improved compared with the direct forecast except 2003. The correction effects of direct forecast are better in 2004 and 2011, while those of 2009 and 2012 are worse, of which the decadal ACC average is 0.07, indicating that the overall result is not satisfactory. The forecast with the removal of warming trend is better in 2007, 2010 and 2011, of which the ACC values are all higher than 0.7. However, the forecasts in the two years are with abnormally low temperature, of which the ACC values

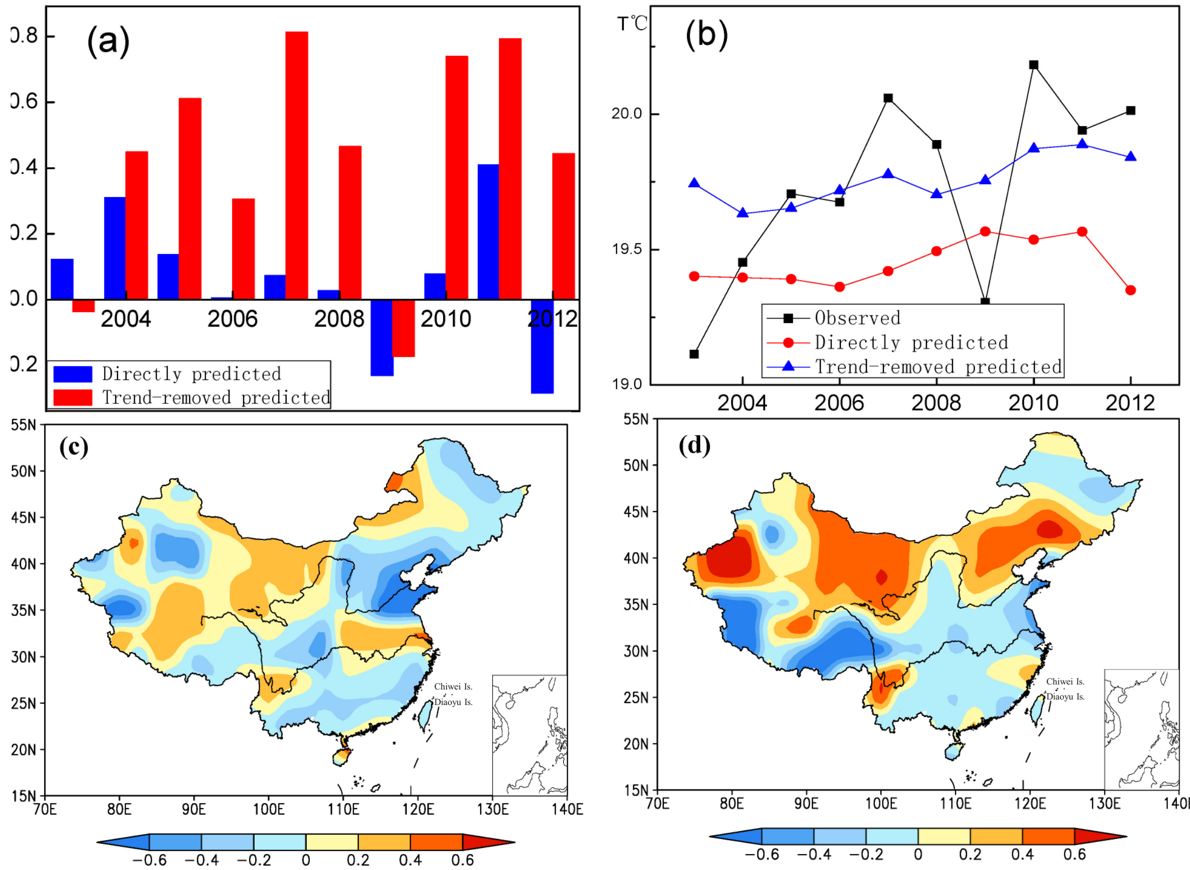

Figure 6. Comparison of direct forecast with trend-removed forecast from 2003 to 2012.

are negative, and the decadal ACC average is 0.44, greatly improved compared to the direct forecast.

Figure 6b shows the distribution of temperature averages with China's summer observed, directly forecast and trend-removed forecast in the period from 2003 to 2012. The results reveal that except for 2003 and 2009 which were with abnormally low temperature, directly forecast results are significantly lower than the observed summer temperature average, especially in 2007 and 2010. The decadal summer average of observed temperature is 19.73℃, while that of directly forecast result is 19.45℃, lower by nearly 0.3℃. It is found through analysis that due to insufficient simulation of model result on global warming trend, a warming trend exists in model error, leading to systematic bias of model error correction results. This problem can be solved by removing the warming trend of observed temperature. The decadal summer average is 19.75℃ , indicating the necessity of removing warming trend in temperature forecast from the perspective of summer average.

Figure 6c and 5d show the TCC (temporal correlation coefficient) distribution of directly forecast result and warming-trend-removed forecast result with observed temperature in the latest decade respectively. The results reveal that the correlation of warming-trend-removed forecast results with observed temperature is significantly higher in North China, Northeast China and Inner Mongolia region than that of directly forecast results. However, these regions show the most significant rising trend of observed temperature in the three decades, laterally indicating that it needs to remove multi-year warming trend in the forecast of China's summer temperature.

Two different ideas, i.e., direct forecast without considering the impact of temperature trend on forecast effect and error correction with removing linear trend of observed temperature, are combined with dynamics-statistics similarity error correction method to comparatively analyze the impact of global warming on China's summer temperature forecast. The results show that the warming trend of China's summer temperature leads to a significant bias between directly corrected results and observations. However, the method of first removing linear trend and then adding it posterior to forecast can effectively solve the problem of lower direct forecast. The corrected results are superior in both spatial correlation of each year and multi-year temporal correlation, able to effectively apply the optimal multi-factor portfolio dynamics-statistics-combined forecast method to seasonal temperature forecast.

According to the process handling, top 30 factors are chosen as the key factors to every region, which are sorted by EOF decomposition method. Due to the limitation of text, only top five factors are given in Table 1 after being sorted from 1983 to 2012. The main factors that affect the Chinese summer temperature are snow area, subtropical high, solar vortex and SST of warm pool area index. These factors can help us forecast effectively in operation.

Table 1. The top five factors in the eight regions.

Region	First factor	Second factor	Third factor	Fourth factor	Fifth factor
1	North Pacific Pattern (NP)	Indian Ocean warm pool area index	Atlantic intergenerational oscillation index for years	North Atlantic subtropical high	Snow area of northeast
2	snow cover area in the northern hemisphere	tropical north Atlantic SST index	Indian Ocean warm pool area index	Pacific subtropical high area index	Atlantic subtropical high ridge line in North America
3	Atlantic subtropical high area index of North America	Equatorial Upper 300m temperature Average anomaly (180°—100°W)	North Africa subtropical high area index	Atlantic subtropical high intensity index of North America	Eurasian snow cover
4	snow cover area in the northern hemisphere	Kuroshio SST index	Snow area of northeast	Pacific subtropical high ridge line	AAO
5	western Pacific warm pool area index	Atlantic European polar vortex intensity index	Pacific trade wind index in 850 hPa	Pacific subtropical high ridge line	Atlantic subtropical high the north side
6	western Pacific warm pool area index	Atlantic intergenerational oscillation index for years	western Pacific warm chi area index	50 hPa zonal wind index	intensity of polar vortex center of the northern hemisphere
7	western Pacific warm pool area i index	sea ice intensity of the northern hemisphere	western Pacific warm chi area index	sea ice intensity of the northern hemisphere	western Pacific warm chi area index
8	sea ice intensity of the northern hemisphere	northern hemisphere polar vortex center weft position	East Asian trough position	European Atlantic circulation type E	Sea surface temperature anomaly index in NINO z

4.2 *Case year analysis*

From the overall perspective of ACC, TCC and summer average of decadal independent sample return forecast, the impacts of removing rising trend of observed temperature on China's summer temperature forecast are analyzed in the previous section. In this section, 2011 is taken as a case year to analyze the impact of global warming on summer temperature.

Figure 7 shows the observed temperature in 2011 and the forecast results of two different forecast schemes. In 2011, China's summer temperature is characterized by the distribution of being warmer in northern China while being colder in Tibet and some southwestern regions, of which the average is 19.94 ℃. Fig.7 (b) shows the model result that includes the warming trend in 2011 and the effect of forecast is not so good. It is obviously warmer than observed results in northeast and eastern regions, and the symbol of temperature anomaly is opposite to the observed results in Inner Mongolia and south China regions, of which ACC is 0.21, and the summer average is 17.43 ℃. The directly forecast results are deficient to forecast the warmer characteristics of northeast regions, especially in the forecast results of northern northeast regions, which are contrary to the observed results. However, a deficiency also exists in forecasting the warmer characteristics of Inner Mongolia and northwest regions, of which ACC is 0.41, and the summer average is 19.56 ℃, significantly lower than the observed temperature. The forecast results with removing the rising trend of observed temperature can not only reflect the characteristics of being warmer in the north but colder in the southwest and Tibet, but also qualitatively forecast the warming and cooling degree, of which ACC is 0.79, greatly improved as compared with directly forecast results, while the national average is 19.89, closer to the observed results.

The case analysis for 2011 shows that the directly forecast results are not sufficient in qualitative judging various regions, because the forecast results are definitely contrary to the observed temperature in some areas, and a deficiency also exists in the forecast of warming or cooling degree of most regions. The forecast results with removal of warming trend are significantly better than that of the directly forecast results. It is proven from the case that global warming has a greater impact on model error correction method. In the forecast on China's summer temperature, it needs

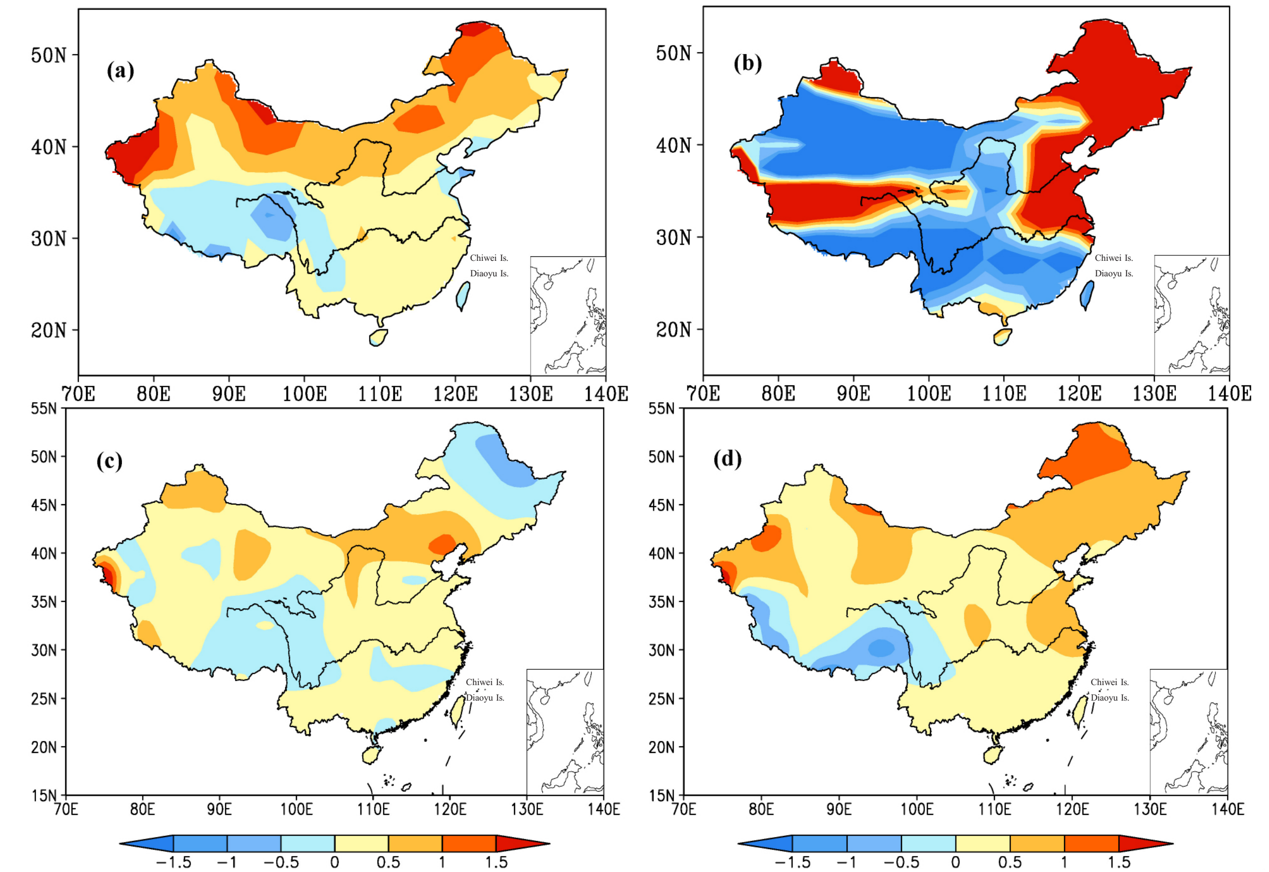

Figure 7. The anomaly of the summer in 2011. a: observed result; b: model result including warming trend; c: direct forecast; d: trend-removed forecast.

to remove the rising trend of observed temperature.

5 CONCLUSIONS

Based on the previous application to China's short-term climate forecast, the dynamics-statistics forecast method is attempted to be used for China's summer temperature forecast in this study, combining the characteristics of summer temperature. It is found that the rising trend of observed temperature has a significant impact on the effect of dynamics-statistics forecast method. Therefore, a linear trend-removed method is applied to remove the rising trend of observed temperature, which obtains the non-trend sequence and avoids the trend change of observed temperature in model error correction process in this study. On this basis, a dynamics-statistics forecast is carried out to obtain non-trend forecast results, and then add it to the original warming trend to get final forecast results, significantly improving forecast results. The main conclusions are shown as follows:

(1) China's summer temperature shows a general rising trend in the three decades. The climate trend coefficient is used to analyze the warming trend of various regions in China. It is found that most Chinese regions are warming up significantly, especially in Northeast China, Inner Mongolia and the entire eastern regions, while some regions such as Southwest China show a multi-year cooling trend. Moreover, a linear fitting is applied to carry out trend quantification for each grid data. It is indicated from the analysis of CGCM model temperature by National Climate Centre that no significant trend change exists, leading to a warming trend of model forecast error between observed and model temperature, which has a likely impact on the summer forecast method, with model forecast error correction requiring a reference of historical model forecast error values in available years.

(2) The linear fitting trend of China's summer temperature in the three decades is removed to eliminate the rising trend of model error in this study. The results show that this method has significant effects. The climate trend coefficient of temperature data after the removal of trend is not significanct at the 0.05 level except an extremely small portion of the regions. It is indicated that the trend-removed method is effective in avoiding the deficiency of model results to simulate global warming by use of dynamics-statistics-combined model error correction method.

(3) The dynamics-statistics-combined correction method with optimal multi-factor portfolio is used for summer temperature forecast. It is found that the

warming-trend corrected results of model forecast error are significantly lower than that of the observed temperature. The linear trend is first removed, and then the correction method with optimal multi-factor portfolio is used for model forecast error correction, and finally the linear trend is included again. This method is able to remove the impact of linear trend of observed temperature on correction method, and effectively solve the problem of lower directly corrected results. The national average temperature of corrected results in a case year is compared by ACC and TCC of corrected effects, proving the necessity and importance of removing linear trend of observed temperature in summer temperature forecast.

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