Reliability Analyses of Anomalies of NCEP/NCAR Reanalyzed Wind Speed and Surface Air Temperature in Climate Change Research in China*

SHI Xiaohui[1†](施晓晖), XU Xiangde[1] (徐祥德), and XIE Li'an[2] (谢立安)

1 *State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing* 100081*, China*

2 *Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh NC* 27695-8208*, USA*

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ABSTRACT

By means of varied statistical methods, such as normalized root mean square error (RMSE), correlation analysis, empirical orthogonal function (EOF) decomposition, etc., the reliability of the varied seasonal anomalies of NCEP/NCAR reanalyzed wind speed and surface air temperature (SAT) data frequently used in the climate change research in China is studied. Results show that RMSEs of meteorological variables are smaller in eastern China than in western China, i.e., the reliability of NCEP/NCAR reanalysis in eastern China is better than that in western China. This could be due to effects of the topography in the reanalysis model and the disposition of "dense-in-eastern-and-sparse-in-western" of meteorological stations in China. The RMSE of anomalies of reanalyzed wind speeds decreases with increasing height, further confirming the possible impact of topography on reliability of reanalysis. Results of correlation analysis inversely correspond to those of RMSE analysis, i.e., if the RMSE is larger, the correlation between reanalyzed and observed data is worse, and vice versa. It is found from comparing the EOF eigenvectors of anomaly of reanalyzed and observed data that if a meteorological variable has smaller RMSE, the spatial patterns of corresponding EOF eigenvectors of anomaly of reanalyzed and observed data are similar and their time coefficients are significantly correlated, and vice versa. Therefore, the similarity of EOF modes and the consistency of their time coefficients can be used to objectively assess the reliability of the reanalysis. On the whole, the reliability of the reanalyzed wind speed is better in spring, summer, and autumn, but worse in winter; and for the reanalyzed SAT, it is the best in winter and the worst in summer.

Key words: NCEP/NCAR reanalysis, RMSE, correlation analysis, EOF decomposition, data reliability

1. Introduction

In the early 1990s, the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) began the "NCEP/NCAR Reanalysis Project" (NNRP) (Kalnay et al., 1996). About 60-yr (from 1948 to present) reanalysis for global meteorological observation has been accomplished, becoming the longest reanalysis datasets used in climatic research. It is widely applied in the work of climatic diagnosis, East Asian monsoon, water cycle, etc. It is also used as the initial and boundary conditions of regional climate model in the climatic simulation and prediction, or to verify the numerical model (Zhang et al., 1997; Annamalai et al., 1999; Zhang and Qian, 1999; Xiong, 2001; Wang, 2003; Tao et al., 2001; Xu et al., 2002; Wu and Xie, 2003; Ding and Hu, 2003; Qian et al., 2004; Miao et al., 2005).

Kalnay et al. (1996) introduced integrally the working flow, involved data, and the assimilation system of NNRP. Investigating the reliability of NCEP/NCAR reanalysis (the brief reanalysis), they revealed that the upward/downward shortwave and outgoing longwave radiations at the top of the atmosphere from the reanalysis during 1985-1989 agree with the climatological estimates, but the upward shortwave radiation is 11 W m^{-2} stronger than the climatological estimates. At the surface radiation and heat

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†Corresponding author: sxh@cams.cma.gov.cn.

budget, surface fluxes are close to the climatological estimates, except that the atmosphere loses additional 5.5 W m^{-2} to the surface. The atmosphere loses more energy in the top and surface, which is consistent with the slight cooling in NCEP model. The zonal-mean and regional distributions of surface fluxes in the reanalysis also appear to be consistent with climatological estimates.

Considering the significant impacts of the quality and reliability of reanalysis on the confidence of the climatic diagnosis, the stability and simulation/prediction results of climatic model, many meteorologists, by different methods and from various viewpoints, assessed the reliability of different variables from reanalysis (Basist, 1997; Poccard et al., 2000; Shen et al., 2001; Reid et al., 2001; Josey, 2001; Renfrew et al., 2002). Focusing on China, Zhao et al. (2004) compared the reanalysis and observation in China, and found that the monthly mean reanalyzed temperature data are generally lower than observations, but the monthly total precipitation data are higher. Involving the seasonal variation, the reliabilities of summertime and annual mean reanalysis are better than those of wintertime. Su et al. (1999) checked the reliability of reanalysis in the Tibetan Plateau (TP) and adjacent areas. According to the results, the reanalyzed temperature, pressure, wind, humidity, and precipitation are similar to the climatological observation, suggesting the basic reliability of the reanalysis in the TP. Other results (Song et al., 2000; Wei and Li, 2003a, b; Li et al., 2004) show that the reanalyzed surface air temperature (SAT) is systematically lower than the observation over the TP, while the precipitation is higher. Even though, the annual variations of SAT and precipitation are mostly held. The interannual variations of SAT and precipitation over the TP are also well depicted in the reanalysis. The reanalyzed surface heat fluxes in the TP can also represent the annual and interannual variations of surface heat source intensity in the TP. Furthermore, these researches revealed that the main cause for the cooling in the reanalysis is the difference of topography height in reanalysis model from the altitude of observatories. The higher reanalyzed surface albedo on the snow cover leads to the lower surface net radiation in winter and enhances the difference of wintertime SAT. Summing up above results, the reanalysis can well reproduce the annual and interannual climate change, reliable to a certain extent.

Now, the uncertainty of the reanalysis in the long-term climatic variation has been attracted more attention. Many overseas researchers (Santer et al., 1999, 2000; Curt et al., 2002) investigated and found that there exist some uncertainties in reanalyzed air temperature at lower-middle levels of troposphere. Xu et al. (2001) analyzed the confidence of reanalyzed surface pressure and SAT in recent 50 years in the climatic change study of China, and revealed that there are some uncertainties in studying the trends of climatic change, in which the confidence of SAT is better than that of surface pressure. However, the confidences of other reanalyzed variables have not been investigated in their work. In this paper, the observed wind speed from 147 sounding stations and SAT from 160 surface observatories in China will be selected and interpolated to $2.5° \times 2.5°$ gird as same as that of the reanalysis. Then, different will objective analysis methods will be applied to compare the reanalysis and observation, to investigate the difference between them and assess the reliabilities of reanalyzed wind speed and SAT in China, primarily focused on the reliabilities of their anomalies.

2. Data and methods

2.1 Treatment of data

The data used in this paper are: (1) the 1978-2003 wind direction and speed data with twice daily at 850, 500, and 200 hPa in 147 sounding stations in China provided by the National Meteorological Information Center of China Meteorological Administration (NMIC/CMA). The monthly and seasonal mean values of the zonal and meridional winds are derived from the daily data and interpolated to $2.5° \times 2.5°$ grid matching with the reanalysis by means of Cressman objective analysis; (2) the 1961-2000 monthly mean SAT data in 160 surface observatories in China also provided by NMIC/CMA. Calculated seasonal mean values are also interpolated to $2.5° \times 2.5°$ grid by the above method; and (3) the reanalyzed monthly mean zonal and meridional winds at 850, 500, and 200 hPa, as well as SAT, provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at <http://www.cdc.noaa.gov>. The seasonal mean values are calculated too, and their durations are consistent with the observation.

2.2 Methods

For quantitatively understanding the difference between the reanalysis and observation, the normalized root mean square error (RMSE) of reanalyzed elements from observed data in a grid is calculated respectively, which is defined as

$$E = \frac{1}{\delta_{\rm r}}\left[\frac{1}{N}\sum_{n=1}^{N}(f_n - r_n)^2\right]^{1/2}. \tag{1}$$

The normalized RMSE of their anomalies is also calculated, defined as

$$E' = \frac{1}{\delta_{\rm r}}\left\{\frac{1}{N}\sum_{n=1}^{N}\left[(f_n - \overline{f}) - (r_n - \overline{r})\right]^2\right\}^{1/2}. \tag{2}$$

Variables f and r in Eqs.(1) and (2) are the reanalyzed and observed data, respectively. N is the sample size and $\delta_{\rm r}$ is the standard deviation (SD) of observed data.

The correlation analysis and empirical orthogonal function (EOF) decomposition are also used to study the consistency of the climate trends of reanalyzed and observed data.

3. Results of RMSE and correlation analysis

3.1 SAT

Investigating the normalized RMSE of reanalyzed SAT in spring, summer, autumn, and winter during 1961-2000 (Fig.1), we can find that the errors of reanalyzed SAT are obvious in the four seasons, while

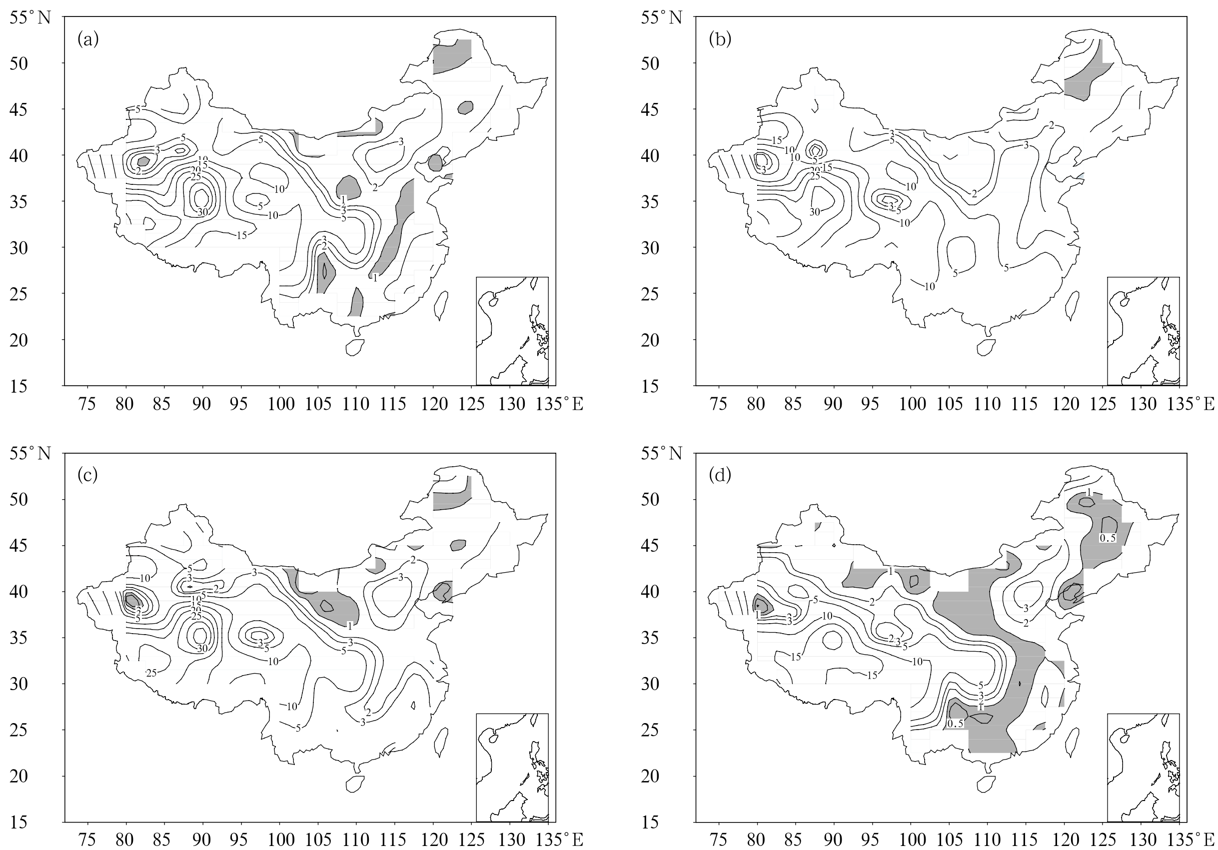

Fig.1. Normalized root mean square errors (RMSEs) of the reanalyzed SAT. (a) Spring, (b) summer, (c) autumn, and (d) winter. Values⩽1.0 are shaded.

the error in winter is a bit smaller than that in the other three seasons. Viewed from their spatial distribution, the RMSE in the TP is the most significant with large values 10-30 times of the SD of observed SAT in part areas. The possible cause is the great difference of the topography between the reanalysis model and observed, as well as the sparse surface observatories in the TP (Wei and Li, 2003a). The RMSE in East China is generally 2-3 times of the SD of the observed SAT, but the RMSE of South China in summer is more evident, beyond 5 times of the SD of observed SAT.

According to the definition of the normalized RMSE, the value larger than 1.0 denotes that the RMSE of reanalysis in a gird exceeds the SD of the observed data, i.e., the error of reanalysis is obvious, and vice versa. The above results show that reanalyzed SAT is markedly different from the observed SAT in magnitude.

Compared Fig.1 with Fig.2, the RMSEs of anomalies of reanalyzed SAT are obviously smaller than those of original reanalyzed SAT. The most significant decreasing of RMSE appears in the TP where the largest RMSE is only 1.5 times of the SD anomalies of observed SAT. In other regions, the RMSEs are mostly lower than the SD anomalies of observed SAT. In the four seasons, the RMSE is the greatest in summer, and less in autumn and winter (Fig.2). That is to say, although the original reanalyzed SAT has a remarkable error, the error of its anomaly is much smaller.

Correlation analysis is adopted to investigate the consistency of the interannual variations of the SAT from the reanalysis with that from observations. Figure 3 shows the correlation coefficients between reanalyzed and observed SATs in various seasons during 1961-2000. The correlations between the reanalyzed and observed SATs in eastern China are sufficiently significant in all of the four seasons, passing the

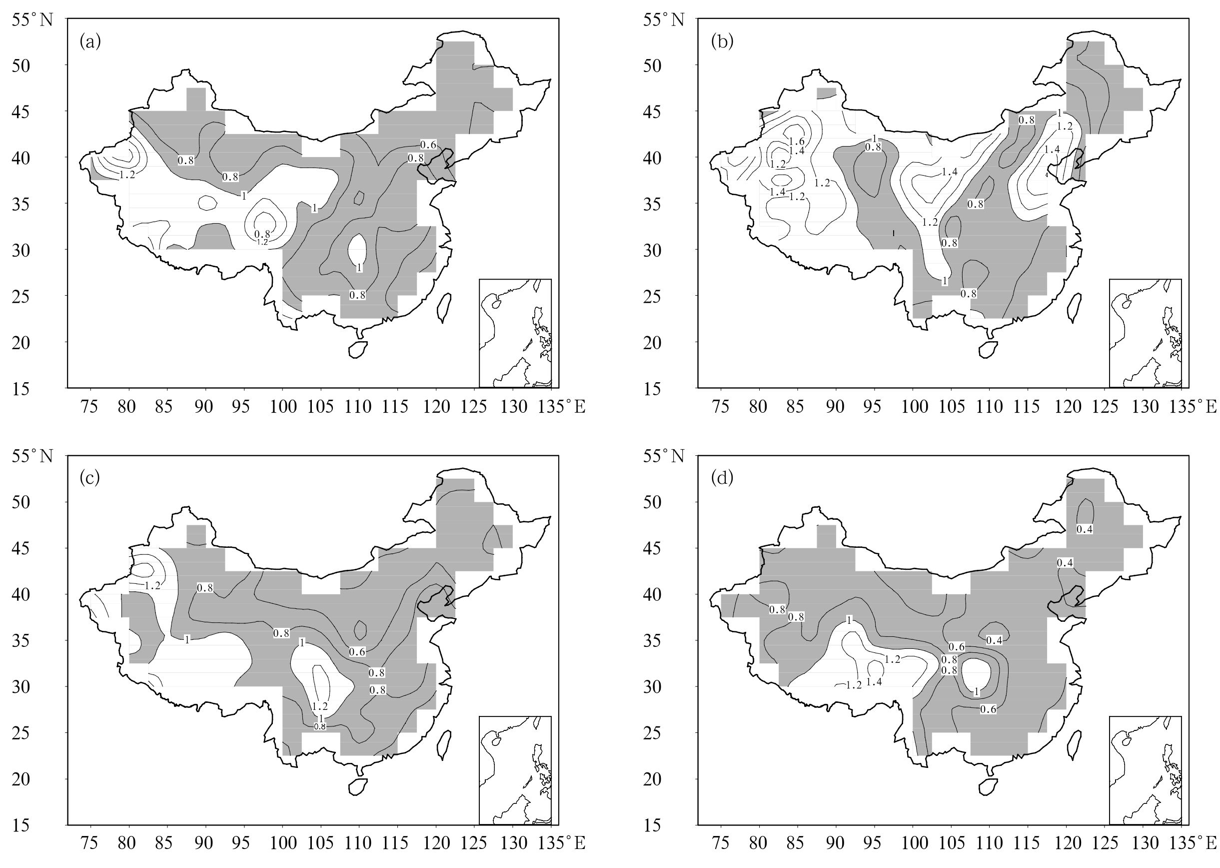

Fig.2. Normalized RMSEs of the anomalies of the reanalyzed SATs. (a) Spring, (b) summer, (c) autumn, and (d) winter. Values⩽1.0 are shaded.

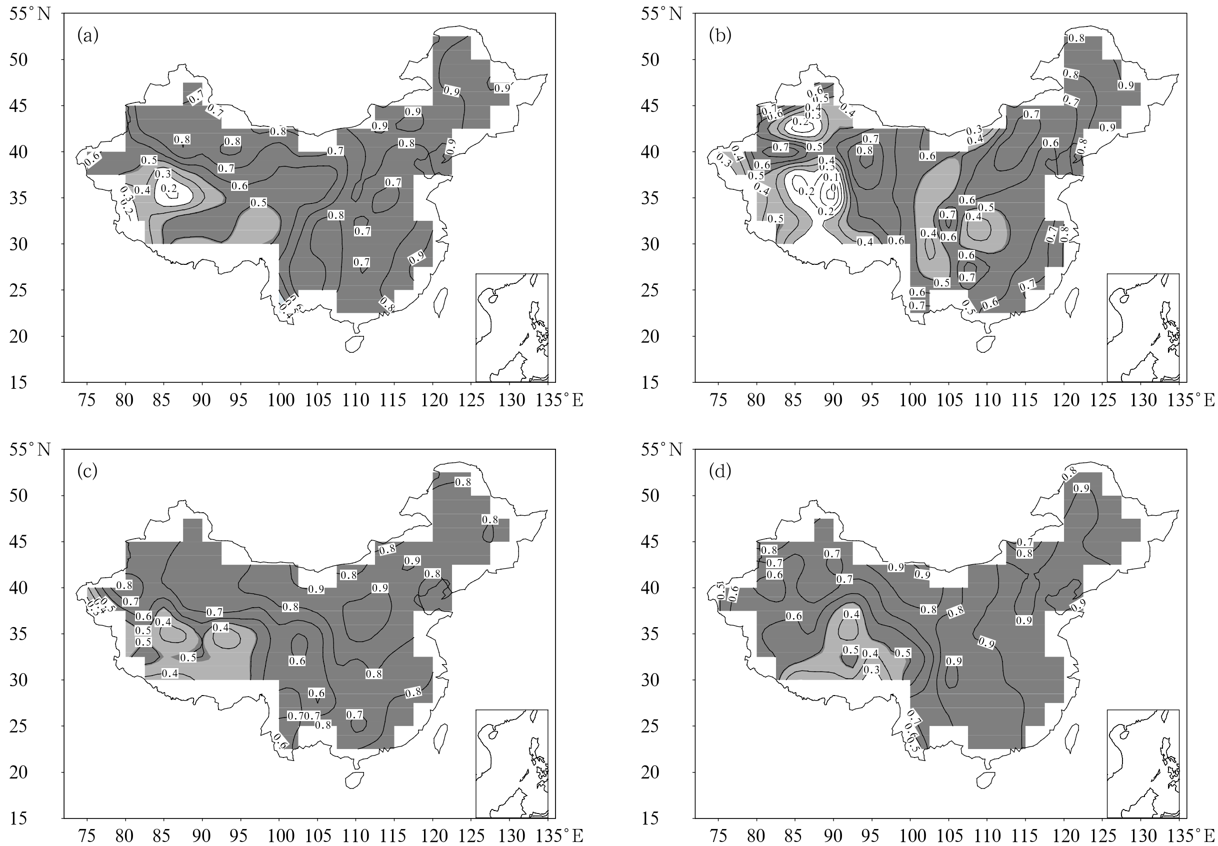

Fig.3. Correlation coefficients between reanalyzed and observed SATs. (a) Spring, (b) summer, (c) autumn, and (d) winter. Correlations passing through the test at α=0.05 and 0.001 confidence level are lightly and heavily shaded, respectively.

significance test with α=0.001. The relation in western China is a bit worse, especially in the TP. On the whole, the correlation between reanalyzed and observed SAT is the worst in summer and the best in winter.

Combined with the results of the RMSE analysis, it can be found that the reanalyzed SAT is markedly different from the observed SAT in value, but the difference between their anomalies is very small, furthermore their interannual variations are consistent, especially in eastern China. The reanalyzed SAT can be used in climatic change research in China.

3.2 Wind

In order to discuss the reliability of reanalyzed winds, we make 850, 500, and 200 hPa represent low, middle, and high levels of atmosphere, respectively.

The normalized RMSEs of the anomalies of seasonal mean zonal and meridional winds at 850 hPa during 1978-2003 (Fig.4) show that the spatial distributions of RMSEs of anomalies of zonal and meridional are similar. The RMSEs of eastern China in spring, summer, and autumn are less than the SD of observed data, but in winter, almost all regions are greater. High values of normalized RMSEs in Sichuan Basin and Northwest China in the four seasons denote large errors in these areas, related to the sparse sounding stations and complicated topography which are difficult to be perfectly described in the reanalysis model. Compared with the normalized RMSEs of original reanalyzed winds (figure omitted), the errors of anomalies of reanalyzed zonal and meridional winds are markedly less. This is consistent with the condition of SAT.

The common features of the normalized RMSEs of seasonal mean 850-hPa zonal and meridional winds

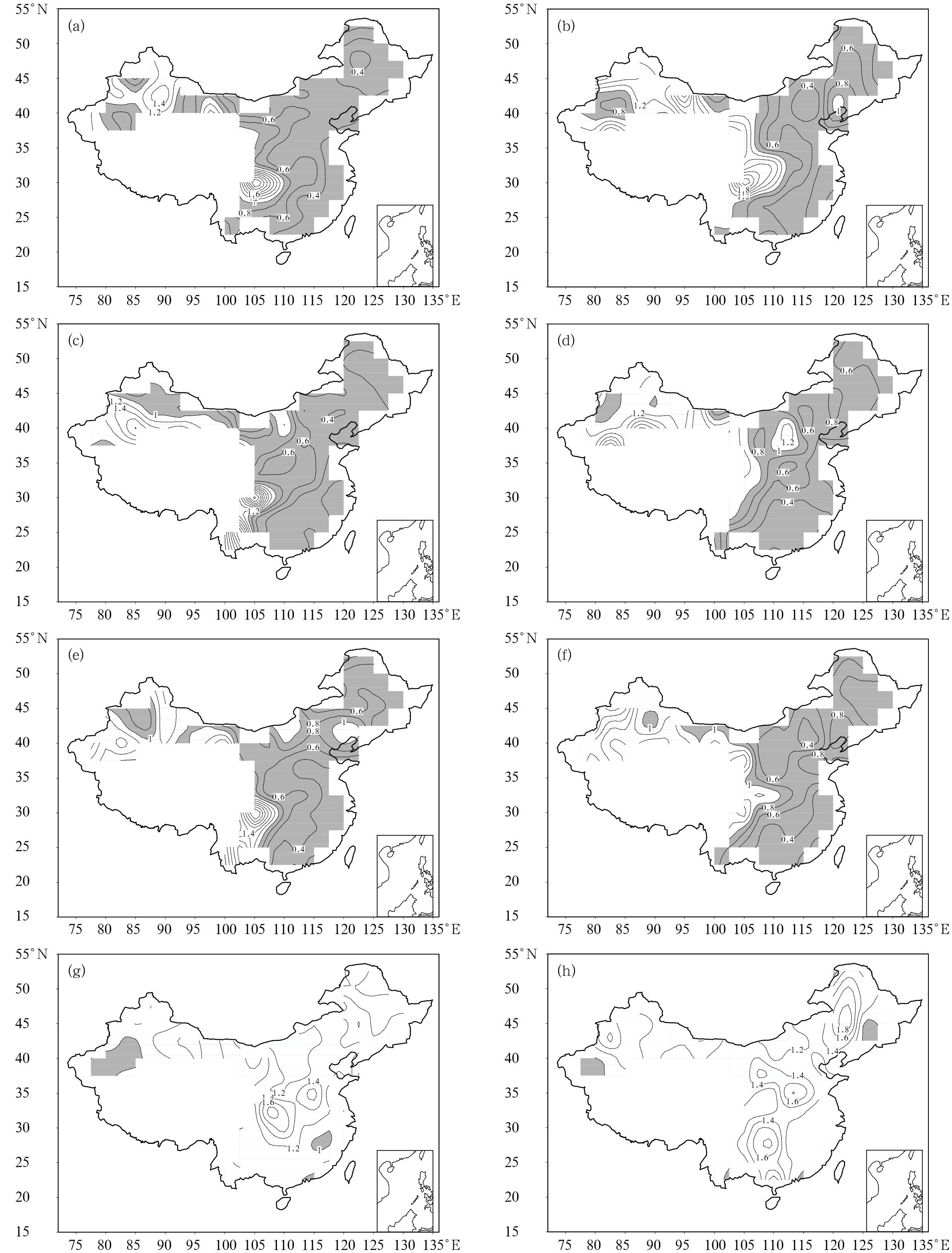

Fig.4. Normalized RMSEs of the anomalies of the reanalyzed 850-hPa zonal (u; a, c, e, and g) and meridional (v; b, d, f, and h) winds. (a), (b) Spring; (c), (d) summer; (e), (f) autumn; and (g), (h) winter. Values$\leqslant$1.0 are shaded.

reveal that the errors of reanalyzed low level wind in the eastern China are less than those in the western China, which might be a result of the conjunct influence of the topography in the reanalysis model and the distribution of "dense-in-eastern-and-sparse-in-western" of meteorological stations in China, but the reason why the errors in winter are obviously greater than those in the other three seasons needs more researches to explore.

Figures 5 and 6 are the normalized RMSEs of the anomalies of reanalyzed zonal and meridional winds at 500 and 200hPa, respectively. The feature that the errors in the eastern China are less than those in the western China can also be found. Furthermore, the normalized RMSEs of the anomalies of reanalyzed winds in different seasons and levels are still less than those of original reanalyzed winds (figure omitted). It can be found from comparison with Fig.4 that the errors of the anomalies of reanalyzed 500- and 200-hPa winds are smaller than those of 850 hPa, which denotes the decrease of the normalized RMSE of the anomalies of reanalyzed winds against increasing height, further confirming the possible impact of topography on reliability of reanalysis. On the other hand, the errors of reanalyzed winds at 500 and 200 hPa in winter are also greater than those in the other three seasons, implying the season-dependent impact of systematic error in reanalysis model on the reliability of reanalyzed winds, but its cause is unclear. The cause for the high error belt of 200-hPa reanalyzed winds in spring and autumn located at central China also needs further investigation.

The correlation coefficients between the seasonal mean reanalyzed and observed zonal and meridional winds at 850, 500, and 200 hPa during 1978-2003 are calculated, respectively. Results show that, except winter, the correlations of meridional winds at various levels in the other three seasons are significant, especially in the eastern China where it passes the test at α=0.001 confidence level. Similarly, the counterparts of zonal winds at various levels in spring, summer, and autumn are also significant, but there exists a low center at 200 hPa in spring and autumn. It agrees with the results of normalized RMSE. From the above results, such a conclusion can be drawn that except for winter, the interannual variations of reanalyzed winds are consistent with those of observed data, especially in the eastern China. The reliability of reanalyzed winds is reasonable in the eastern China, but a bit worse in winter. Due to the limitation of space, only the correlation coefficients of reanalyzed and observed meridional winds at 850, 500, and 200 hPa in summer are given in Fig.7. It can be found that the correlation at higher levels is better than that at lower levels, which agrees with the decrease of normalized RMSE of the anomalies of reanalyzed winds against increasing height.

Comparison of the results of normalized RMSE analysis with those of correlation analysis shows that, a good relationship exists between them, i.e., the larger the normalized RMSE, the worse the correlation between reanalyzed and observed data, and vice versa. This implies that there are some connections between these two analysis methods. However, some differences also exist, e.g., the correlation analysis mainly reveals the consistency of their change trends, but the normalized RMSE analysis can figure out the relative magnitude of error with some superiorities.

The results of normalized RMSE analysis of SAT and winds show that the error of reanalyzed wind is smaller than that of SAT, i.e., the reliability of reanalyzed wind is better than that of SAT. It might be related to the impact of urbanization on observed SAT to a certain extent. On the other hand, the reliability of reanalysis in eastern China is better than that in western China, which probably is a conjunct effect of the topography error in the reanalysis model and the distribution of "dense-in-eastern-and-sparse-in-western" of meteorological observatories in China.

In a word, the normalized RMSEs of the anomalies of various reanalyzed variables are less than those of original data, and thus using anomalies of reanalysis to investigate the long-term climatic trends in China is reasonable.

4. Results of EOF decomposition

EOF decomposition is a statistic method widely

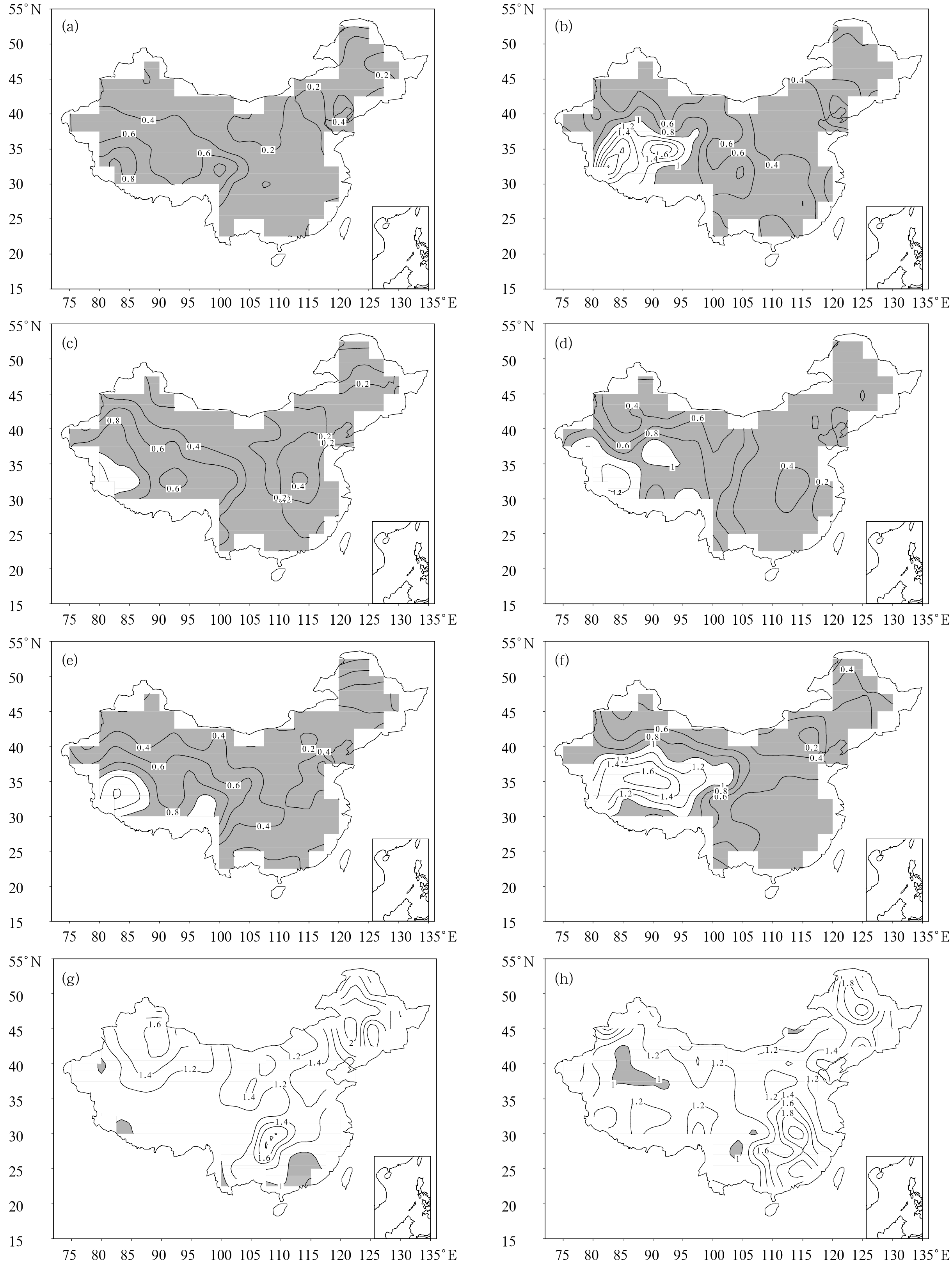

Fig.5. As in Fig.4, but for 500 hPa.

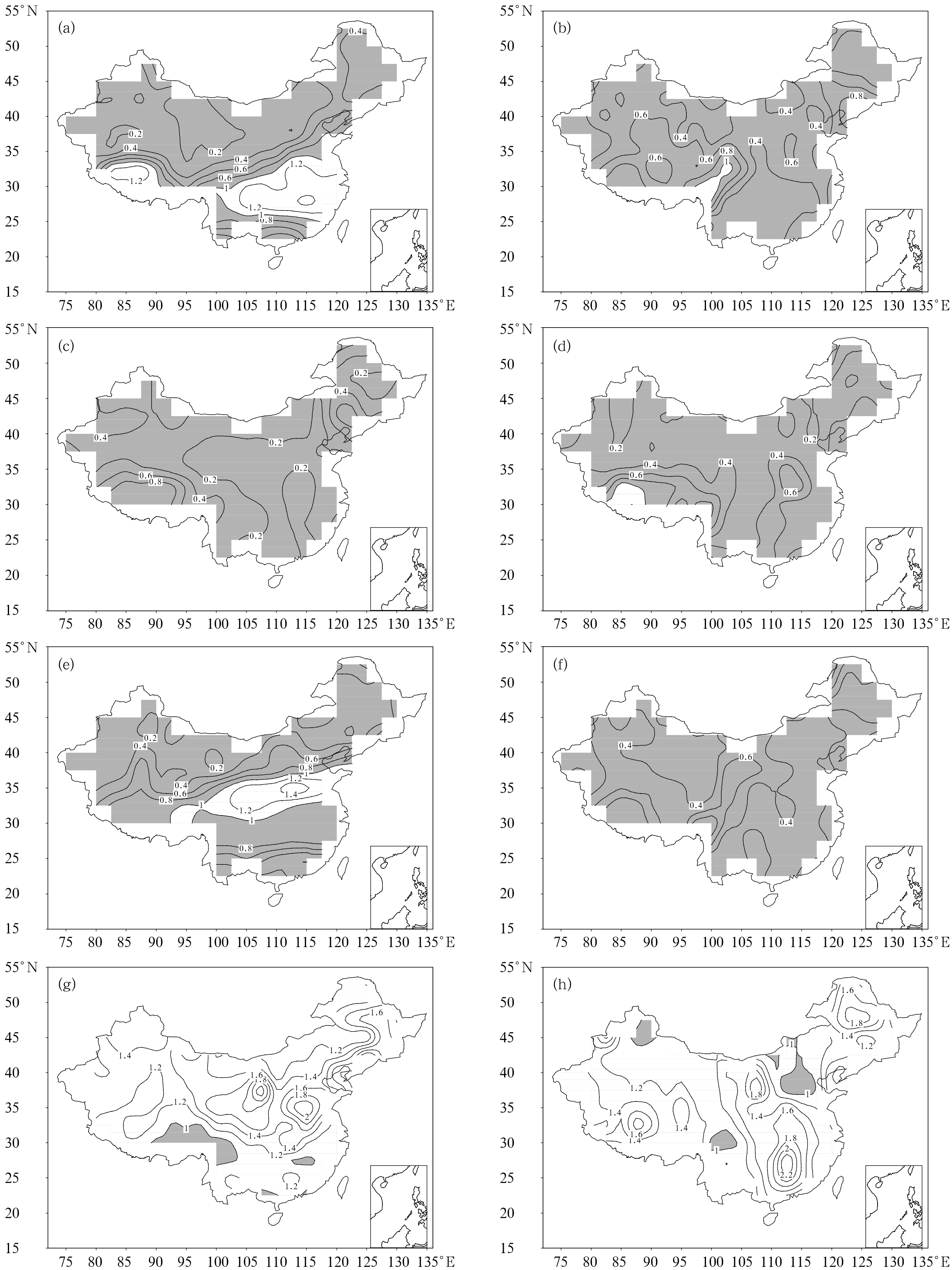

Fig.6. As in Fig.4, but for 200 hPa.

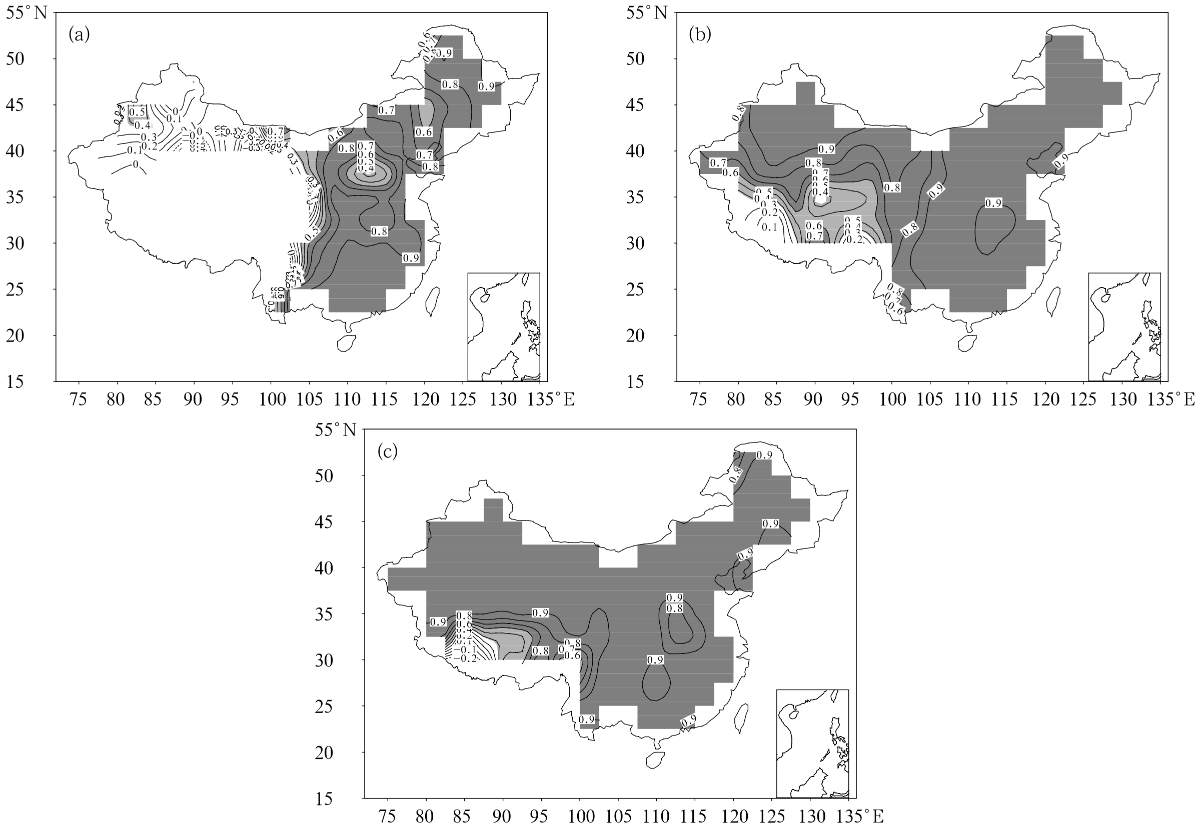

Fig.7. Correlation coefficients between reanalyzed and observed meridional winds in summer. (a) 850 hPa, (b) 500 hPa, and (c) 200 hPa. Correlations passing through the test at α=0.05 and 0.001 confidence level are lightly and heavily shaded, respectively.

used in climatic analysis. According to its fundament, the eigenvectors can characterize the distributive structures (spatial patterns) of a regional climatic variable field and the time coefficients can delineate the temporal variation of the spatial patterns. In this paper, the similarities of the spatial patterns of EOF eigenvectors of reanalyzed and observed data are analyzed to investigate whether the reanalysis data exhibit the main spatial variations of observations. Then the associated time coefficients are compared with each other to check the consistencies of temporal variations of the spatial patterns of reanalysis data with those of observations. It will help us to further understand the reliability of reanalysis by co-analyzing the EOF eigenvectors and associated time coefficients.

Figure 8 shows the spatial patterns of the first two EOF eigenvectors of the anomalies of reanalyzed and observed SATs in winter during 1961-2000. The accumulative variance contributions of these first two EOF eigenvectors of reanalysis (variance contributions are 57% and 18%, respectively) and observations (variance contributions are 57% and 15%, respectively) reach 75% and 72%, respectively. It denotes that the first two EOF eigenvectors of the reanalyzed and observed SATs can represent the primary features of the spatial patterns of themselves. It can be found from Fig.8 that the spatial patterns of reanalyzed and observed SATs in winter are very similar except for some differences in values.

The variations of associated time coefficients of the first two EOF eigenvectors indicate the consistence of the variations of the spatial patterns of reanalyzed and observed SATs in winter (only the first time coefficients are given in Fig.9). The correlation coefficients of the associated time coefficients of the first and second EOF eigenvectors are 0.9683 and 0.8730, respectively. All of them are far beyond the significant level at α=0.001. These results show that the anomalies of

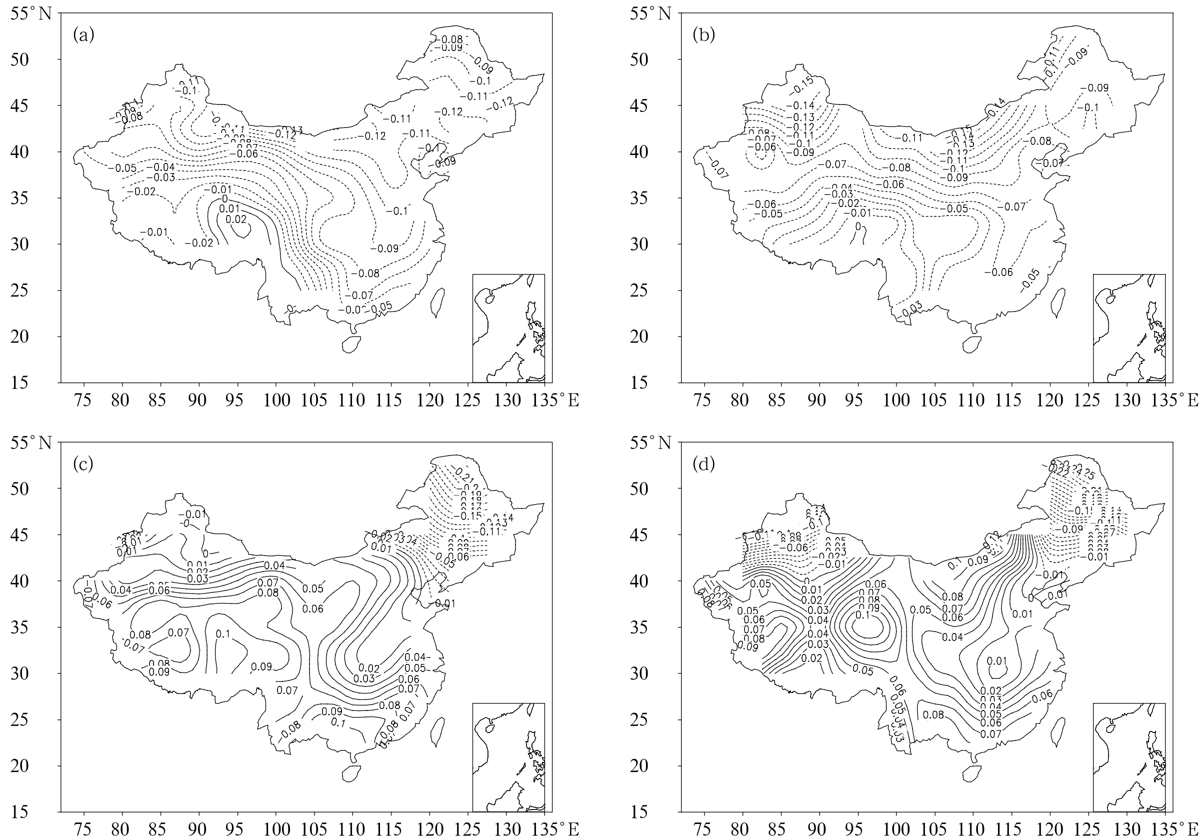

Fig.8. Spatial patterns of the first (a, b) and second (c, d) EOF eigenvectors of the anomalies of reanalyzed (a, c) and observed (b, d) SATs in winter during 1961-2000.

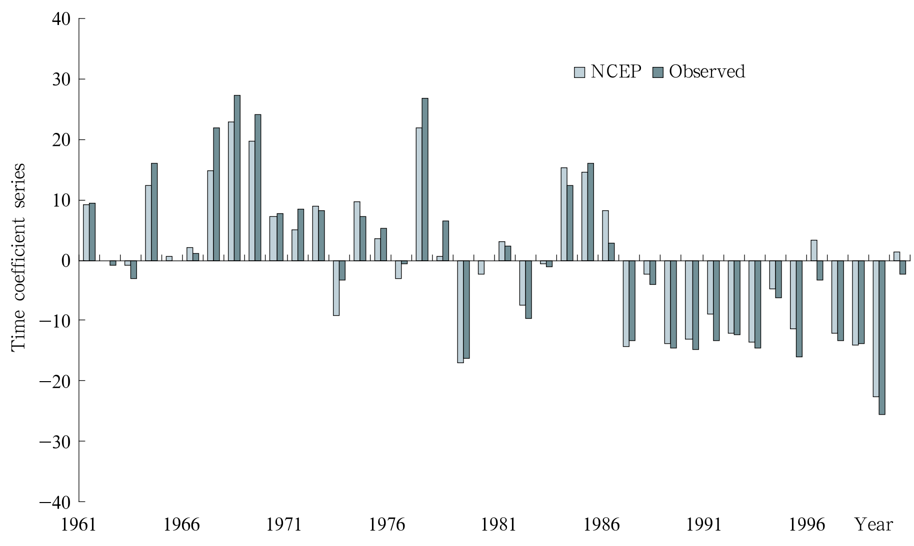

Fig.9. Time coefficient series for the first EOF eigenvectors of the anomalies of reanalyzed and observed SATs in winter during 1961-2000.

reanalyzed SAT in winter can perfectly characterize the spatial-temporal variations of observed SAT in China with reasonable reliability.

Furthermore, the spatial patterns and the correlation between the associated time coefficients of the first three EOF eigenvectors of reanalyzed and observed data for various meteorological variables are investigated. Results show that a variable with smaller RMSE has similar spatial patterns of corresponding EOF eigenvectors of anomaly of reanalyzed and observed data (figure omitted) and significantly correlated time coefficients (Table 1), such as the SATs in spring and autumn, the zonal and meridional winds at 850 and 500 hPa in spring, summer, and autumn, and the zonal and meridional winds at 200 hPa in summer. Contrarily, a meteorological variable with bigger RMSE has dissimilar spatial patterns of corresponding EOF eigenvectors of anomaly of reanalysis and observation and lower correlated time coefficients, such as the zonal and meridional winds at 850, 500, and 200 hPa in winter, and SAT in summer. The results of EOF decomposition are consistent with those of RMSE and correlation analysis. Therefore, the similarity of EOF modes and the consistency of their time coefficients can be used to objectively assess the reliability of reanalysis.

Table 1. Correlation coefficients between the time coefficient series for the first three EOF eigenvectors of reanalyzed and observed temperature and wind anomalies.

	Season	SAT	850-hPa wind		500-hPa wind		200-hPa wind	
			Zonal	Meridional	Zonal	Meridional	Zonal	Meridional
The first EOF eigenvector	Spring	0.7183	0.9260	0.7905	0.9925	0.7216	0.8971	0.5980
	Summer	0.4202	0.9740	0.9641	0.8925	0.9820	0.9741	0.9840
	Autumn	0.8862	0.7634	0.9116	0.9954	0.9844	0.8134	0.5848
	Winter	0.9683	0.4048	0.3286	0.2325	0.1265	0.3271	0.0250
The second EOF eigenvector	Spring	0.6721	0.9209	0.8315	0.9850	0.7339	0.2911	0.7574
	Summer	0.2863	0.9498	0.9141	0.8980	0.9752	0.9566	0.9429
	Autumn	0.6766	0.5737	0.9458	0.9524	0.9576	0.2708	0.3353
	Winter	0.8730	0.0950	0.3336	0.4704	0.3280	0.2043	0.0512
The third EOF eigenvector	Spring	0.5705	0.8149	0.5874	0.9739	0.8718	0.0017	0.4895
	Summer	0.5134	0.7072	0.8940	0.8779	0.9120	0.8514	0.5697
	Autumn	0.0688	0.2993	0.0974	0.9282	0.8988	0.4049	0.0941
	Winter	0.0178	0.2908	0.1330	0.0446	0.1474	0.2523	0.2907

Note: the numbers with underline are significant at α=0.001 confidence level.

5. Conclusions and discussions

According to the forementioned results, some conclusions can be drawn as follows:

(1) The normalized RMSEs of meteorological variables in eastern China are less than those in western China. This spatial distribution reveals that the reliability of reanalysis is influenced by the topography error in reanalysis model and the disposition of "dense-in-eastern-and-sparse-in-western" of meteorological observatories in China.

(2) Compared with the original reanalyzed, the normalized RMSEs of the anomalies of reanalyzed data obviously decrease. The reanalysis is reasonable for the climatic trend research in China.

(3) The normalized RMSE of the anomalies of reanalyzed winds decreases with increasing height, further revealing the possible impact of topography on reliability of reanalysis. The errors of reanalyzed winds at 850, 500, and 200 hPa in winter are greater than those in the other three seasons, which shows the seasonal-dependent impact of system error in the reanalysis model.

(4) It is also found from the correlation analysis that the reliability of reanalysis in eastern China is better than that in western China. Furthermore, the results of correlation analysis have some correspondence to those of RMSE analysis, i.e., the larger the normalized RMSE is, the worse the correlation between reanalyzed and observed data is, and vice versa.

(5) A meteorological variable with smaller RMSE has similar spatial patterns of corresponding EOF eigenvectors of anomaly of reanalyzed and observed data and significantly correlated time coefficients, and vice versa. The results of EOF decomposition are consistent with the results of RMSE and correlation

analysis. Therefore, the similarity of EOF modes and the consistency of their time coefficients can be used to objectively assess the reliability of reanalysis.

(6) Summing up the results of normalized RMSE, correlation analysis and EOF decomposition, we can conclude that the reliability of the reanalyzed wind is better in spring, summer, and autumn, but worse in winter; while for the reanalyzed SAT, it is the best in winter and the worst in summer. Viewed from the space, the reliability of reanalysis is better in eastern China.

Besides, there are larger differences in the magnitudes between reanalyzed and observed data. The possible causes are: (I) the lower resolution of the reanalysis model, which resulted in the inaccurate descriptions of the topography and the microscale and mesoscale weather systems; (II) the limitation of the observed data, such as its obvious heterogeneity and the impacts of the "urban heat island" on SAT, etc.

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