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Global and Planetary Change 37 (2003) 315–325
GLOBAL AND PLANETARY CHANGE
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Association between winter temperature in China and upper air circulation over East Asia revealed by canonical correlation analysis

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Accepted 25 July 2002

Abstract

Canonical correlation analysis (CCA) was used to study the relationship between the winter temperature in China and the circulation at 500 hPa over East Asia. CCA identifies a number of paired patterns that depend on Principle Component (PC) truncation of the two fields. Retaining more PCs usually gives more physically meaningful CCA patterns, but the leading paired pattern has often less explained variance. When fewer PCs are adopted, the leading pattern possesses larger variance. However, it is often distorted in comparison with PC or rotated PC patterns. Various combinations with different PC and CCA patterns remained were tried, which shows that retaining as many PCs as possible and using the first several CCAs instead of only the first give most reasonable connection mechanisms. A statistical downscaling model based on CCA modes linking temperature with circulation was established to quantify the extent to which temperature variation can be explained by circulation. The model was optimised by varying numbers of the PCs and the CCA modes retained. With 13th PC truncation in the circulation and 8th PC truncation in the temperature as well as five CCA modes retained, the optimal CCA model is achieved based on cross-validation. The optimal downscaling model accounts for 47.5% temperature variance on average. However, there is a remarkable regional difference, which ranges from 10% to 70% in brier-based score (BBS). It is concluded that 500-hPa circulation is strongly linked to surface temperature in parts of the country, but it alone is not sufficient to achieve a successful statistical downscaling of the temperature for whole China.
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Keywords: Upper air circulation; 500-hPa geopotential; Monthly surface temperature; CCA; Statistical downscaling; China

1. Introduction

General circulation model (GCM) is the primary source of information for assessments of the future impacts of climate change (Murphy, 1999). However, typical GCM resolution today is about 300 km, which is the smallest scale of GCM output. von Storch et al. (1993) indicate that GCMs are more skilful at the

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doi:10.1016/S0921-8181(02)00206-0

multiple grid points than at the single grid point level. Society needs reliable prediction of climate variables with scales much smaller than GCM output (i.e. local-scale and regional-scale) for use in agriculture, hydrology, and many other activities. Thus, there is a need to transform large-scale GCM output into local-scale variables. This is called downscaling. In addition to dynamical downscaling, statistical downscaling provides a relatively simple, yet useful alternative, as both techniques can have comparable skills (e.g. Hellström et al., 2001). In a statistical downscaling model, variables related to atmospheric circulation such as sea level pressure (SLP) are often chosen as predictors since long-time data are available (Chen, 2000; Zorita et al., 1992). However, downscaling models with a 500-hPa height as predictors often manifest greater skill than those with SLP as predictors (Huth, 1999).

China is under strong influence of monsoon due to the geographical settings. The monsoon system over China is further strengthened by the Tibetan Plateau. In summer, the southeasterly airflow causes moisture advection, thus summer rainfall has a close relationship with East Asia monsoon circulation (Samel et al., 1999). The northeasterly winter monsoon, however, can bring cold air from Siberian high, which leads to cold and dry weather. The East Asia trough at a 500-hPa height is an important characteristic of the circulation in wintertime (Ding and Krishnamurti, 1987); its position and intensity can cause temperature anomaly in China.

This study focuses on establishing the link between the winter temperature in China and the upper level circulation over East Asia using Canonical Correlation Analysis (CCA). The main objective is to determine the extent to which temperature variability can be related to circulation variability via an optimal CCA downscaling model. The result should be useful for better understanding of climate variability and for further development in statistical downscaling. The data used are introduced in Section 2. Section 3 describes the methods employed. Section 4 shows the results, followed by Section 5 that summarises the study.

2. Data

The atmospheric circulation is represented by a 500-hPa geopotential height over East Asia (70–150°E and 10–60°N) from the NCEP/NCAR reanalysis (Kalnay et al., 1996) with a resolution of 2.5° in latitude and longitude (Fig. 1a). The uneven density of the data distribution would bias the principle component analysis (PCA). The problem is usually solved with an area weighting of the original data. Here, the grid points were selected so as to minimise the uneven distribution. The final data set selected consists of 544 grid points (Fig. 1b). Monthly temperatures from 1951 to 1998 at 160 first-order stations all over China were screened by a quality control procedure. Obvious errors were found at 13 stations that were removed from further analysis. The final 147 stations are shown in Fig. 1c. The winter seasonal data series from 1951/1952 to 1997/1998 were obtained by making traditional average of December, January and February (DJF). The anomaly data are used in all further analysis.

3. Methodology

In developing a downscaling model (Zorita and von Storch, 1999), CCA has the advantage of representing large-scale fields better than the grid point data that represents the minimum GCM scale information (Busuioc et al., 2001a,b). Huth (1999) shows that the PC patterns are almost unaffected by the omission of 1-year data but point wise screening has much less stability and different grid points are selected in different chosen samples. In using CCA to establish links, PCA is often invoked prior to CCA (Barnett and Preisendorfer, 1987). PCA does not only effectively reduce the dimension of original climate variable and extract large-scale information, but also pre-filters the data to reduce noise (e.g. Xoplaki et al., 2000). However, how many PCs should be retained for further CCA analysis is nontrivial. In this work, some experiments with different PC truncations are made to examine their impact on both CCA patterns and CCA model skill. Furthermore, number of CCA modes retained is varied to examine the impact on the CCA model skill.

The skill of the model is checked with cross-validation. In this method, all data except one sample, which is to be used for validation, are used to develop the model. This procedure is repeated until each sample has a chance to be used to validate the model. The cross-validation is meaningful only if the predictors are serially uncorrelated (Barnett and Preisendorfer, 1987). Generally, the autocorrelation with 1-year lag is very

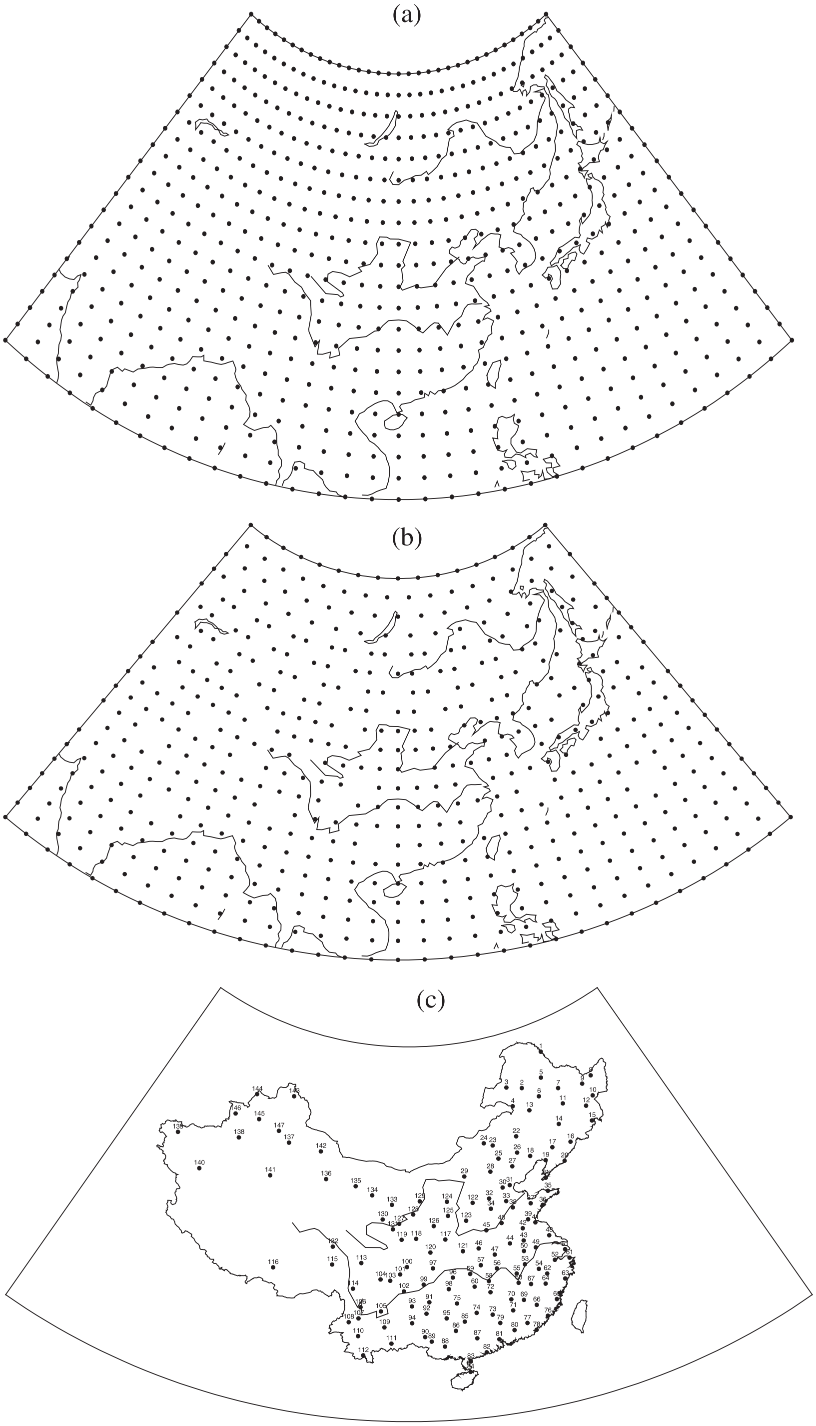

Fig. 1. The data point distributions for the circulation with original grid points (a), selected grid point (b) and the temperature stations used (c).

Table 1
Explained variance (%) of the PCA and the correlation coefficient of the CCA

PC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Gp	34.9	26.5	16.5	7.5	3.7	3.3	2.4	1.3	0.9	0.6	0.5	0.4	0.3	0.2	0.2
CumGp	34.9	61.5	78.0	85.5	89.2	92.5	94.8	96.2	97.0	97.6	98.1	98.5	98.8	99.0	99.2
Temp	47.2	15.1	10.3	5.0	3.3	2.1	1.8	1.6	1.4	1.3	1.1	0.9	0.9	0.7	0.7
CumT	47.2	62.3	72.5	77.5	80.8	82.9	84.8	86.4	87.8	89.1	90.2	91.1	92.0	92.7	93.3
CCA15	0.98	0.97	0.96	0.94	0.92	0.84	0.80	0.71	0.69	0.55	0.43	0.38	0.30	0.17	0.09
CCA10	0.96	0.95	0.93	0.83	0.73	0.67	0.57	0.42	0.13	0.05					
CCA05	0.89	0.86	0.63	0.40	0.02										

Temp is for the temperature and Gp for the geopotential height at 500 hPa, while CumT and CumG denote their cumulated variances, respectively. CCA05, CCA10 and CCA15 refer to CCA correlation coefficients for 5th, 10th and 15th PC truncation, respectively.

small in wintertime so the cross-validation can be used effectively, while in summertime, the autocorrelation may be, or is usually large enough to destroy effectiveness of cross-validation.

There are a variety of criteria to measure validation skill score, such as correlation coefficient, mean-squared error (MSE), and brier-based score (BBS) (e.g. Busuioc et al., 2001a). The last one can be defined as: BBS=(1 − MSE/VAR)*100, where VAR is the variance of the data used for validation. If $0 < \text{BBS} \leq 100$, the model has some skill, while $\text{BBS} \leq 0$ indicates completely wrong modelled result.

4. Results

4.1. The impact of PC truncation on CCA pattern

Three cases of PC truncations at 5th, 10th and 15th PC are considered to show how CCA patterns

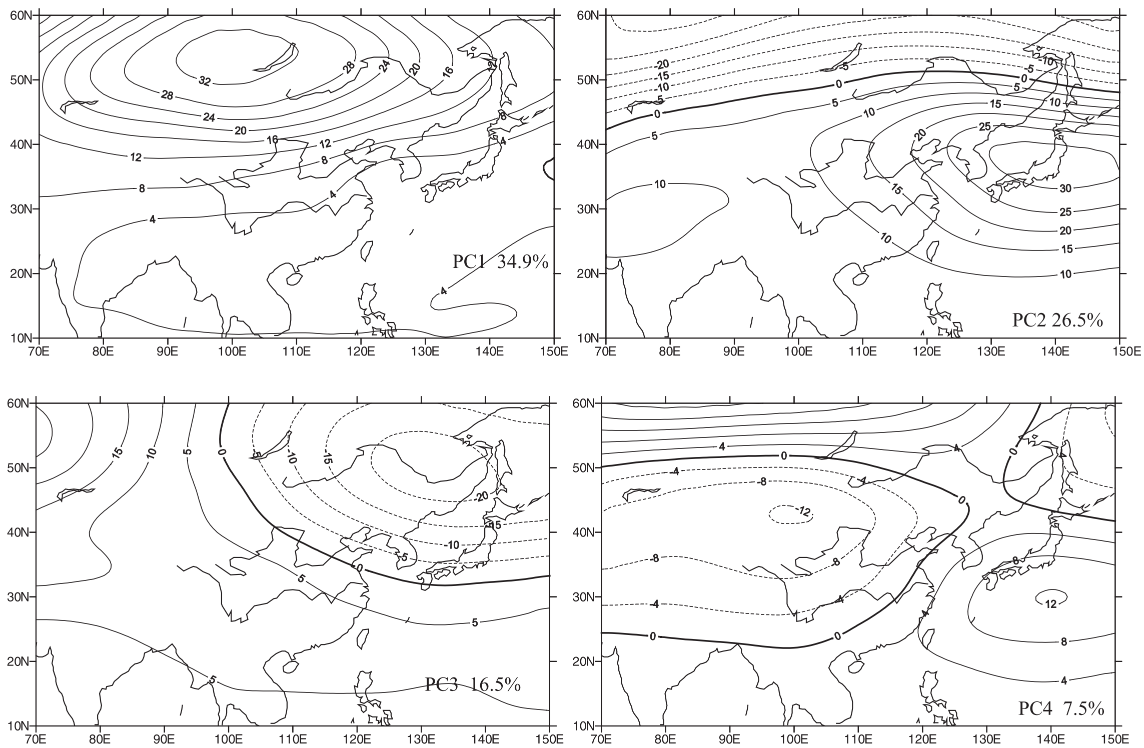

Fig. 2. The leading four PC patterns of the 500-hPa geopotential height.

are affected. The PC variance and canonical correlation coefficients for the three cases are listed in Table 1. The canonical correlation increases when more PCs are retained, which shows the over fitting problem (von Storch, 1995). Fig. 2 shows the leading four PC patterns at 500-hPa height. Varimax rotation gives similar results. PC1 mainly represents the variation of East Asia trough, an important feature at 500 hPa in the Northern Hemisphere in winter. PC2 reflects the variation of the Siberian high. These two patterns have a cumulated variance of 61.5%. The PC3 and PC4 patterns have relatively small importance.

The first four CCA patterns for the 500-hPa height at 5th, 10th and 15th PC truncation are displayed in Figs. 3, 4 and 5, respectively. The variance explained by CCA patterns is shown in the lower right-hand corner of each panel. CCA variances are virtually the redistribution of the total PC variance. More PCs result in more CCA patterns, but each paired pattern explains a smaller fraction of the total variance. Therefore, the CCA pattern variances only indicate the relative importance of each of the CCA patterns. In fact, like PCA, CCA are also eigenvector techniques and CCA patterns can be just 'mathematical' rather than physical. Of course, CCA patterns with physical meanings are desirable, which can be achieved by physical understanding of the relevant processes or other independent methods.

A comparison between Figs. 2 and 3 shows that the CCA patterns with five PCs retained coincide fairly well with the PC patterns. However, the first CCA and PC patterns, both possess relatively larger variance, show considerable inconsistency. The CCA patterns with 10 PCs retained (Fig. 4) resemble PC patterns (Fig. 2) much better than those with 5 PCs retained (Fig. 3), but the order of patterns is different. The second and the third CCA patterns in Fig. 4 correspond to the first and the second PC patterns and the first CCA pattern in Fig. 4 shows some similarity to the third PC pattern. The comparison between Figs. 2 and 5 shows that the CCA patterns in 15th PC truncation are closest to the PC patterns. The first CCA pattern in Fig. 5 greatly resembles the fourth PC

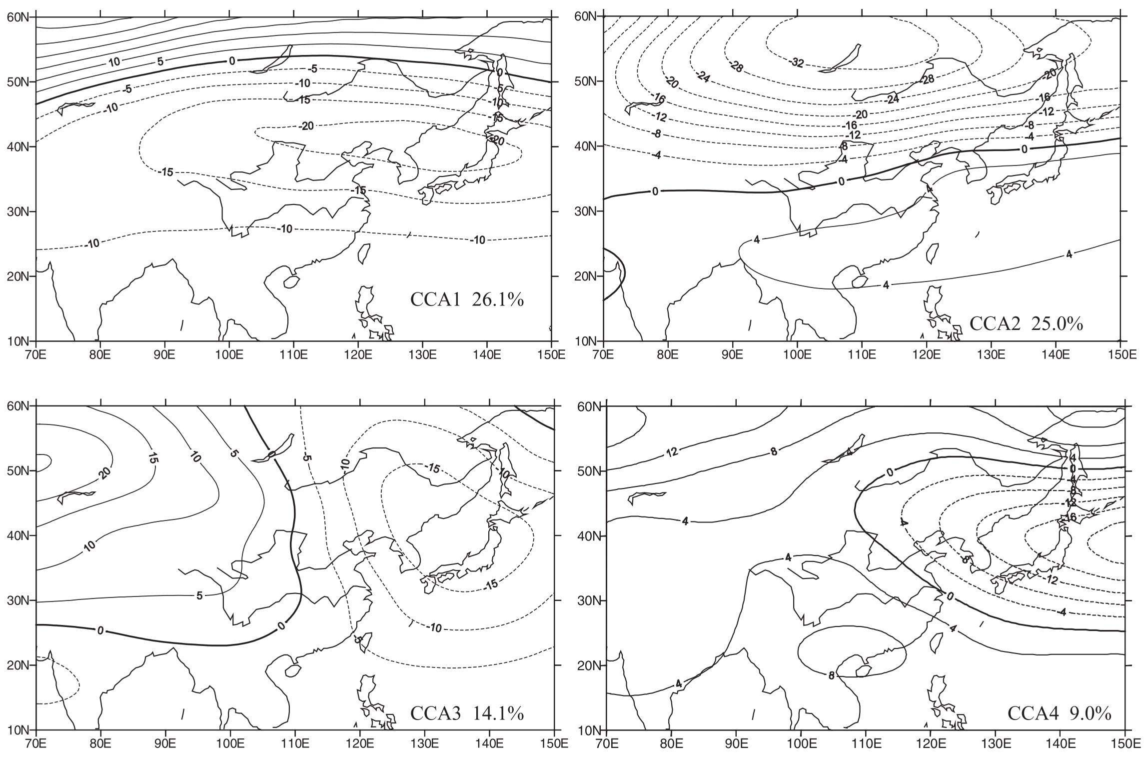

Fig. 3. The first four CCA patterns for the 500-hPa height at 5th PC truncation.

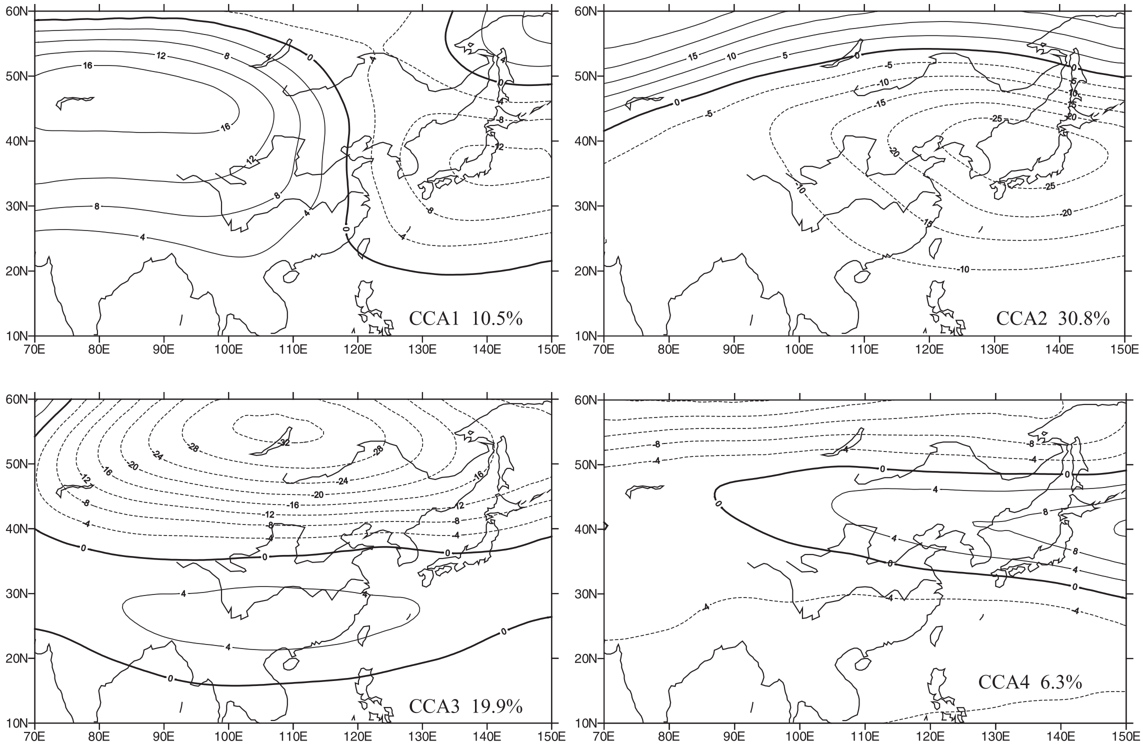

Fig. 4. The first four CCA patterns for the 500-hPa height at 10th PC truncation.

pattern in Fig. 2 while the second and third CCA patterns in Fig. 5 are similar to the first and the second PC patterns. The fourth CCA pattern in Fig. 5 shows relatively little similarity with the third PC pattern.

In terms of similarity between the PC and CCA patterns, more PC truncation produces more similar CCA patterns while less PC truncation often causes the resulting CCA pattern to be distorted. The first two PC patterns appear to be important because they have a clear physical interpretation and account for a relatively large variance change of circulation and always appear as the CCA patterns. These two patterns are the leading CCA patterns when less PC truncation is adopted but are slightly distorted in comparison with the PC patterns (see Figs. 2 and 3). However, the PC patterns with smaller variance may become leading CCA patterns when more PC truncation is adopted. These results confirm the findings of O'Lenic and Livezey (1988) who show that under-rotation (less PC truncation being used) tends to cause rotated PC pattern distortion.

4.2. Connection revealed by CCA patterns

Fig. 6 shows the first four temperature CCA patterns corresponding to CCA patterns of 500-hPa height with 15 PC truncation (Fig. 5). The first paired pattern shows that whole China is under a positive anomaly in 500-hPa geopotential height, with a centre in the northwest of the country. At the same time, temperature has positive anomaly all over China with a high temperature anomaly centre located also in the northwest of the country. This discloses a direct link between geopotential height and temperature. The second paired patterns in Figs. 5 and 6 reflect the impact of the East Asia trough anomaly on temperature variation. When the East Asia trough becomes stronger, the original northwesterly wind in front of the trough will become more northerly, which brings cold air from high latitudes and results in decreased temperature. The third CCA pattern in Fig. 5 may be associated with the Siberian High, which is not present at 500-hPa height because of its shallow

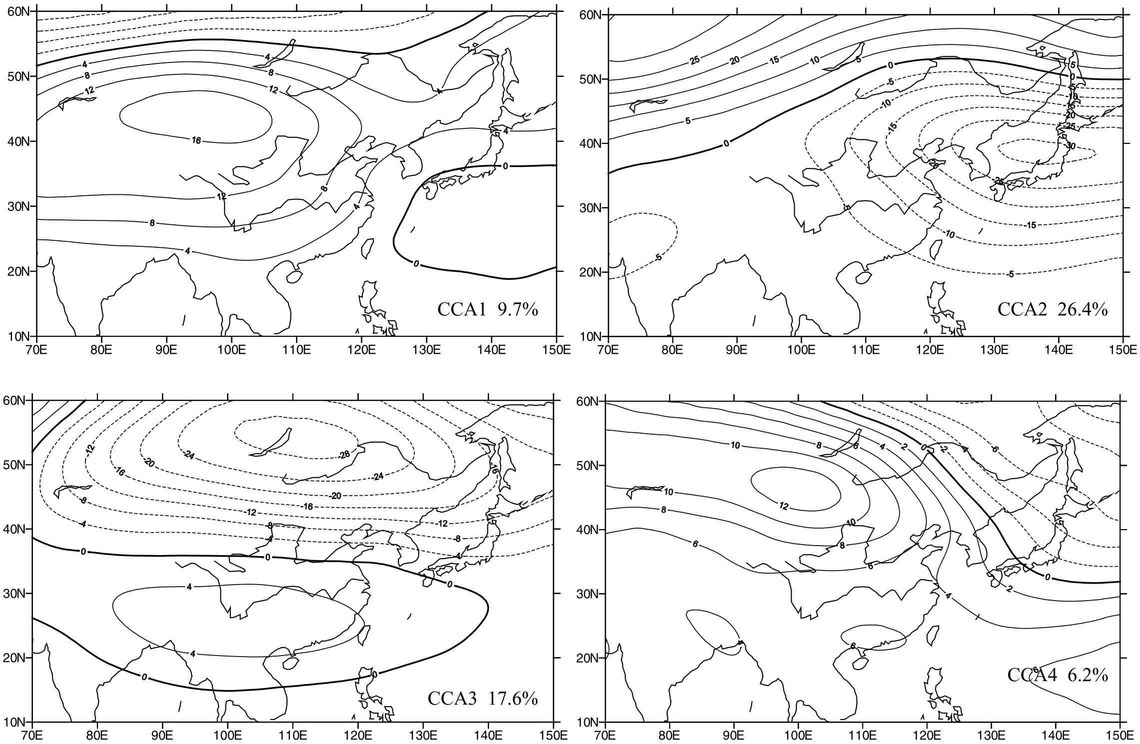

Fig. 5. The first four CCA patterns for the 500-hPa height at 15th PC truncation.

feature (Samel et al., 1999). In southern China, the circulation is controlled by a weak positive anomaly. This pattern can account for reversed temperature change between the north and the south of China. The strong westerly wind due to larger pressure gradient in high latitudes brings cold air from inland, which leads to decreased temperature, while the weak positive anomaly in the south is linked to the above-normal temperature. The fourth paired patterns in Figs. 5 and 6 display a similar connection to the first paired patterns, although some details are slightly different (e.g. the anomaly centre).

In all the CCA paired patterns, the circulation anomaly corresponds vertically to temperature anomaly. The radiation budget at the surface plays a role in temperature change. Also, negative anomaly is often accompanied by strong westerly winds, which bring cold air from inland and cause the temperature to drop. In addition, the CCA patterns show that the different circulation situations can cause the same sign of temperature variation all over the country as shown by the first, the second and the fourth CCA paired patterns. This explains why the first PC temperature pattern accounts for a great fraction of variance (Table 1).

It can be seen that a close connection exists between the circulation variation at 500-hPa level in East Asia and temperature anomaly in China. The second and the third CCA patterns in Fig. 5 especially have a relatively large variance, representing the important and stable connection with temperature change. With these connections, part of the temperature variation can be inferred from the circulation variation at 500-hPa level by using a downscaling model.

4.3. Optimal downscaling model

It is established in the previous sections that the PC truncation has a profound impact on CCA patterns and the CCA model skill. An optimal model is sought by varying PC and CCA modes truncations. The model skill is expressed by an average BBS over the 147 temperature stations under study. First the model was established with different PC truncations

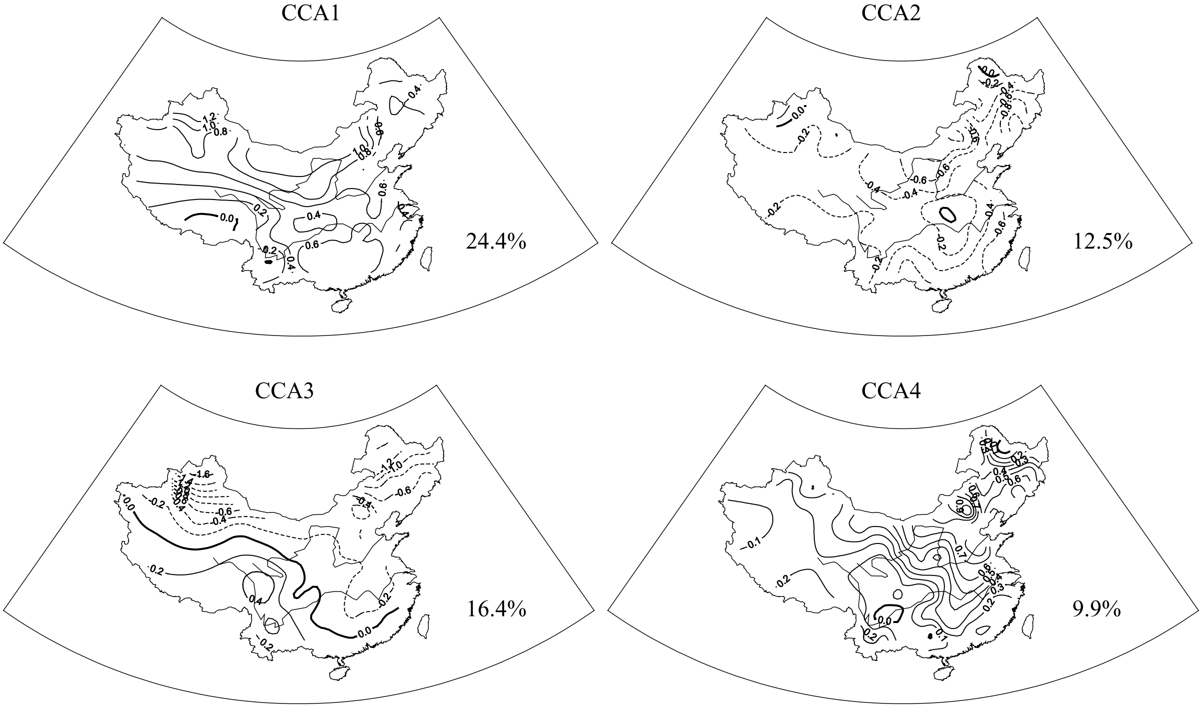

Fig. 6. The first four CCA patterns for the temperature at 15th PC truncation.

from 1st PC to 15th PC for both 500 hPa and temperature and all the CCA modes available are used to develop the model. It was found that the first eight PCs retained produce the best skill (42.5% in Table 2). However, the advantage of CCA is not fully utilised if all CCA modes are used. This is because CCA attempts to divide the signal and noise in the connection between two climate fields but the noise is also used for developing model. A better way is to use those significant CCA modes only for establishing the model. For example, when 15th PC truncation was adopted for both circulation and temperature, the first 5 of a total 15 CCA modes gave the best model skill of 44.6%, which is a significant improvement over the skill of 38.6% when all the CCA modes are used. Following this principle, the optimal choice of CCA modes was sought by changing PC truncation from 1 to 15 and the best model skill of 46.2% can be found with 13 PC truncation and 5 CCA modes (Table 2). It is also found from Table 2 that, except for 1st–5th PC truncation, the best choice of CCA modes retained is in the range 4–6 depending on PC truncation. It seems that retaining the first five CCA modes is the most favourable choice.

So far, the same number of PCs has been retained for the two climate fields in the CCA model. According to an objective criteria of PC truncation suggested by Kaiser (1958), the threshold of 1.0 is used here to

Table 2
The model skill expressed by an averaged BBS over the 147 temperature stations

PCs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
BBS-1	8.6	25.3	26.6	40.2	39.4	40.6	40.5	**42.5**	41.4	40.7	42.2	41.0	42.2	40.4	38.6
Modes	1	2	3	3	4	5	5	5	6	6	4	5	5	6	5
BBS-2	8.6	25.3	26.6	40.4	39.5	40.7	41.5	44.7	43.7	42.8	45.0	44.7	**46.2**	44.0	44.6

BBS-1 means skills of the models with all available CCA modes and BBS-2 refers to skills with the optimal choice of CCA modes. The best skill is bolded.

truncate PC, which results in 8 PCs in 500 hPa and 11 PCs in temperature. As an alternative, two other cases were also examined with fixed 8-PC truncation in temperature and 11- or 13-PC truncation in the 500-hPa height. The PC truncation based on Kaiser's criteria gives a skill of 43.3%, which is lower than the skill for temperature (44.7%) even with 8-PC truncation. It appears that more PC retained in temperature does not increase model skill. On the contrary, 11th PC truncation in 500 hPa and 8th PC truncation in temperature produce a better result (46.1%) and the optimal model (47.5%) could be achieved with 13th PC truncation in 500 hPa and 8th PC truncation in temperature and five CCA modes retained. The experiments show that the optimal model needs more variance retained from 500 hPa than from temperature. A similar conclusion was drawn by Livezey and Smith (1999).

The optimal model is found based on the average skill. However, the model skill varies from region to region. Fig. 7 shows the distribution that ranges from 10% to 70%. In the middle and west of the country, the skill increases toward higher latitudes, but there is almost no latitude dependence of skill in eastern China. The maximum skill is located in Inner Mongolia and lower skill areas are mainly located in the southwestern part of the country such as Southern Xinjiang, Tibetan Plateau, Yunnan Plateau and Sichuan Basin. The circulation impact on the winter climate in China is principally through the Siberian High. The high latitude that is directly influenced by the Siberian High shows a high skill. The high mountains ranging from west to east in southwestern China preclude airflow from the Siberian High passing through this area, resulting in the lower skill. This is especially true for the Sichuan Basin that has a basin topography surrounded by high mountains. In the vast area of eastern China, where no major topographical obstacle exists, the airflow induced by the Siberian High can go through this area fluently, which can explain the homogenous skill.

5. Discussion and conclusion

The CCA paired patterns depend remarkably on PC truncation. The more PCs that are retained the more physically meaningful the CCA patterns, but the leading paired pattern is less important in terms of the explained variance. If less PCs are adopted, the leading pattern possesses larger variance. However, it is often distorted in comparison with PC or rotated PC patterns. A better way is to retain as many PCs as possible and use the first few paired patterns instead of the first one to interpret the connection mechanisms between the two climate fields. In addition, the CCA paired patterns are nonorthogonal to each other so that several paired patterns may represent similar connection characteristics.

The CCA paired patterns obtained in this study clearly shows that positive (negative) anomaly at 500 hPa results in above (below) normal temperature

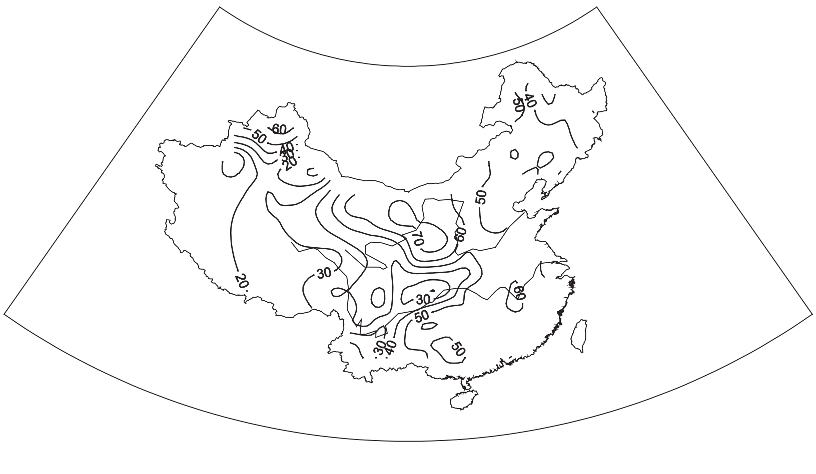

Fig. 7. The BBS distribution of the optimal model with cross-validation.

change underneath. The temperature changes in winter are strongly coherent, since the different circulation anomalies revealed by the CCA patterns often cause the same sign of temperature variation all over the country.

Many plausible CCA downscaling models can be obtained, depending on the numbers of the PCs and the CCA modes retained. The challenge is to find the optimal model in terms of a predefined skill score. With 13th PC truncation in 500 hPa and 8th PC truncation in temperature and five CCA modes retained, the optimal CCA model is achieved based on cross-validation. The optimal downscaling model has a different accumulated variance for circulation (about 99% with 13 PCs) and temperature (about 86% with 8 PCs). If as many PCs as possible are retained and five to six CCA modes are used, the resulting models are very close to the optimal model. It seems that over fitting is a problem with respect to CCA modes but not with respect to PC truncation in the development of a CCA model.

The optimal model accounts for 47.5% temperature variance on average. However, there is a remarkable regional difference, which ranges from 10% to 70% in BBS. Obviously, there are a number of factors that may have an influence on the model skills. First, the 500-hPa height as the only predictor is not sufficient to describe temperature change. A successful statistical downscaling requires that other relevant variables be included. Some other studies with 850-hPa temperatures as predictors have shown a marked improvement of downscaling model skill (Huth, 1999; Sailor and Li, 1999). Second, the linear presumption of the relationship between circulation and temperature may lose some information of nonlinear connection. The variation of validation skill over China reflects the impact of the topography. Higher skill occurs in places without influence of high mountains so that the airflow from the Siberian High can easily reach the area, while areas downstream from the high mountainous areas often show lower skill because the mountain interrupts the airflow.

Acknowledgements

This research is supported by Chinese Academy of Sciences and Swedish Institute. Supports from a NSFC/NFR co-financed project and SWECLIM, which is funded by MISTRA and SMHI, are also acknowledged. The manuscript is improved by constructive comments from two anonymous referees.

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