A Hybrid Dynamical-Statistical Approach for Predicting Winter Precipitation over Eastern China*

LANG Xianmei† (郎咸梅)

International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

(Received June 21, 2010; in final form April 8, 2011)

ABSTRACT

Correlation analysis revealed that winter precipitation in six regions of eastern China is closely related not only to preceding climate signals but also to synchronous atmospheric general circulation fields. It is therefore necessary to use a method that combines both dynamical and statistical predictions of winter precipitation over eastern China (hereinafter called the hybrid approach). In this connection, seasonal real-time prediction models for winter precipitation were established for the six regions. The models use both the preceding observations and synchronous numerical predictions through a multivariate linear regression analysis. To improve the prediction accuracy, the systematic error between the original regression model result and the corresponding observation was corrected. Cross-validation analysis and real-time prediction experiments indicate that the prediction models using the hybrid approach can reliably predict the trend, sign, and interannual variation of regionally averaged winter precipitation in the six regions of concern. Averaged over the six target regions, the anomaly correlation coefficient and the rate with the same sign of anomaly between the cross-validation analysis and observation during 1982–2008 are 0.69 and 78%, respectively. This indicates that the hybrid prediction approach adopted in this study is applicable in operational practice.

Key words: winter precipitation, dynamical and statistical predictions, multivariate linear regression analysis, seasonal prediction model, hybrid approach

Citation: Lang Xianmei, 2011: A hybrid dynamical-statistical approach for predicting winter precipitation over eastern China. *Acta Meteor. Sinica*, **25**(3), 272–282, doi: 10.1007/s13351-011-0303-5.

1. Introduction

Climate change over China has a significant impact on industrial and agricultural production, especially on food supply and energy and water resources, and is directly related to the sustainable development of the society. As one of the most important and active subjects in the geosciences, climate change has been a major concern of key international interdisciplinary research programs, such as the well-known World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme (IGBP). In the context of climate change, climate prediction on the seasonal timescale has been one of the foci of the climate variability and predictability studies.

China is greatly affected by the East Asian monsoon with severe weather and climate disasters occurring frequently across the country. In recent years, anomalous climate events frequently take place in China and the neighboring countries during wintertime, such as the extra-strong warm winter event in northern Asia in 2001, the disaster of low temperature, frozen rain, snow, and frost in southern China in January and early February 2008, and the persistent snowstorm event in most parts of northern China in winter 2009. They have seriously impacted on many aspects of the society, particularly on people's everyday life, energy, and traffic systems. Accordingly, much attention has been paid to climate anomalies during winters as well as their causes and effects (Wang, 2003; Tao and Wei, 2008; Wen et al., 2009; Wang and Sun, 2009; Sun et al., 2009). Besides,

*Supported by the Knowledge Innovation Project of the Chinese Academy of Sciences (KZCX2-YW-Q03-3), National Basic Research Program of China (2009CB421406), Special Public Welfare Research Fund for Meteorological Profession of China Meteorological Administration (GYHY200906018), and National Natural Science Foundation of China (40875048).

†Corresponding author: langxm@mail.iap.ac.cn.

(Chinese version to be published)

climate conditions in winter have an important influence on dust weather in northern China during the subsequent spring (Zhang et al., 2005; Lang, 2008). Therefore, it is imperative to improve the seasonal prediction of winter precipitation especially in the real-time mode.

It has been amply documented that winter precipitation over China is closely related to both antecedent and synchronous climate factors. As far as the internal atmospheric variability is concerned, the Antarctic Oscillation (AAO) and the Arctic Oscillation (AO) are the dominant modes of the atmospheric general circulation in mid and high latitudes in each hemisphere. AAO has been found to influence winter and spring climate over China (Fan and Wang, 2004, 2006), and AO has been found to impact significantly winter precipitation over China (Gong and Wang, 2003; Yang and Li, 2008). In addition, winter precipitation over China is also affected by anomalies of geopotential height at 500 hPa and meridional wind in the lower troposphere (Shi, 1996; Gong and Wang, 2001). The former represents westerly circulation in the middle troposphere over the Eurasian continent, and the latter represents the intensity of cold air into China. On the other hand, sea surface temperature (SST), one of the most well-known external forcing factors of the atmosphere, has been revealed to impact notably winter climate over China (Chang et al., 2008). For example, the El Niño and La Niña events have been put forward as indicators of winter monsoon anomaly in East Asia (Mu and Li, 1999). The warm phase of the Atlantic oscillation of SST on the multidecadal timescale has been linked to a below (above) normal precipitation pattern in southern (northern) East China (Li and Bates, 2007). These studies and related achievements have improved our knowledge of climate variability of East Asia on the seasonal scale, and at the same time, provided foundation to development of seasonal prediction of winter precipitation over China using statistical and dynamic approaches.

Preliminary prediction experiments have shown that although winter precipitation over China is somewhat predictable, the prediction skill for associated meteorological disasters, such as persistent precipitation anomaly, is generally low on the monthly to seasonal timescales (Wang et al., 2003; Chen et al., 2008; Wei et al., 2008). On the whole, the prediction skill for winter precipitation over China, using either purely statistical or dynamical approach, is still relatively limited on the seasonal timescale. This brings the following question: if valuable original information can be effectively taken from both the dynamic numerical prediction and the preceding observation (note the information from the latter has not been sufficiently included in the seasonal numerical prediction but is statistically significantly correlated with winter precipitation over China), i.e., by using a combination of both statistical and dynamical predictions (a hybrid approach), can the prediction skill of winter precipitation over China be improved? Wang and Fan (2009) indicated that the prediction skill for summer rainfall in East Asia is increased when the numerical predictions in the tropics are merged with some observations. In this study, a new approach for predicting winter precipitation over China by use of a hybrid dynamical-statistical approach is proposed, in which the observed antecedent predictors and the synchronous predictions that correlate closely to winter precipitation and meanwhile numerically predictable are combined.

2. Data and method

In consideration of the reliability of data, the study starts from 1982 when satellite data became available. Observed monthly precipitation data at 160 stations were provided by the National Climate Center, China Meteorological Administration. The data of the predictors can be grouped into two types: reanalysis data and numerical prediction outputs. Monthly AO and AAO data were obtained from the Climate Prediction Center of the National Weather Service of the US National Oceanic and Atmospheric Administration. The AO (AAO) is represented by the time coefficient series of the first mode of the empirical orthogonal function analysis of 1000-hPa (700-hPa) geopotential height anomalies poleward of 20°N (20°S). Monthly wind and geopotential height data with a horizontal resolution of 2.5°×2.5° were obtained from the National Centers for Environmental

Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset (Kalnay et al., 1996). Monthly SST data with a horizontal resolution of 1°×1° were from the US National Aeronautics and Space Administration (Reynolds et al., 2002).

Dynamic numerical prediction data of winter climate were derived from a set of ensemble hindcast experiments undertaken by an atmospheric general circulation model developed at the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP9L-AGCM). For each year from 1982 to 2008, the ensemble hindcast experiments consisted of 7 integrations starting from October 28 through to the end of the subsequent February, which were forced by observed monthly SSTs and initialized from atmospheric conditions on 25–31 October from the NCEP-NCAR reanalysis dataset. The result of each year was expressed as the ensemble mean of the seven integrations with the same weight. It is worth noting that observed SSTs were used in the experiments of IAP9L-AGCM, thus putting IAP9L-AGCM results in the best possible performance.

From the real-time prediction point of view, the purpose of this study is to establish a hybrid dynamical-statistical seasonal prediction model for winter precipitation over eastern China through a multivariate linear regression analysis, in which both the antecedent and synchronous predictors are used. According to the work of Lang and Wang (2010), systematic prediction errors between the results of the original prediction model and the observations were corrected. Northern Northeast China (46°–53°N, 116°–133°E), southern Northeast China (36.5°–46°N, 119°–133°E), Hetao area and North China (36.5°–46°N, 100°–119°E), Yellow-Huai River basin (30°–36.5°N, 105°–122°E), southeastern coastal China (21°–26.5°N, 112°–120°E), and southern Yangtze River (26.5°–30°N, 112°–123°E) were chosen for the present analysis in light of the regionalization of precipitation regimes in China (Chen et al., 2009). Spring is defined as the average for March–April–May, summer as the average for June–July–August, autumn as the average for September–October–November, and winter as the average for December through to the subsequent February.

3. Hybrid prediction model for winter precipitation over China

3.1 Identifying antecedent predictors for winter precipitation

3.1.1 Relationship between winter precipitation and AAO/AO

During 1982–2008, the lagged relationship between the preceding seasonal AAO or AO, one season to one year in advance, and regionally averaged winter precipitation in eastern China was calculated on a region-by-region basis. The largest anomaly correlation coefficients (ACCs) between each other in the six regions defined in Section 2 are given in Table 1. It can be found that the most significant signals occur in the preceding autumn for all the regions. Moreover, except for northern Northeast China, the lead times are all one season for the remaining five regions. Comparatively, the role of AAO is more significant than that of AO, indicating a closer relationship between the atmospheric general circulation in mid-high latitudes of the Southern Hemisphere during the preceding autumn and the precipitation over eastern China during the subsequent winter. Based on the above, the preceding AAO or AO listed in Table 1 was chosen as a predictor for winter precipitation in each target region.

3.1.2 Relationship between winter precipitation and 500-hPa geopotential height

The correlation analysis for each 20-yr moving window during 1982–2008 indicated that the preceding 500-hPa geopotential height (H500) correlates stably

Table 1. The maximum ACC between regionally averaged winter precipitation and the preceding seasonal AAO or AO, one season to one year in advance during 1982–2008*

Target region	Autumn AAO (Y_0)	Autumn AO (Y_0)	Autumn AO (Y_{-1})
Northern Northeast China			–0.42
Southern Northeast China		0.36	
Hetao area and North China	–0.47		
Yellow-Huai River basin	–0.40		
Southeastern coastal China	–0.45		
Southern Yangtze River	–0.48		

*Y_0 (Y_{-1}) denotes current (last) year throughout this article.

and significantly with regionally averaged precipitation during the subsequent winter in the target regions excluding northern Northeast China (figures omitted). More details on the lead times, regions, and ACCs between each other are given in Table 2. Collectively, regionally averaged winter precipitation in Hetao area and North China, Yellow-Huai River basin, and southern Yangtze River, is closely related to the preceding H500, one year in advance, at the mid-high southern latitudes, while the winter precipitation in southern Northeast China and southeastern coastal China is linked to the preceding H500, half a year in advance, over the middle and eastern equatorial Pacific and the northern Eurasian continent.

Table 2. The regions where the preceding H500 correlates stably and significantly with regionally averaged winter precipitation during 1982–2008. Also given are lead time and the corresponding ACC between each other

Target region	Season	Region of H500	ACC
Southern Northeast China	Spring (Y_0)	2°–14°S, 150°–180°W	–0.58
Hetao area and North China	Winter (Y_{-1})	58°–74°S, 80°–110°W	–0.64
Yellow-Huai River basin	Winter (Y_{-1})	38°–50°S, 25°–50°W	0.56
Southeastern coastal China	Winter (Y_{-1})	66°–70°N, 80°–120°E	0.50
Southern Yangtze River	Spring (Y_0)	34°–46°S, 15°–45°W	0.59

3.1.3 Relationship between winter precipitation and SST

Regionally averaged winter precipitation in each of the six region is statistically significantly correlated with the preceding SST, one to three seasons in advance, in the respective ocean region corresponding to the target region. Moreover, the preceding valuable SST information for winter precipitation over the six regions of concern appears mainly in the antecedent spring and then in summer and autumn (see Table 3). Like the above result of the predictors determined from the atmospheric general circulation, the key ocean region for northern Northeast China is largely different from those for the other five regions. This means that the physical and dynamic processes governing precipitation in northern Northeast China are somewhat different from the remaining regions. It should be noted that this region is located under the westerlies in the mid-high northern latitudes, and, therefore, northwesterly is stronger there than over the other five regions.

Table 3. The regions where the preceding regionally averaged SST correlates stably and significantly with regionally averaged winter precipitation during 1982–2008. Also given are lead time and the corresponding ACC between each other

Target region	Season	Region of SST	ACC
Northern Northeast China	Autumn (Y_0)	35°–50°N, 155°–175°E	0.68
Southern Northeast China	Spring (Y_0)	5°–17°S, 120°–155°W	–0.71
Hetao area and North China	Spring (Y_0)	20°–30°S, 145°–165°W	0.63
Yellow-Huai River basin	Spring (Y_0)	38°–50°S, 128°–145°E	0.60
Southeastern coastal China	Spring (Y_0)	19°–28°S, 15°–40°W	–0.70
Southern Yangtze River	Summer (Y_0)	47°–55°N, 142°–168°W	0.63

3.2 *Identifying synchronous predictors for winter precipitation*

In the real-time prediction practice, synchronous predictors for winter precipitation can only be accessible through dynamic numerical predictions of the climate models. To apply the hybrid approach, to what extent synchronous predictors can be included in the real-time seasonal prediction models of winter precipitation depends essentially on the ability of the climate model to predict these climate signals. As a first step, the relationship between regionally averaged winter precipitation and the accompanying atmospheric general circulation in the troposphere was investigated using observed and reanalysis data. It was found that both meridional wind at 1000 hPa along coastal China and that at 200 hPa over the Eurasian continent are statistically significantly correlated with regionally averaged winter precipitation in each of the regions excluding northern Northeast China. This means that when above normal cold air moves southward along eastern China during winter, precipitation over eastern China tends to increase owing to an intensified interaction between cold and warm air there. However, regionally averaged winter precipitation over northern Northeast China is not significantly correlated with these two meteorological fields, but with H500 over southern Atlantic during the same period. Again, this implies the special nature of physical and dynamic processes governing precipitation over northern Northeast China during winter. Based on the above, the synchronous predictors for regionally averaged winter precipitation in each target region were chosen and listed in Table 4.

Table 4. The ACC between the regionally averaged variable derived from reanalysis data and the observed precipitation during winter 1982–2008

Target region	Variable	Region of variable	ACC
Northern Northeast China	H500	42°–54°S, 25°–55°W	0.68
Southern Northeast China	V200	42°–54°N, 115°–130°E	–0.71
Hetao area and North China	V1000	6°–14°N, 100°–110°E	–0.63
Yellow-Huai River basin	V1000	22°–30°N, 125°–140°E	–0.64
Southeastern coastal China	V1000	14°–26°N, 125°–140°E	–0.68
Southern Yangtze River	V1000	10°–22°N, 105°–120°E	–0.73

3.3 Construction of the hybrid prediction model

To evaluate the effect of the above precursory and synchronous predictors on the prediction model of winter precipitation in each region, purely statistical prediction models and hybrid statistical-dynamical prediction models were established by using the precursory predictors alone and both the precursory and synchronous predictors through a multivariate linear regression analysis, respectively. It should be reminded that the synchronous predictors were derived from reanalysis data at this stage. The prediction skill was assessed by the ACC between the cross-validation analysis results and observations, the root-mean-square error (RMSE) and mean absolute error (MAE) of the cross-validation analysis results with respect to the observations, and the rate with the same sign of anomaly (RSSA) between the cross-validation analysis results and observations (i.e., the ratio of the number of the years in which predicted anomalies are the same in sign as observed ones within the entire study period).

It was found that, when only the precursory predictors were considered, the values of ACC, RMSE, MAE, and RSSA are 0.60–0.74, 0.67–0.81, 0.51–0.65, and 70%–89%, respectively. By contrast, when both the precursory and synchronous predictors were considered, not only ACC and RSSA were enlarged but also RMSE and MAE were decreased (Fig. 1). This suggests that both the precursory and synchronous predictors are important in establishing the prediction models of winter precipitation in the target regions, and, therefore, should be taken into account in the real-time prediction practice.

In reality, however, winter reanalysis data for the above synchronous predictors are not available, and they may only be obtained by dynamic numerical prediction of the climate models, as the real-time prediction for winter precipitation is started in every early autumn. To find out the synchronous predictors derived from the numerical predictions of winter climate so as to realize the hybrid statistical-dynamical prediction approach from the perspective of real-time prediction, only those predictors that are not only closely related to regionally averaged winter precipitation in each region but also numerically predictable are to be considered. In this regard, the prediction skill of the climate model is critically important.

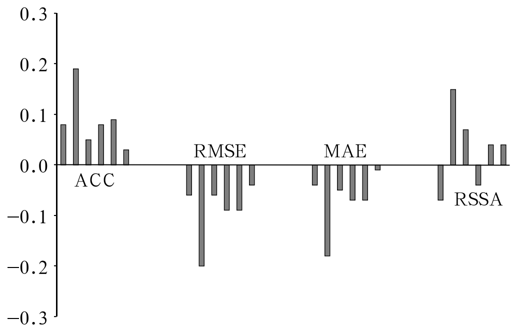

Fig. 1. Differences in statistical variables between the hybrid (both the precursory and synchronous predictors derived from the obsevations/reanalysis are considered) and purely statistical (only the precursory predictors derived from the observations are considered) approach results, with respect to the observations. Column charts arranged from left to right for each variable correspond to northern Northeast China, southern Northeast China, Hetao area and northern China, Yellow-Huai River basin, southeastern coastal China, and southern Yangtze River, respectively.

Accordingly, a set of ensemble hindcast experiments for winters of 1982–2008 were carried out by using IAP9L-AGCM in this study. The numerical predictability of the synchronous predictors for winter precipitation was evaluated by the temporal ACC of regionally averaged value between the reanalysis data and IAP9L-AGCM results in each key region as given in Table 4. Figure 2 indicates that almost all of the predictors are numerically predictable, particularly for meridional wind at 1000 hPa (V1000) in the regions concerned with southeastern coastal China and southern Yangtze River. This is undoubtedly in favor of realizing the hybrid statistical-dynamical prediction approach. For southern Northeast China, however, IAP9L-AGCM has no prediction skill for meridional wind at 200 hPa (V200) in the region of interest. This can be seen in Table 5, in which the ACC of V200 is negative. In contrast, the ACC values of the other predictors vary from 0.47 to 0.71, at least exceeding the 95% confidence level. Therefore, an additional analysis of zonal wind at 200 hPa (U200) derived from IAP9L-AGCM outputs was performed to look for a suitable predictor for precipitation in southern Northeast China. U200 within the range of 10°–18°N, 50°–75°W was found to be closely linked to winter precipitation in this region. Moreover, the temporal ACC of regionally averaged U200 between the reanalysis data and IAP9L-AGCM result is 0.37, close to the 95% confidence level, indicating a level of predictability.

Based on the above preceding (from reanalysis data) and synchronous (from IAP9L-AGCM results) predictors, statistically and dynamically hybrid prediction models for winter precipitation over the six regions were established through a multivariate linear

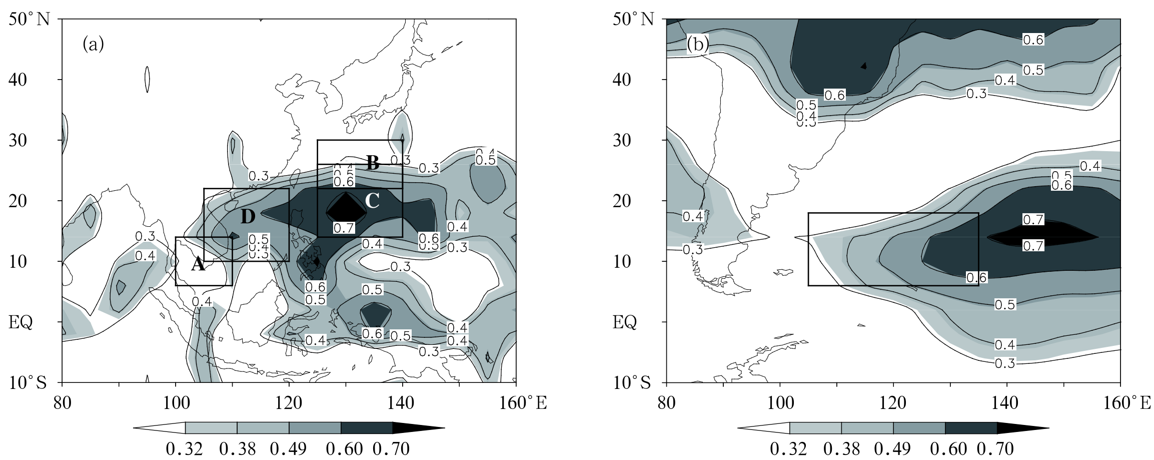

Fig. 2. Distributions of temporal ACCs between the IAP9L-AGCM hindcast experiment results and the corresponding observations during winters of 1982–2008 for (a) V1000 (marks A to D are defined in Table 4 and denote the regions where regionally averaged V1000 is taken as a predictor for winter precipitation over Hetao area and northern China, Yellow-Huai River basin, southeastern coastal China, and southern Yangtze River, respectively), and (b) geopotential height at 500 hPa (the rectangle is defined in Table 4 and denotes the region where regionally averaged H500 is taken as a predictor for winter precipitation over northern Northeast China).

Table 5. The ACC of regionally averaged variables obtained from the IAP9L-AGCM hindcast experiment results and the reanalysis data during winters of 1982–2008

Target region	Variable	Region of variable	ACC
Northern Northeast China	H500	42°–54°S, 25°–55°W	0.57
Southern Northeast China	V200	42°–54°N, 115°–130°E	–0.03
Hetao area and North China	V1000	6°–14°N, 100°–110°E	0.47
Yellow-Huai River basin	V1000	22°–30°N, 125°–140°E	0.57
Southeastern coastal China	V1000	14°–26°N, 125°–140°E	0.71
Southern Yangtze River	V1000	10°–22°N, 105°–120°E	0.71

regression analysis. The performance of the models to predict precipitation during winters of 1982–2008 was evaluated by using the cross-validation analysis. It can be seen in Fig. 3 that both the trends and interannual variations of regionally averaged precipitation derived from the prediction models are almost identical with

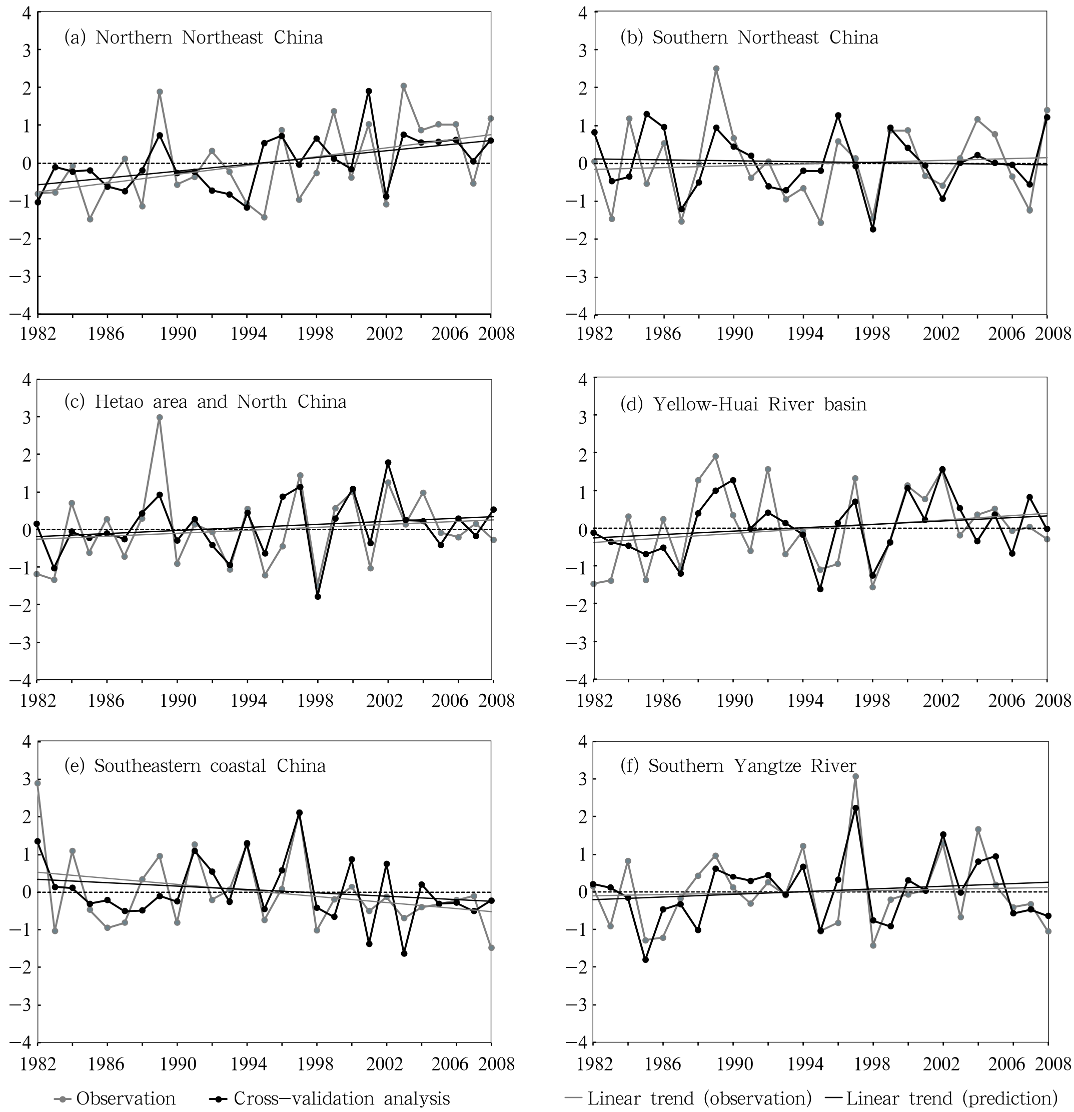

Fig. 3. Regionally averaged winter precipitation (curves) and its linear trend (straight lines) derived from observation (black) and cross-validation analysis (grey) of the hybrid prediction models for the six regions indicated on the top of each panel. Abscissa and ordinate denote year and the normalized percentage anomaly of winter precipitation during 1982–2008, respectively. Dashed line denotes a zero value.

those of the observation, and even the values from both kinds of sources are very close to each other in certain years. In a quantitative manner, ACC and RSSA between the predictions and observations are 0.60 and 82% in northern Northeast China, 0.64 and 82% in southern Northeast China, 0.74 and 74% in Hetao area and North China, 0.71 and 78% in Yellow-Huai River basin, 0.70 and 74% in southeastern coastal China, and 0.77 and 78% in southern Yangtze River, respectively.

In a further step to evaluate the advantage of the hybrid approach compared to purely statistical approach, changes in ACC, RMSE, MAE, and RSSA derived from the former relative to the latter were further calculated. As shown in Fig. 4, except for northern Northeast China and Yellow-Huai River basin, when both the preceding observed predictors and synchronous IAP9L-AGCM-based predictors are combined, ACCs of regionally averaged precipitation between the predictions and observations are increased, and, at the same time, the corresponding RMSE and MAE are decreased over the remaining four target regions. All of these mean a higher prediction skill of the hybrid approach than that of the purely statistical

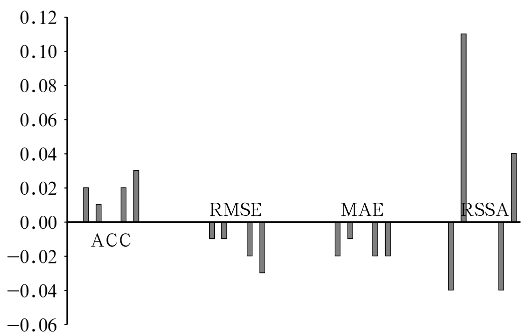

Fig. 4. Differences in statistical variables between the hybrid (using both the precursory observed predictors and synchronous IAP9L-AGCM predicted predictors) and purely statistical (using only the precursory observed predictors) approach results, with respect to the observations. Column charts arranged from left to right are the same as in Fig. 1. ACC, RMSE, and MAE equal zero in northern Northeast China and Yellow-Huai River basin, and RSSA equals zero in Hetao area and northern China and Yellow-Huai River basin.

approach. Therefore, the hybrid approach is indeed valuable in practice as a whole. On the other hand, the improvement of the prediction skill due to the synchronous predictors from the IAP9L-AGCM results is limited by and large, particularly with RSSA. It is likely that the prediction skill of winter precipitation can be a benefit from the hybrid approach if other climate models with better demonstrable skill are used.

4. Conclusions and discussion

Seasonal predictions of winter precipitation for six regions of eastern China have been performed in this study. First, both the key precursory and synchronous predictors for each of the regions were identified through correlation analysis. In the context of real-time prediction, a statistically and dynamically hybrid prediction approach by using these two kinds of predictors to establish the prediction models of winter precipitation was then configured. Given that the synchronous predictors may only be obtained by dynamic numerical prediction of climate models in practice, a set of ensemble hindcast experiments of winter climate during 1982–2008 were performed by using IAP9L-AGCM. In this way, the synchronous predictors that are not only closely related to winter precipitation but also numerically predictable by IAP9L-AGCM were determined. Finally, the hybrid statistical-dynamical prediction model for regionally averaged winter precipitation over each of the six regions of eastern China was finalized through a multivariate linear regression analysis, in which systematic errors between the original prediction and its observational counterpart was corrected over the most recent ten years.

Cross-validation analysis was used to investigate the ability of the hybrid approach to predict regional winter precipitation. It was found that the accuracy of the predictions, with respect to the observations, is relatively high, as they can reliably predict the trend, sign, and interannual variation of the regionally-averaged winter precipitation in each region. Averaged across all the six regions, ACC and RSSA between the observations and cross-validation analysis results are 0.69 and 78% during 1982–2008, respectively. Comparatively, the corresponding ACC and RSSA are reduced to 0.65 and 75%, respectively, when systematic errors between the original model prediction results and the corresponding observations are neglected, highlighting the importance of the above error correction scheme. In future, it is necessary to perform a set of real-time numerical prediction experiments of IAP9L-AGCM by using predicted SSTs rather than the present observed SSTs. Such a work can assess the skill of a fully real-time prediction for winter precipitation by use of the hybrid approach, and, hence, provide more valuable advice to operational prediction activities.

Climate factors that influence the winter precipitation over China are complex owing to special geographic location and topographic features of the country and also due to changes in the climate regimes. Uncertainty and limitation are inevitably embedded in the present hybrid approach. Several points are worth noting within the context of its application. First, a valuable predictor must satisfy the precondition that its relationship with the predictand is statistically significant and stable over time. Accordingly, special attention should be paid to the relationship between the winter precipitation over China and its potential predictors, such as snow over the Qinghai-Tibetan Plateau (Qin et al., 2006) and the Eurasian continent (Chen and Sun, 2003), sea ice at the high northern latitudes (Fang, 1987; Liu et al., 2007), and intensity of the high pressure system over North Pacific (Zhu et al., 1997). It is necessary to adjust the predictors in time for new predictions. Second, there are still debates on the seasonal difference in winter climate predictability in middle and high northern latitudes. For example, the maximum (minimum) predictability was suggested in spring (autumn) by Branković et al. (1994), Rowell (1998), and Zhao et al. (2000), while in summer (winter) by Yang et al. (1998). In contrast, Kumar et al. (2003) displayed a similar level of predictability of winter and summer climate. Using IAP9L-AGCM, Lang and Wang (2005) showed that the prediction skill is generally low in spring, but high either for surface temperature and geopotential height in the middle and upper troposphere during summer or for wind and precipitation during winter. As such, much attention should be given to the evaluation of the ability of climate models in predicting the synchronous predictors for winter precipitation from the perspective of real-time prediction, and, then, we shall make the best use of the dynamic predictions so as to improve the prediction skill of the hybrid approach. Given that the atmospheric general circulation fields most significantly correlated to winter precipitation over China are located over the Eurasian continent and coastal East Asia, the application of regional climate models may be helpful. In addition, winter precipitation over China is also linked to other climate factors beyond the consideration of the present work, such as the North Atlantic oscillation and Siberian high (Wu and Huang, 1999; Wang and Ding, 2006; Gao, 2009), which needs to be explored in depth. At last, the hybrid prediction approach in the present study may be applicable for seasonal climate predictions of the regions outside China, such as North America and Africa.

Acknowledgments. The author would like to sincerely thank the anonymous reviewers for their helpful comments and suggestions. Appreciation also goes to Dr. WANG Huijun of IAP, CAS for his valuable contribution to this work.

REFERENCES

Branković, Č., T. N. Palmer, and L. Ferranti, 1994: Predictability of seasonal atmospheric variations. *J. Climate*, **7**, 217–237.

Chang Rui, Zhang Qingyun, and Peng Jingbei, 2008: Response of the atmospheric circulation with heavy snow over southern China to the sea surface temperature anomaly in the key areas. *Climatic and Environmental Research*, **13**, 468–477. (in Chinese)

Chen Haishan and Sun Zhaobo, 2003: The effects of Eurasian snow cover anomaly on winter atmospheric general circulation. Part I: Observational studies. *Chinese J. Atmos. Sci.*, **27**, 304–316. (in Chinese)

Chen Hong, Lang Xianmei, Zhou Guangqing, et al., 2008: Prediction of climate anomalies over China in January 2008 with IAP climate models and its verification. *Climatic and Environmental Research*, **13**, 531–538. (in Chinese)

Chen Lijuan, Chen Deliang, Wang Huijun, et al., 2009:

Regionalization of precipitation regimes in China. *Atmospheric and Oceanic Science Letters*, **2**, 301–307.

Fan Ke and Wang Huijun, 2004: Antarctic oscillation and the dust weather frequency in North China. *Geophys. Res. Lett.*, **31**, L10201, doi: 10.1029/2004GLD 19465.

—— and ——, 2006: Interannual variability of Antarctic Oscillation and its influence on East Asian climate during boreal winter and spring. *Science in China* (*Series D*), **49**, 554–560.

Fang Zhifang, 1987: Interaction between subtropical high and polar ice in Northern Hemisphere. *Chinese Science Bulletin*, **32**, 330–335.

Gao Hui, 2009: China's snow disaster in 2008, who is the principal player? *Int. J. Climatol.*, **29**, 2191–2196.

Gong Daoyi and Wang Shaowu, 2001: Structure of the zonal-mean circulation over the Northern Hemisphere and its impact on climate of China in winter. *Scientia Geographica Sinica*, **21**, 108–112. (in Chinese)

—— and ——, 2003: Influence of Arctic Oscillation on winter climate over China. *Acta Geographica Sinica*, **58**, 559–568. (in Chinese)

Kalnay, E., M. Kanamitsu, R. Kistler, et al., 1996: The NCEP/NCAR reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–472.

Kumar, A., S. D. Schubert, and M. S. Suarez, 2003: Variability and predictability of 200-mb seasonal mean heights during summer and winter. *J. Geophys. Res.*, **108**(D5), 4169, doi: 10.1029/2002JD002728.

Lang Xianmei, 2008: Prediction model for spring dust weather frequency in North China. *Science in China* (*Series D*), **51**, 709–720.

—— and Wang Huijun, 2005: Seasonal differences of model predictability and the impact of SST in the Pacific. *Adv. Atmos. Sci.*, **22**, 103–113.

—— and ——, 2010: Improving extraseasonal summer rainfall prediction by merging information from GCMs and observations. *Wea. Forecasting*, **25**, 1263–1274.

Li, S., and G. T. Bates, 2007: Influence of the Atlantic multidecadal oscillation on the winter climate of East China. *Adv. Atmos. Sci.*, **24**, 126–135.

Liu, J., Z. Zhang, R. M. Horton, et al., 2007: Variability of North Pacific sea ice and East Asia-North Pacific winter climate. *J. Climate*, **20**, 1991–2001.

Mu Mingquan and Li Chongyin, 1999: ENSO signals in the interannual variability of East-Asian winter monsoon. Part I: Observed data analyses. *Chinese J. Atmos. Sci.*, **23**, 275–285. (in Chinese)

Qin Dahe, Liu Shiyin, and Li Peiji, 2006: Snow cover distribution, variability, and response to climate change in western China. *J. Climate*, **19**, 1820–1833.

Reynolds, R. W., N. A. Rayner, T. M. Smith, et al., 2002: An improved in situ and satellite SST analysis for climate. *J. Climate*, **15**, 1609–1625.

Rowell, D. P., 1998: Assessing potential seasonal predictability with an ensemble of multidecadal GCM simulations. *J. Climate*, **11**, 109–120.

Shi Neng, 1996: Secular variation of winter atmospheric teleconnection pattern in the Northern Hemisphere and its relation with China's climate change. *Acta Meteor. Sinica*, **54**, 675–683. (in Chinese)

Sun Jianqi, Wang Huijun, and Yuan Wei, 2009: A preliminary investigation on causes of the catastrophic snowstorm in March 2007 in the northeastern parts of China. *Acta Meteor. Sinica*, **67**, 469–477. (in Chinese)

Tao Shiyan and Wei Jie, 2008: Severe snow and freezing-rain in January 2008 in the southern China. *Climatic and Environmental Research*, **13**, 337–350. (in Chinese)

Wang Huijun, 2003: the extra-strong warm winter event in North Asia and its accompanying anomalous atmospheric circulation. *Chinese Sci. Bull.*, **48**, 1031–1033.

—— and Fan Ke, 2009: A new scheme for improving the seasonal prediction of summer precipitation anomalies. *Wea. Forecasting*, **24**, 548–554.

—— and Sun Jianqi, 2009: Variability of Northeast China river break-up date. *Adv. Atmos. Sci.*, **26**, 701–706.

——, Lang Xianmei, Zhou Guangqing, et al., 2003: A preliminary report of the model prediction on the forthcoming winter and spring dust climate over China. *Chinese J. Atmos. Sci.*, **27**, 136–140. (in Chinese)

Wang Zunya and Ding Yihui, 2006: Climate change of the cold wave frequency of China in the last 53 years and the possible reasons. *Chinese J. Atmos. Sci.*, **30**, 1068–1076. (in Chinese)

Wei Jie, Tao Shiyan, and Zhao Linna, 2008: Predictability of snow storm and freezing rain disaster in southern China in January 2008. *Climatic and Environmental Research*, **13**, 520–530. (in Chinese)

Wen, M., S. Yang, A. Kumar, et al., 2009: An analysis of the large-scale climate anomalies associated with the snowstorms affecting China in January 2008. *Mon. Wea. Rev.*, **137**, 1111–1131.

Wu Bingyi and Huang Ronghui, 1999: Effects of the extremes in the North Atlantic oscillation on East Asian winter monsoon. *Chinese J. Atmos. Sci.*, **23**, 641–651. (in Chinese)

Yang Hui and Li Chongyin, 2008: Influence of Arctic Oscillation on temperature and precipitation over winter. *Climatic and Environmental Research*, **13**, 395–404. (in Chinese)

Yang, X. Q., J. L. Anderson, and W. F. Stern, 1998: Reproducible forced modes in AGCM ensemble integrations and potential predictability of atmospheric seasonal variations in the extratropics. *J. Climate*, **11**, 2942–2959.

Zhang Li, Ding Yihui, and Ren Guoyu, 2005: Variation of dust weather and its climatic attribution analysis in northern part of China. *J. Appl. Meteor. Sci.*, **16**, 583–592. (in Chinese)

Zhao Yan, Guo Yufu, Yuan Chongguang, et al., 2000: Study on the predictability of numerical short-term climate prediction. *J. Appl. Meteor. Sci.*, **11**(Suppl.), 64–71. (in Chinese)

Zhu Qiangen, Shi Neng, Wu Zhaohui, et al., 1997: The long-term change of atmospheric active centers in northern winter and its correlation with China climate in recent 100 years. *Acta Meteor. Sinica*, **55**, 750–758. (in Chinese)