Seasonal Prediction of Spring Dust Weather Frequency in Beijing*

LANG Xianmei† (郎咸梅)

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

(Received July 5, 2010; in final form April 8, 2011)

ABSTRACT

In this paper, seasonal prediction of spring dust weather frequency (DWF) in Beijing during 1982–2008 has been performed. First, correlation analyses are conducted to identify antecedent climate signals during last winter that are statistically significantly related to spring DWF in Beijing. Then, a seasonal prediction model of spring DWF in Beijing is established through multivariate linear regression analysis, in which the systematic error between the result of original prediction model and the observation, averaged over the last 10 years, is corrected. In addition, it is found that climate signals occurring synchronously with spring dust weather, particularly meridional wind at 850 hPa over western Mongolian Plateau, are also linked closely to spring DWF in Beijing. As such, statistical and dynamic prediction approaches should be combined to include these synchronous predictors into the prediction model in the real-time operational prediction, so as to further improve the prediction accuracy of spring DWF in Beijing, even over North China. However, realizing such a prediction idea in practice depends essentially on the ability of climate models in predicting key climate signals associated with spring DWF in Beijing.

Key words: spring dust weather frequency in Beijing, prediction model, systematic error, climate model

Citation: Lang Xianmei, 2011: Seasonal prediction of spring dust weather frequency in Beijing. *Acta Meteor. Sinica*, **25**(5), 682–690, doi: 10.1007/s13351-011-0511-z.

1. Introduction

China is one of the countries which suffer from the most severe meteorological disasters. Drought, flood, dust weather, low temperature during summer, frost, cold disaster, snowstorm, landfalling typhoon, etc., are main weather and climate disasters in China (Huang et al., 2003). In recent years, spring dust weather occurring frequently in northern China has impacted upon many aspects of the social system, leads to considerable economic loss by influencing air quality, regional climate, traffic, human heath, etc., and becomes one of the severest natural disasters in the country. Dust weather is closely linked to geophysical environment and meteorological conditions. Its occurrence is determined mainly by land surface characteristics and weather and climate conditions in the dust source area, while its transformation is determined mainly by weather and climate conditions. At present, seasonal prediction of spring dust weather is a key issue in the field of short-term climate prediction in China. For example, spring dust weather forecasting meetings have been held twice annually in the National Climate Center since 2003. One of the key topics at the meeting is about the seasonal and extra-seasonal prediction of spring dust weather in China.

In general, two methods are taken in predicting spring dust weather on the seasonal timescale, i.e., purely statistical and dynamic methods. The former uses statistical method to establish prediction models on the basis of precursory atmospheric circulation modes and meteorological variables that are closely related to spring dust weather (Quan et al., 2001; Mao et al., 2005). The latter predicts spring weather directly by using the dust module embedded in climate models (Nickovic et al., 2001), or indirectly by using a synthesis of dust weather-related atmospheric factors and meteorological variables derived from a dynamic prediction system (Wang Huijun et al., 2003; Chen et al., 2004). On the whole, owing to the

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

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

complicated nature of the precursory climate predictors of spring dust weather in China, the skill of the pure statistical prediction approach needs to be improved, particularly in the way to reasonably identify the precursory predictors. On the other hand, the dynamic prediction system and its performance are limited overall in terms of accuracy due to the imperfection of climate models. Accordingly, the prediction by use of dynamically predicted main climate factors of dust weather is largely uncertain. Taken together, the skill of spring dust weather prediction needs to be further improved although many advances have been achieved in recent years.

Based on a pure statistical approach alone and a combination of statistical and dynamic approaches, Lang (2008) predicted spring dust weather in northern China on the seasonal and extra-seasonal scales, respectively, which provides a new implementation in this area. However, the corresponding prediction skill of spring dust weather is still limited in practice. An important reason is that the number of predictors is relatively large, which tends to lead to the instability of prediction, particularly when the relationship between some predictors and dust weather weakens or is even not statistically significant any more. Therefore, three steps have been taken in this study to improve the seasonal prediction of spring dust weather in Beijing. First, to improve the skill and stability of the prediction model, the number of predictors is reduced, in which only the critical precursory and synchronous predictors are considered. Second, the areas where predictors such as regionally averaged precipitation and surface air temperature are identified cover the global, rather than China as before. Finally, the systematic error between the result of the original prediction model and the observation is corrected so as to improve the accuracy of prediction.

2. Data and method

Winter is defined as the average of December–January–February (DJF), and spring as the average of March–April–May (MAM). Spring dust weather frequency (DWF) is defined as the sum of the days with blown sand, floating dust, or dust storm. DWF observation at Beijing was obtained from the National Climate Center of the China Meteorological Administration. Since spring DWF in Beijing is almost the same as that in northern China on the whole (Zhou, 2001; Wang Shigong et al., 2003; Wang and Zhai, 2004), the result of this study based on Beijing station is appropriate for addressing spring DWF prediction related problems over the whole northern China.

The precursory variables and climate factors during last winter consist of meridional wind at 850 hPa (V850, northward wind speed is positive), surface air temperature (SAT), precipitation (PRE), sea surface temperature (SST), the Arctic Oscillation (AO), the Antarctic Oscillation (AAO), the Southern Oscillation index (SOI), and Eurasian westerly index (EUI). V850, PRE, AO, AAO, SOI, and geopotential height at 500 hPa used for calculating EUI were obtained from the Climate Prediction Center (CPC) of the National Weather Service of the US National Oceanic and Atmospheric Administration (NOAA). The horizontal resolution of V850 and PRE data is $2.5^\circ\times2.5^\circ$. The AO (AAO) is defined as the time coefficient series of the first mode of empirical orthogonal function analysis of the geopotential height anomalies at 1000 hPa (700 hPa) poleward of 20°N (20°S). The EUI is defined as the normalized difference of zonally averaged geopotential height at 500 hPa along 40°–65°N, 60°–120°E. The SAT data, with a horizontal resolution of $2.5^\circ\times2.5^\circ$, were obtained from the US National Centers for Environmental Prediction (NCEP). The SST data, with a horizontal resolution of $1^\circ\times1^\circ$, were from the National Aeronautics and Space Administration (NASA) (Reynolds et al., 2002). The present study period is 1982–2008, during which the reanalysis data are more reliable than before owing to the availability of satellite data.

To investigate the effect of synchronous factors on spring dust weather prediction, a set of hindcast experiments of spring climate during 1982–2008 were performed by using an atmospheric general circulation model developed at the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP9L-AGCM). The model has a horizontal resolution of

5°×4° and 9 levels in the vertical, with the top at 10 hPa. The model has been widely used in the numerical simulation and short-term climate prediction studies (Jiang and Zhang, 2006; Lang and Wang, 2008). For each year, the ensemble hindcast experiments were composed of seven integrations from February 25 to the end of May, which were forced by observed monthly SSTs and initialized from the atmospheric conditions on 22–28 February from the NCEP/NCAR reanalysis dataset (Kalnay et al., 1996). The result was expressed as the ensemble mean of the seven integrations with the same weights.

3. The seasonal prediction model

3.1 Correlation analysis between spring DWF in Beijing and climate factors during last winter

It has been documented that surface wind strength, SAT, and precipitation are main factors determining spring dust weather in northern China (Zhang and Ren, 2003; Kang and Wang, 2005; Fan and Wang, 2006) and dominant factors for changes in spring DWF in Beijing (Zhang et al., 2005). On the other hand, the preceding SST has been well known as an important predictor of short-term climate and plays an important role in climate prediction on the seasonal scale (Goddard et al., 2001). Taken together, the relationship between spring DWF in Beijing and the preceding V850, SAT, PRE, and SST during last winter is first analyzed during 1982–2008, respectively.

It can be seen in Fig. 1a that spring DWF in Beijing has a statistically significant positive correlation with the preceding V850 over northwestern Badain Jaran desert and Hunshandake sand land during last winter, with the strongest relationship seen over western Mongolia and north of this region. In other words, spring DWF in Beijing is more than normal when low-tropospheric meridional wind strength is above normal, and vice versa. This means that dust weather

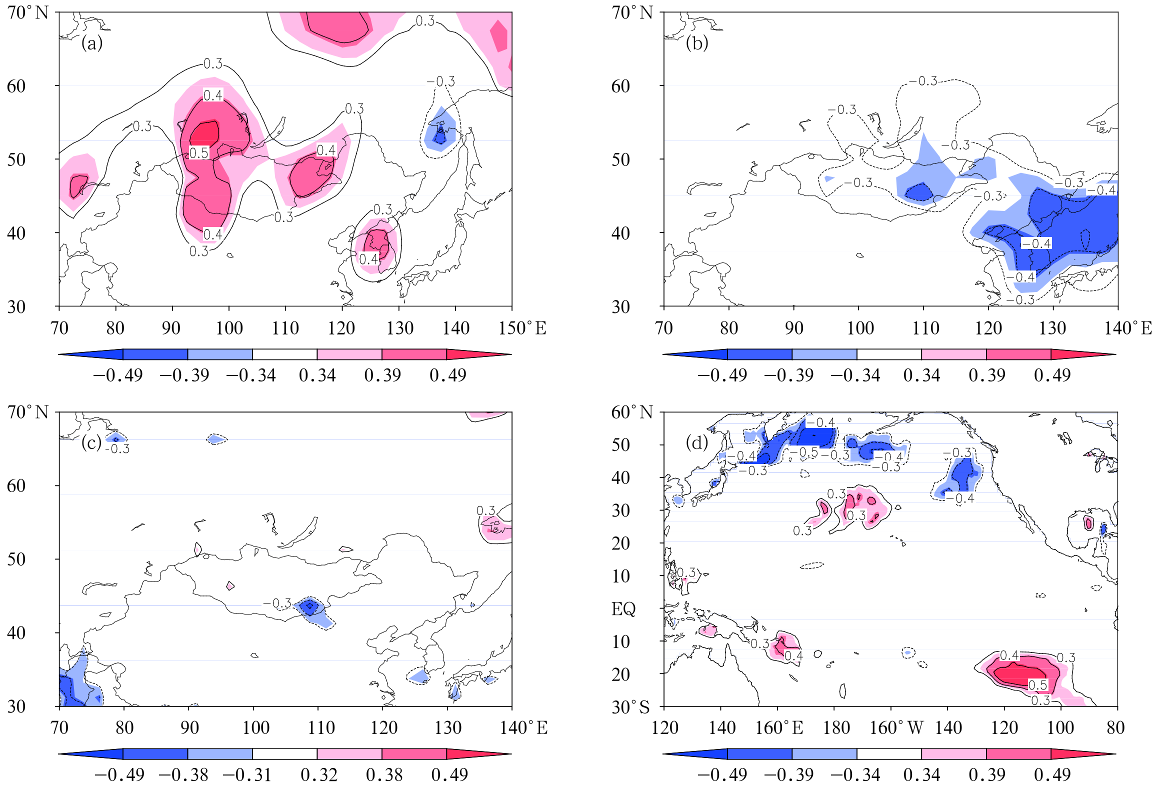

Fig. 1. The geographical distribution of the correlation coefficient between spring DWF in Beijing and the preceding (a) V850, (b) SAT, (c) PRE, and (d) SST during last winter during 1982–2008. Light to dark shadings correspond to the 90%, 95%, and 99% confidence levels, respectively.

occurring over the dust source area is inclined to move into northern China when the intensity of cold air is above normal over northern China and neighbouring areas in the north during last winter. This corroborates, to a certain degree, that the Mongolian cyclone during last winter can impact upon spring dust weather in northern China (Li et al., 2008), and that Hunshandake sand land is a main source of spring dust weather in Beijing (Qiu et al., 2008). Figures 1b and 1c show statistically significant negative correlations of spring DWF in Beijing with SAT and PRE over southwestern Buyant-Uhaa of Mongolia during last winter. According to the studies of Wang et al. (1995) and Zhang et al. (2002), the probable cause could be the following. The southern part of this area south to the adjacent mid-western Inner Mongolia of China is covered to a large extent by sand, and drier and looser than normal dust material tends to accumulate there when SAT and precipitation are below normal during the preceding winter. As such, when the ground of this area becomes warm and the soil thaws during spring, more dust material will be transformed along with northerly and northwesterly wind from Mongolia into northern China, where spring dust weather is therefore increased. Given that the locations where SAT and PRE are statistically significantly correlated to spring DWF in Beijing are almost the same, and that the mechanisms through which they affect spring dust weather in Beijing are similar, plus, the area with a statistically significant correlation coefficient between SAT and spring DWF in Beijing is overall larger, SAT rather than PRE is chosen as a predictor of spring DWF in Beijing, and SAT averaged over the regions from the northern part of northern China to Northeast China is chosen as one of the prediction factors.

On the other hand, sea surface condition, as an external forcing of atmosphere, has caught much attention in studies of spring dust weather forecast problems in northern China (Ye et al., 2000). Thus, the key oceanic region in which SST is closely related to spring DWF in Beijing and where the correlation is relatively large in extent is selected. As shown in Fig. 1d, spring DWF in Beijing is significantly correlated to the preceding SST in 1) northern North Pacific, 2) central North Pacific in the middle latitudes, and 3) the tropical southwestern Pacific during last winter, particularly in the third region where the obtained relationship is the largest as a whole. To examine the stability of such a relationship, the correlation coefficient between spring DWF in Beijing and regionally averaged SST in each of the above three oceanic regions is further calculated for each 20-yr moving window. A statistically significant and stable relationship is found only between spring DWF in Beijing and the preceding regionally averaged SST in the tropical southwestern Pacific during last winter, which is accordingly taken as a predictor for spring DWF in Beijing, although the underlying mechanism for the relationship is unclear. Collectively, regionally averaged V850, SAT, and SST addressed above are finally chosen as the critical predictors of spring dust weather condition in Beijing, and the corresponding correlation coefficient between each of them and the spring DWF in Beijing passes the significance test at the 99%, 95%, and 99.5% confidence level, respectively. The key region concerning each variable is given in Table 1.

Table 1. The region where the preceding regionally averaged variable during last winter is used as a predictor for spring DWF in Beijing. Also listed is the temporal correlation coefficient (ACC) between each predictor and the spring DWF in Beijing during 1982–2008

Variable	Region	ACC
V850	50.0°–55.0°N, 115.0°–127.5°E	0.54
SAT	Regions over China with confidence level above 95% in Fig. 1b	–0.46
SST	25.5°–14.5°S, 233.5°–260.5°W	0.60

Besides the above variables, relationships between spring DWF in Beijing and AO, AAO, EUI, and SOI on the interannual and interdecadal (smoothed over 11 yr) scales are also investigated. ACC between spring DWF in Beijing and each of the four factors is small overall on the interannual scale (Table 2). By contrast, except for SOI, the correlation is obviously large on the interdecadal scale, with ACC being significant at the 98% (AO), 98% (AAO), and 99% (EUI) confidence level, respectively. Since the systematic error between the original prediction model result and the observation over the most recent 10 years is removed, the final prediction result involves, to a certain extent, the interdecadal variation of predictors. It is therefore necessary to take AO, AAO, and EUI into consideration when establishing the seasonal prediction model of spring DWF in Beijing.

Table 2. ACC between spring DWF in Beijing and the preceding climate factors during last winter during 1982–2008

Factors	AO	AAO	EUI	SOI
ACC on the interannual scale	–0.19	–0.10	–0.32	0.09
ACC on the interdecadal scale	–0.47	–0.48	–0.68	0.11

3.2 Prediction model of spring DWF in Beijing

According to the above analyses, the preceding regionally averaged V850, SAT, and SST (AO, AAO, and EUI) during last winter are chosen as critical (alternative) predictors of spring DWF in Beijing during 1982–2008. A seasonal prediction model of spring DWF in Beijing is then constructed through multivariate linear regression analysis. Note that the prediction model is not finalized until the systematic error of spring DWF in Beijing between the original prediction model result and the observation over the most recent ten years is removed. This procedure has been found valuable for further improving the accuracy of prediction (Lang and Wang, 2010).

The ability of the prediction model is assessed by the ACC between the cross-validation analysis result of spring DWF in Beijing and its observational counterpart. Where a full range of combinations of all the above predictors are concerned, the combined effect of V850, SAT, SST, and AAO is found to be the most outstanding in terms of the accuracy of prediction and hence is taken in the present study. In this manner, if Y_0 and Y' denote the original prediction model result and the systematic error respectively, the predicted spring DWF (Y) in Beijing in a certain year can be expressed as follows:

$$Y_0 = A_0 + \sum_{i=1}^{m} A_i (x_i)_{\rm DJF},$$

$$Y' = \frac{1}{n}\sum_{j=1}^{n}((Y_0)_j - {\rm DWF}_j^{\rm obs}),$$

$$Y = Y_0 - Y', \qquad (1)$$

where x_i denotes the normalized series of AAO, regionally averaged V850, SAT, and SST; i and j represent the number of predictors and years for calculating the systematic error, respectively, i.e., 4 and 10; A_i denotes the weight coefficient of predictors in the regression equation. Additionally, for each year, the data of predictors cover the preceding 20 years, and A_i is therefore altered with target year.

Seasonal prediction of spring DWF in Beijing during 1982–2008 is performed by using cross-validation analysis with the above prediction model. It can be seen in Fig. 2 that the cross-validation analysis result of spring DWF in Beijing obtained by the prediction model is in a good agreement with observation in terms of interannual variation and linear trend, even values in certain years. During 1982–2008, ACC and RSSA (rate of the same sign of anomaly, i.e., the rate of the number of the years in which predicted anomalies are the same in sign as observation to the entire studied years) between the prediction and observation are 0.77 and 74%, respectively, indicating a high skill of the prediction model. It is worth noting that the corresponding ACC is reduced to 0.68 when the systematic error between the original prediction model result and the observation is neglected, suggesting the importance of such an error correction approach. In addition, to evaluate, in a quantitative manner, the effect that the predictors have in the prediction model, they are used to construct the fitting equation of spring DWF in Beijing during 1982–2008. The weight coefficient and partial correlation coefficient (at least at the 95% confidence level) of each predictor given in Table 3 indicate that, among all the predictors considered, SST (AAO) is the most (second) important for spring dust weather in Beijing, corroborating that the preceding AAO during last winter is indeed a valuable predictor of the subsequent spring dust weather in China, although the mechanism behind remains unclear (Fan and Wang, 2004; Lang, 2008). It is also revealed that the roles of V850

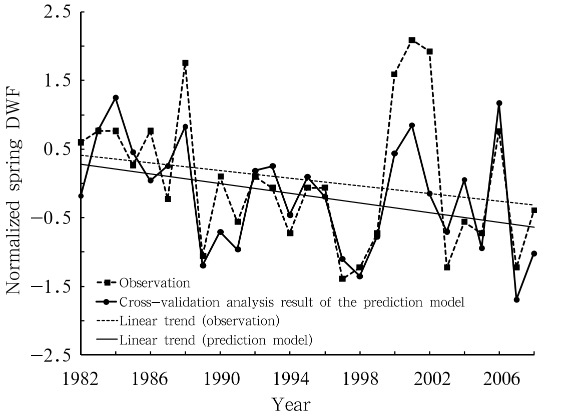

Fig. 2. The normalized interannual variation of spring DWF in Beijing during 1982–2008 as derived from the observation and cross-validation reanalysis result of the prediction model, respectively.

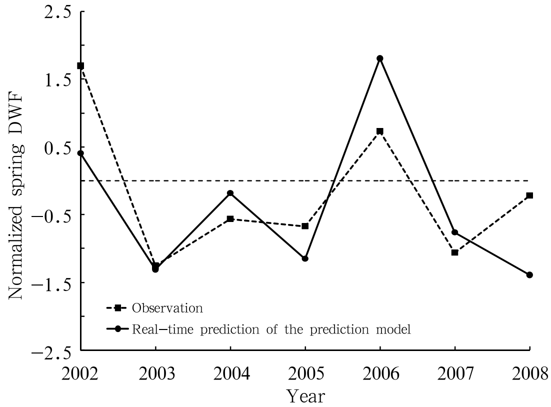

Fig. 3. The normalized interannual variation of spring DWF in Beijing during 2002–2008 as derived from the observation and real-time prediction of the prediction model, in which only the preceding predictors during last winter are used.

Table 3. Weight coefficient and partial correlation coefficient of each predictor in the fitting equation of spring DWF in Beijing during 1982–2008

	V850	SAT	SST	AAO
Weight coefficient	0.28	–0.29	0.59	0.45
Partial correlation coefficient	0.42	0.43	0.70	0.48

and SAT in predicting spring DWF in Beijing are comparable.

3.3 Seasonal real-time prediction of spring DWF in Beijing

The performance of a certain prediction model should be evaluated in practice. In this connection, seasonal real-time prediction of spring DWF in Beijing during 2002–2008 is performed by using the model constructed above. For each target year, the normalized value of each predictor is calculated on the basis of observation for the preceding 20 years. On the whole, the skill of prediction is high in terms of the interannual variation and RSSA of spring DWF in Beijing, with respect to observation (Fig. 3), particularly in 2003, 2004, and 2007. On the other hand, the magnitude of prediction disagrees in general with observation, and the interannual variation between the prediction and observation is not always the same, such as in 2008. This can be, at least partly, explained by the fact that spring dust weather in Beijing is closely related to not only the preceding climate factors, but also the synchronous climate conditions during spring. From the perspective of real-time prediction, only the preceding four predictors during last winter are used in the present prediction model. The synchronous valuable predictors are neglected, which inevitably restricts the skill of the prediction model. Given that the synchronous climate factors are not available in practice, an effective approach is to turn to the dynamic prediction of spring climate.

3.4 Idealized seasonal prediction model of spring DWF in Beijing

There is a close relationship between spring dust weather in northern China and the synchronous climate conditions. This brings the question as to the degree to which the skill of the prediction model may be changed if the synchronous valuable predictors during spring are included into the prediction model. To this end, the temporal correlation coefficient between spring DWF in Beijing and synchronous V850, SAT, and PRE reanalysis data is calculated, respectively, so as to examine the corresponding relationship between each other. It is found that spring DWF in Beijing has a statistically significant positive correlation with the synchronous V850 over western Mongolian Plateau, and a negative correlation with precipitation over eastern North China and SAT over mid-western Inner Mongolia, with the positive correlation being notably larger than the negative ones. Such being the case, the synchronous V850 over western Mongolian Plateau is further taken into account in Eq. (1) of the regression prediction model, so as to establish a new prediction model (hereinafter referred to as the idealized prediction model since the synchronous climate of spring dust weather is unavailable in the real-time operational prediction). The cross-validation analysis of the idealized prediction model during 1982–2008 indicates that the corresponding ACC and RSSA, with respect to observation, are increased to 0.82 and 82%, respectively. Moreover, the real-time prediction of the idealized model is closer to observation during 1982–2008 in terms of interannual variation, magnitude, and RSSA (being 100%). Compared to the skill of the prediction model in which only the preceding predictors during last winter are considered, ACC and RSSA are respectively increased by 0.11 and 13%, while root-mean-square error (RMSE) and mean absolute error (MAE) are respectively decreased by 0.19 and 0.17 (Fig. 4).

The above analysis indicates that the synchronous V850 over west of the Mongolian Plateau is valuable for predicting spring DWF in Beijing. A following issue of concern is how about the potential predictability

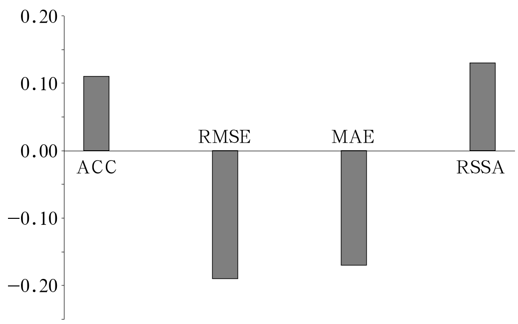

Fig. 4. Differences in ACC, RMSE, MAE, and RSSA of the predicted spring DWF in Beijing during 2002–2008 between the idealized (using both the precursory and synchronous predictors from observation) and real-time (using only the precursory predictors from observation) prediction model.

of this predictor in the climate model, as dynamic prediction is an effective way to obtain the data. Accordingly, a set of seasonal ensemble hindcast experiments of spring climate during 1982–2008 are performed by IAP9L-AGCM, and the predictability of V850 is examined. IAP9L-AGCM demonstrates a level of prediction skill for V850 in some regions, but a statistically significant skill cannot be seen over western Mongolian Plateau (figure omitted). That is to say, IAP9L-AGCM cannot provide a valuable real-time prediction for V850 needed by the idealized prediction model in practice. In future work, to realize a dynamical and statistical hybrid prediction approach for spring DWF in Beijing, two studies are imperative. One is to improve the skill of IAP9L-AGCM to predict spring climate through an effective correction scheme, and the other is to make use of the result of other climate models with a demonstrable prediction skill of spring climate. These shall be helpful for further improving the real-time prediction skill of spring dust weather in northern China.

4. Conclusions and discussion

In this study, the preceding V850, SAT, SST, AAO, AO, and EUI during last winter are first identified as predictors of spring DWF in Beijing by the correlation analysis. A seasonal prediction model of spring DWF in Beijing is then constructed through multivariate linear regression analysis, in which the systematic error between the original prediction model result and the observation is removed. Compared to the study of Lang (2008), the prediction model established here is much better. First, the valuable information of V850, SAT, PRE, and SST are looked for on the global scale, and the resultant predictors are therefore more representative. Second, the number of predictors is notably decreased. This procedure simplifies the formula of the regression prediction model and enhances the stability of the prediction skill as well. Finally, the accuracy of prediction is improved through an error correction scheme presented by Lang and Wang (2010). Therefore, the newly established prediction model of spring DWF in Beijing is more valuable in practice according to both the easiness of construction and the demonstrable skill of prediction.

When only the preceding V850, SAT, SST, and AAO during last winter are used as the predictors of spring DWF in Beijing, ACC and RSSA between the cross-validation analysis result and the observation are 0.77 and 74% during 1982–2008, respectively, and linear trend agrees well with each other as well, indicating a high skill of the prediction model. Furthermore, when the synchronous V850 during spring is additionally taken into account, not only ACC and RSSA are increased to 0.82 and 82%, respectively, but also the linear trend between the prediction and observation is more consistent. This gives importance to the use of the synchronous predictors of spring dust weather in Beijing. In practice, seasonal real-time prediction of spring dust weather in China is performed in late winter to early spring. As such, a dynamical and statistical hybrid prediction approach may be an effective way to take into account the predictors during both last winter and the synchronous spring. That is to say, the preceding predictors during last winter are obtained from observation, while the synchronous predictors are obtained from seasonal dynamic prediction of spring climate. It is seen from the earlier analysis this paper that the synchronous predictors of spring dust weather in northern China exist mainly in the middle and high latitudes, where the prediction skill of spring climate, as derived from climate models, is low overall. To apply the dynamical and statistical hybrid approach, one way is to develop an effective error correction scheme in light of the present prediction system of IAP9L-AGCM. On the other hand, special attention should be paid to the construction of new dynamic prediction systems with a demonstrable better performance. In this regard, the regional climate model suitable for the East Asian monsoon area should be emphasized, which has been an important aspect of climate model development in China (Fu et al., 2005; Gao et al., 2006). Finally, observational change in spring dust weather is in general consistent throughout northern China (Zhou, 2001; Wang Shigong, 2003; Wang and Zhai, 2004). Therefore, the present results concerning the seasonal prediction of spring DWF in Beijing are representative for the whole northern China and even a larger area. The prediction approach presented here can also be applied in the seasonal prediction of spring DWF in other regions of China where spring dust weather occurs frequently.

Acknowledgments. The author would like to sincerely thank the anonymous reviewers for their helpful comments and suggestions.

REFERENCES

Chen Hong, Lin Zhaohui, and Zhou Guangqing, 2004: Experimental dynamical prediction of spring dust storm events in China. *Climatic and Environmental Research*, **9**(1), 182–190. (in Chinese)

Fan Ke and Wang Huijun, 2004: Antarctic oscillation and the dust weather frequency in North China. *Geophys. Res. Lett.*, **31**, L10201, doi:10.1029/2002GL019465.

——, and ——, 2006: The interannual variability of dust weather frequency in Beijing and its global atmospheric circulation. *Chinese Journal of Geophysics*, **49**(4), 1006–1014.

Fu Congbin, Wang Shuyu, Xiong Zhe, et al., 2005: Regional climate model intercomparison project for Asia. *Bull. Amer. Meteor. Soc.*, **86**(2), 257–266.

Gao Xuejie, Xu Ying, Zhao Zongci, et al., 2006: On the role of resolution and topography in the simulation of East Asian precipitation. *Theor. Appl. Climatol.*, **86**(1), 173–185.

Goddard, L., S. J. Mason, S. E. Zebiak, et al., 2001: Current approaches to seasonal-to-interannual climate predictions. *Int. J. Climatol.*, **21**(9), 1111–1152.

Huang Ronghui, Chen Jilong, Zhou Liantong, et al., 2003: Studies on the relationship between the severe climatic disasters in China and the East Asian climate system. *Chinese J. Atmos. Sci.*, **27**(4), 770–787. (in Chinese)

Jiang Dabang and Zhang Zhongshi, 2006: Paleoclimate modelling at the Institute of Atmospheric Physics, Chinese Academy of Sciences. *Adv. Atmos. Sci.*, **23**(6), 1040–1049.

Kalnay, E., M. Kanamitsu, R. Kistler, et al., 1996: The NCEP/NCAR reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**(3), 437–472.

Kang Dujuan and Wang Huijun, 2005: Analysis on the decadal scale variation of the dust storm in North China. *Sci. China* (*Series D*), **48**(12), 2260–2266.

Lang Xianmei, 2008: Prediction model for spring dust weather frequency in North China. *Sc. China* (*Series D*), **51**(5), 709–720.

—— and Wang Huijun, 2008: Can the climate background of western North Pacific typhoon activity be predicted by climate model? *Chinese Sci. Bull.*, **53**(15), 2392–2399.

—— and ——, 2010: Improving extraseasonal summer rainfall prediction by merging information from GCMs and observations. *Wea. Forecasting*, **25**(4), 1263–1274.

Li Zhangjun, Sun Zhaobo, and Jiang Xuegong, 2008: Characteristic of dust transportation in dust storm process induced by Mongolia cyclone. *Journal of Desert Research*, **28**(5), 927–930. (in Chinese)

Mao Weiyi, Ali Mamtimin, Chen Sheng, et al., 2005: Relationship between the dust weather events and the eigenvalues of preceding monthly atmospheric circulation in Xinjiang in spring. *Arid Land Geography*, **28**(2), 171–175. (in Chinese)

Nickovic, S., G. Kallos, A. Papadopoulos, et al., 2001: A model for prediction of desert dust cycle in the atmosphere. *J. Geophys. Res.*, **106**(D16), 18113–18129.

Qiu Yujun, Niu Shengjie, Zou Xueyong, et al., 2008: Probability study on causes of dust events in Beijing. *Journal of Natural Disasters*, **17**(2), 93–98. (in Chinese)

Quan Linsheng, Shi Shaoying, Zhu Yafen, et al., 2001: Temporal-spatial distribution characteristics and causes of dust day in China. *Acta Geographica Sinica*, **56**(4), 477–485. (in Chinese)

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**(13), 1609–1625.

Wang Huijun, 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**(1), 136–140. (in Chinese)

Wang Shigong, Wang Jinyan, Zhou Zijiang, et al., 2003: Regional characteristics of dust events in China. *Acta Geographica Sinica*, **58**(2), 193–200. (in Chinese)

——, Yang Debao, Jin Jiong, et al., 1995: Analyses of time-space distribution and formative causes of sandstorms occurred in Northwest China. The Proceeding of the Second Academic Conference of Young Scientists of Chinese Association for Science and Technology. China Sciences and Technology Press, Beijing, 364–370. (in Chinese)

Wang Xiaoling and Zhai Panmao, 2004: The spatial and temporal variations of spring dust storms in China and its associations with surface winds and sea level pressures. *Acta Meteor. Sinica*, **62**(1), 96–103. (in Chinese)

Ye Duzheng, Chou Jifan, Liu Jiyuan, et al., 2000: Causes of sand-stormy weather in northern China and control measures. *Acta Geographica Sinica*, **55**(5), 513–521. (in Chinese)

Zhang Li and Ren Guoyu, 2003: Change in dust storm frequency and the climate controls in northern China. *Acta Meteor. Sinica*, **61**(6), 744–750. (in Chinese)

Zhang Renjian, Han Zhiwei, Wang Mingxing, et al., 2002: Dust storm weather in China: New characteristics and origins. *Quaternary Sciences*, **22**(4), 374–380. (in Chinese)

Zhang Xiaoling, Li Qingchun, Xie Pu, et al., 2005: Features and causes of dust weather in recent years in Beijing. *Journal of Desert Research*, **25**(3), 417–421. (in Chinese)

Zhou Zijiang, 2001: Blowing-sand and sandstorm in China in recent 45 years. *Quaternary Sciences*, **21**(1), 9–17. (in Chinese)