A Review of Seasonal Climate Prediction Research in China

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ABSTRACT

The ultimate goal of climate research is to produce climate predictions on various time scales. In China, efforts to predict the climate started in the 1930s. Experimental operational climate forecasts have been performed since the late 1950s, based on historical analog circulation patterns. However, due to the inherent complexity of climate variability, the forecasts produced at that time were fairly inaccurate. Only from the late 1980s has seasonal climate prediction experienced substantial progress, when the Tropical Ocean and Global Atmosphere project of the World Climate Research program (WCRP) was launched. This paper, following a brief description of the history of seasonal climate prediction research, provides an overview of these studies in China. Processes and factors associated with the climate variability and predictability are discussed based on the literature published by Chinese scientists. These studies in China mirror aspects of the climate research effort made in other parts of the world over the past several decades, and are particularly associated with monsoon research in East Asia. As the climate warms, climate extremes, their frequency, and intensity are projected to change, with a large possibility that they will increase. Thus, seasonal climate prediction is even more important for China in order to effectively mitigate disasters produced by climate extremes, such as frequent floods, droughts, and the heavy frozen rain events of South China.

Key words: seasonal prediction, climate variability, predictability

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1. Introduction

In 1934, a well-known Chinese meteorologist, ZHU Kezhen, published a paper to document the southeastern Asian monsoon's circulation characteristics and its association with rainfall in China (Zhu, 1934). Following that, TU Changwang, who was later the administrator of the China Meteorological Administration in the 1950s, studied the relationship between precipitation in China and atmospheric oscillations and attempted to provide an outlook for summer precipitation in China by considering the early signals of atmospheric oscillations, particularly the Southern Hemisphere oscillation (Tu, 1937). This was the first attempt to address seasonal climate prediction. Tu and Huang (1944) further revealed that the monsoon in China is characterized by seasonal migration from South China to North China during the spring–summer and a retreat during late summer–autumn. Therefore, an efficient outlook for precipitation may be obtained only on the basis of sufficient understanding of the above seasonal movement of the rain belt and its associated atmospheric circulation features, both locally and remotely.

Operational long-range weather forecasting (referring to seasonal climate prediction or short-term climate prediction) started in 1958, based on various empirical methods. YANG Jianchu, a senior climatological expert at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), was the pioneer in this field. He proposed making short-term climate predictions by considering the persistence of meteorological quantities, historical analog patterns, atmospheric periodicities, and atmospheric teleconnection. Following that, various statistical methods were developed and employed in short-term climate predictions for both scientific research and operational applications.

In 1988, the climate model development group at the IAP, led by ZENG Qingcun, conducted a dynamical seasonal climate prediction experiment by running the IAP atmospheric general circulation model (AGCM) coupled with a tropical Pacific oceanic general circulation model (OGCM). The results were encouraging and were published in 1990 (Zeng et al., 1990). The philosophy of the experimental research was based on the impacts of the tropical oceanographic anomalies

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on the global atmosphere, which is the theory of the Tropical Ocean and Global Atmosphere Program (TOGA). Validation of the AGCM's capability to "forecast" the summer rainfall anomaly, given the observed SST, was performed (Wang, 1997). The results revealed a general low predictability of the summer rainfall anomaly over a large part of China, particularly in the northern areas. Therefore, a number of correction techniques were developed to improve the GCM output (Zeng et al., 1994; Wang et al., 2000b). Variable effects were achieved by applying correction schemes.

There have also been scientific endeavors to improve OGCM and ENSO predictions (Zhou et al., 1998; Zhou and Zeng, 2001) and to improve land surface process modeling (Dai and Zeng, 1996). The comprehensive land surface process model developed at the IAP by Dai and Zeng (1996) was adopted as the major basis for coding the common land model at the National Center for Atmospheric Research (NCAR) in the US (Zeng et al., 2002). Meanwhile, the coupled model developed for seasonal climate prediction was later widely used for various purposes, including a doubling CO_2-induced climate change simulation, paleoclimate simulations for the last glacial maximum and the mid-Holocene, and so on (Wang and Zeng, 1992a, 1992b; Wang et al., 1993).

Since global GCMs had course resolutions, dynamical downscaling predictions were tested by several groups in China (e.g., Liu et al., 2005a). Liu et al. (2005a) employed a modified regional climate model (RegCM) to perform a 10-yr (1991–2000) hindcast experiment forced by hindcast results from a coupled GCM (CGCM) that was jointly developed by the IAP and the National Climate Center of China on the basis of the European Center for Medium-Range Weather Forecasting (ECMWF) model. The anomaly pattern correlation coefficient between the observed and simulated summer precipitation demonstrated variable scores from year to year, but with overall limited skill. A study by Gao et al. (2006) demonstrated that the spatial resolution of regional climate models plays an important role in reproducing the summer precipitation anomaly. They indicated that a grid point spacing of at least 60 km is needed to reproduce the observed precipitation patterns reasonably well (Gao et al., 2006).

The role of land surface processes in short-term climate variability in China was first tested through AGCM sensitivity experiments. The results of early experiments by Yeh et al. (1983, 1984) suggested that initial soil moisture or snow cover anomalies may lead to anomalous summer climates. This finding was subsequently demonstrated by several other numerical experiments (e.g., Lin et al., 2001). Therefore, efforts have been made to design soil moisture and temperature assimilation schemes in order to improve seasonal climate prediction skill (Zhan, 2008; Zhan and Lin, 2011). Snow and sea ice cover changes as well as dynamical vegetation processes have also been found to play roles in seasonal climate variability (Zhao et al., 2004b; Chen et al., 2009; Wu et al., 2009a, 2009b; Liu et al., 2012; Ma et al., 2012; Li and Wang, 2012).

Statistical downscaling for rainfall prediction in China using GCM outputs of large-scale circulation (e.g. geopotential height of 500 hPa or sea-level pressure) has been another topic of interest in recent years (Kang et al., 2007; Wang et al., 2007b; Zhu et al., 2008). However, the effectiveness of statistical downscaling is weak when applied to rainfall in China as compared to Southeast Asia (e.g. the Philippines). This is likely attributable to the fact that precipitation in China is substantially affected by mid- and high-latitude variability, which is quite difficult to predict, in addition to low-latitude variability, whereas precipitation in Southeast Asia is mainly modulated by tropical variability. Thus, new statistical downscaling schemes suitable for use in China should be developed in the future to achieve better prediction scores. A recent scheme proposed by Wang and Fan (2009) has the potential to result in higher prediction skill. In their scheme, the summer precipitation anomaly patterns in the historical analog years are considered, together with the model output precipitation anomaly, to compose the final prediction. Outputs from six European CGCMs for the years of 1979–2001 were employed to verify the effectiveness of the new scheme. Cross-validation for summer precipitation prediction shows that the anomaly pattern correlation coefficient increases and the root-mean-square error (RMSE) reduces. Based on the above CGCMs, Liu and Fan (2012a) and Chen et al. (2012) also developed statistical downscaling models to predict spring and summer precipitation in China, separately. Both the statistical downscaling models outperformed the original CGCMs. Also, from the results of Liu and Fan (2012a), it is indicated that a combination of the synchronous and preceding information involved in the statistical downscaling model is an effective method to improve the predictive capability. All of these previous studies developed statistical downscaling schemes to improve regional climate prediction. Recently, Sun and Chen (2012) showed that the statistical downscaling method can also be used to improve global climate prediction if the better predicted and more stable predictors can be successfully selected from the CGCM.

Since 2003, both dynamical and statistical models have been developed to make seasonal forecasts of the climate background conditions for dust weather in North China and tropical cyclones over the western North Pacific (WNP) (Wang et al., 2003; Wang et al., 2006; Lang and Wang, 2008). The results are promising, particularly when the GCM output is combined with the preceding observed SST anomalies, as well as the major atmospheric modes including the Antarctic Oscillation, North Pacific Oscillation etc.

Another interesting finding is associated with the selection of the object that is to be predicted. Traditionally, the precipitation anomaly (or another quantity) in comparison to its multi-year average is selected as the predictand. The year-to-year increment for a quantity is chosen as the new predictand (Wang et al., 2000b; Fan et al., 2008). When new statistical models established for the new predictand, such as those for summer precipitation, surface air temperature, and WNP tropical cyclone frequency, are applied, higher prediction scores can be achieved.

In the context of the above brief history of seasonal climate prediction research, the present paper reviews Chinese studies on the factors and processes associated with precipitation and monsoons, and seasonal predictions for the climate background of dust weather in North China and typhoon activity. A summary and an indication of prospects for future research is provided in the concluding section.

2. Factors and processes associated with summer precipitation and monsoon

2.1. *Major characteristics of the East Asian summer monsoon and precipitation*

A substantial part of China's population lives in the basins of the great rivers such as the Yangtze River. In addition, agricultural production plays a significant role in China's domestic economy. As a result, climate, particularly in the summer, exerts a significant influence on the country. Anomalous climate events, particularly floods and droughts resulting from the East Asian summer monsoon (EASM) anomaly, often cause severe disasters. For example, the devastating floods in the middle and lower basin of the Yangtze River in the summer of 1998 cost over two thousand human lives and resulted in a direct loss of 145.09 billion RMB ($\sim$ 20 billion US dollars). The severe drought in West China in the summer of 1996 resulted in a deficiency of drinking water for a population of 18 million and accounted for a loss of 15 billion RMB ($\sim$ 2 billion US dollars). Thus, the prediction of summer precipitation and the EASM is a major priority for seasonal climate research in China.

It is well known that the formation of monsoons is related to the seasonal transition of the structure of atmospheric circulation. The circulation system forming the EASM is different from that of the Indian summer monsoon, albeit they are linked to each other to some extent, as summarized by Tao and Chen (1987). In comparison to the Indian summer monsoon, the moisture source for the EASM area is not only the Bay of Bengal, but also the South China Sea and the west subtropical Pacific (Wang and Chen, 2012). In contrast, the southwesterly airflow bringing moisture to the Indian summer monsoon rainfall solely originates from the ITCZ, blowing along the Somali coast across the Arabian Sea to reach South Asia. Both the EASM and the South Asian monsoon are strongly regulated by ENSO and the mechanical/thermal effects of the Tibetan Plateau, and this is demonstrated in many recent publications (e.g., Wang et al., 2000a; Zhao et al., 2007; Wang and Chen, 2012). The EASM can be affected by extratropical processes from the Northern Hemisphere (e.g. the Arctic Oscillation, Arctic sea ice extent, North Atlantic Oscillation, North Pacific Oscillation, and the interdecadal modes in the Atlantic and Pacific), as supported by numerous recent evidence (e.g., Sun et al., 2008a, 2008b). In addition, the EASM is affected by synoptic systems of the Southern Hemisphere, including the Mascarene High, Australian High, and Antarctic Oscillation. These features illustrate that complicated systems are involved in the formation of the EASM, and this explains the strong interannual variability of China's rainfall as well as the great challenges encountered in predicting summer rainfall.

Concurrently, the climatological summer seasonal rainfall in China also exhibits some particular features. The onset of the EASM usually begins in South China in May, with a strong rainfall band in coastal southeastern China. Following that, rainfall moves seasonally to the north until mid-August, with a rainfall band shifting to the middle and lower basins of the Yangtze River in mid-June and a further shift northward to North China in mid-July. After mid-August, the EASM retreats swiftly to the south. However, the year-to-year variations of this pattern are considerable, with the sequence of events often being disturbed and causing substantial rainfall anomalies. The variability of rainfall in China usually exhibits two leading patterns, as indicated by the analytical Empirical Orthogonal Function (EOF). The first one is a triple pattern with more/less rainfall in both southeastern China and North China sandwiched between less/more rainfall in the middle and lower basins of the Yangtze River. The second one is a dipolar pattern with more/less rainfall in southern China along with less/more rainfall in northern China. The key to summer rainfall prediction is estimating the occurrence probability of the rainfall pattern.

2.2. *Role of SST*

Due to their longer persistence relative to atmospheric internal anomalies, SSTs play an important role in summer precipitation prediction. As such, the SST is also a practical factor in seasonal climate prediction. El Niño/La Niña events are the strongest signal of global climate on interannual timescales. Naturally, their impacts on the EASM have been investigated in a great number of studies. As early as the 1930s, before a coherent link between El Niño and the Southern Oscillation (SO) had been established, and before the word ENSO had been coined, Chinese scientists had already noted a relationship between summer rainfall in China and the SO. Tu (1937) found that the SO is positively correlated to the rainfall in the middle-lower basin of the Yangtze River, but negatively correlated to the rainfall in southeastern China. Decades later, when a record strong ENSO event occurred in 1982/83, the link between the EASM and ENSO was extensively investigated. Some studies suggested that the impact of ENSO depends on the timing of warm/cold event occurrence or the location where warming/cooling first emerges (Tao et al., 1988; Li, 1990). The impact of ENSO was further clarified and found to depend on the phase stage of the event. In the summer following the mature phase of an El Niño event, such as those in 1983 and 1998, the middle and lower basin of the Yangtze River is expected to receive more rainfall (Huang and Wu, 1989). The time-lagged impact of ENSO on the EASM occurs through a lower-tropospheric anticyclone around the Philippine Sea in the western Pacific. The southwesterly in the rear of the anticyclone overlaps and intensifies the climatological southwesterly in the summer and transports more moisture to East China, resulting in more rainfall in the basin of the Yangtze River. However, the formation of the lower-level anticyclone is controversial. One viewpoint is that it is induced by a tropical Rossby wave propagating westward and that it self-intensifies through local air–sea interactions near the Philippines (Wang et al., 2000a). The Rossby wave is excited by the ENSO-induced diabatic heating anomalies over the central-eastern Pacific. When the wave reaches the western Pacific, it induces an anticyclone near the Philippine Sea. The associated lower-level winds modify the seasonal trade wind, and the local feedback between evaporation and wind favors the enhancement of the anticyclone. The other viewpoint is that the anticyclone is induced by Indian Ocean basin-scale warming following an ENSO event (Yang et al., 2007; Li et al., 2008). The warming is often excited by the ENSO event, with a lag of several months. This process is analogous to charging an electric capacitor. Nonetheless, the underlying physics needs to be further revealed. More recently, the impact of ENSO was found to be nonlinearly dependent on the amplitude of the event itself. However, a stronger ENSO event tends to have a larger impact on summer rainfall in China (Xue and Liu, 2007). On the other hand, there are some studies that have found the relationship between ENSO and East Asian monsoon is unstable (Wang, 2002; Wang and He, 2012; Wang et al., 2013; He et al., 2013; He, 2013; He and Wang, 2013a, 2013b). Over some periods, their relationship is close, but over other periods it is broken, indicating that caution should be applied when making predictions of East Asian monsoon using the ENSO signal.

In comparison with ENSO, the tropical western Pacific exerts a more direct influence on the EASM. The western tropical Pacific is part of the largest warm pool of the world's oceans. Previous studies have revealed that summer rainfall in North China is negatively correlated with the SST in the western Pacific Ocean, and this relationship is opposite for rainfall in central China (Tao et al., 1988). This appears reasonable, since the warmer western tropical Pacific tends to trigger stronger local convection. Enhanced convection intensifies the subtropical anticyclone over the western Pacific, favoring a stronger northward-stretching southwesterly reaching a northerly location. Soon after, the underlying mechanism was extensively explored by Huang and Li (1987) and Nitta (1987), who both proposed a wave train originating from the convection region and propagating to the northeast. They respectively coined the wave train the East-Asian–Pacific (EAP) and Pacific–Japan (PJ) pattern. Since there is a seesaw relationship between the SSTs of the central-eastern and western Pacific, the western Pacific can potentially act as a bridge linking ENSO to East Asia.

In addition to the tropical Pacific, the SST in the WNP, particularly in the region of the Kuroshio Current, is another factor that influences summer rainfall. As early as the 1970s, studies suggested that the winter SST in the region is well correlated with the following summer's rainfall in the middle and lower basin of the Yangtze River. When the primary axis of the region with maximum SST is located in a southerly position, it favors more summer rainfall in central China, and vice versa. Due to the coherence of the Pacific basin SST, the extent and manner in which ENSO acts as a role in this link is unclear. Recently, Zhu et al. (2011) further found that a phase change in the Pacific Decadal Oscillation can contribute to a decadal shift in East Asian monsoon rainfall.

As for the Indian Ocean, Chinese scientists have found that its SST is closely correlated to the June–July mean rainfall in the Yangtze River basin (Luo et al., 1985; Jin and Shen, 1987; Deng et al., 1989). An SST structure with warm anomalies in the eastern Indian Ocean and South China Sea along with cold anomalies in the western part of the Indian Ocean is linked to more rainfall in central China, and vice versa (Chen, 1988). This point was also confirmed by studies on the link between the rainfall in China and the SST contrast between the South China Sea and Arabian Sea (Deng et al., 1989), as well as studies on the impact of the Indian SST dipolar mode (Li and Mu, 2001). In addition to this structure, the basin-scale warmth/coldness, which is the leading mode on interannual timescales, is another SST pattern that influences the EASM. Numerical experiments by Wu and Liu (1995) revealed that the Indian Ocean basin-scale anomalies excite not only neighborhood rainfall responses but also large-scale circulation anomalies in the western tropical Pacific. In view of the excitation role of western Pacific heating on the EAP or PJ wave train, the hypothesis that the Indian Ocean SST influences East Asian summer rainfall seems reasonable. As mentioned above, recent studies have illustrated that this pattern indeed favors an enhancement of summer rainfall in central China by forcing an anticyclone over the Philippine Sea (Yang et al., 2007; Li et al., 2008). This provides an alternative explanation for the increased summer rainfall in El Niño events that follow these summers.

As for the Atlantic Ocean, the winter North Atlantic SST can be a precursor to the following summer's rainfall in the middle and lower basin of the Yangtze River. An early warm North Atlantic favors an early onset of the following summer's Mei-yu in central China, and vice versa (Xu et al., 2001). Additionally, a dipolar SST pattern with warm water in the latitudes north of Newfoundland and cold water in the south favors the emergence of meridional circulation patterns in both the winter and the following summer, causing more summer rainfall in northeastern China (Bai, 2001). These Atlantic impacts are physically reasonable, because two wave trains, an arched extratropical one and another jet-guided subtropical one, have been found to link East Asia to the North Atlantic (Li, 2004; Sun et al., 2009). These impacts have already been verified in recent studies on the Atlantic Multidecadal Oscillation (Lu et al., 2006; Wang et al., 2009).

2.3. *Role of land surface processes*

The impact of land surface processes on the East Asian monsoon climate has been illustrated in many studies (e.g., Lin et al., 1996; Yang and Lau, 1998). By introducing an improved climate model with modified land surface parameterization, Lin et al. (1999) found that the prediction skill can be improved to some extent. Wang (2001) conducted ensemble integrations with the IAP AGCM to investigate the mechanism of severe flooding over the Yangtze River valleys in 1998 and found that the excessive snow cover over the Tibetan Plateau during winter and springtime can lead to a weakening of the South Asian High, followed by a weakening of the East Asian monsoon circulation and its associated monsoon precipitation over the lower reaches of the Yangtze River valleys. This result was further demonstrated in similar research (Zhang and Tao, 2001).

Meanwhile, the impact of soil moisture on the simulation of EASM has also been revealed by Wang (2001); he suggested that wet soil conditions during springtime over South China can lead to a weakening of the EASM followed by increased monsoon precipitation over the lower reaches of the Yangtze River valleys. Using observational data over the Huaihe River basin from HUBEX (Huaihe River Basin Experiment in China), Lin et al. (2001) further indicated that the sensitivity of the land surface model to the initial soil moisture is quite strong in late spring and summer over the Huaihe River basin; however, this sensitivity becomes relatively weak in autumn. Using the IAP AGCM, Guo and Wang (2003) suggested that the prediction skill of the 1998 summer rainfall anomalies could be increased by introducing more realistic initial soil moisture.

Furthermore, Zhan and Lin (2011) investigated the impact of initial soil moisture anomalies over the Yangtze and Huaihe river basins that were induced by the extreme freezing-rain disasters of January 2008, on the seasonal predictive skill of spring rainfall anomalies over China using the IAP AGCM, whose land surface process scheme had been replaced with Common Land Model (CoLM) (Liu, 2007). They suggested that, when the "observed" initial soil moisture anomalies are taken into account, the model's predictive skill in terms of the spring precipitation anomalies in 2008 can be substantially increased. In particular, over North and Northwest China, the model predicted rainfall anomalies that agreed quite well with the observations, and the anomaly pattern correlation coefficient (ACC) between the observed and predicted spring precipitation over the whole of China increased from -0.02 to 0.11.

Recently, the influence of land surface conditions on dynamical seasonal forecasts was systematically assessed through two sets of June–July–August (JJA) hindcasts for the 20-yr period from 1981 to 2000 by an IAP AGCM that has been coupled with CoLM (Zhan, 2008). In these two sets of experiments, 10 ensemble members were conducted each year using the model atmospheric initial conditions from 00 UTC 10–19 May, and then the model was integrated from 15 May to 31 August; the observed SST data from the UK Meteorological Office HadiSST dataset was applied in both sets of experiments. The only difference between the two experiments was that, in the second set, when driving the land surface model CoLM in the coupled experiment, the model-simulated rainfall at each time-step was discarded and replaced by the observed GPCP (Global Precipitation Climatology Project) precipitation data. Given that rainfall is the primary factor determining land surface conditions (soil moisture, in particular), forcing the surface model with the observed rainfall at each time-step ensured that realistic representation of the land surface conditions during the model hindcast integrations; this experiment was designated as EXP_SSTs+SM, and the one without rainfall replacement was EXP_SSTs.

Results from the spatial anomaly correlations between the hindcast rainfall anomalies and observed results for 20-yr JJA ensemble hindcasts during 1981–2000 over China show that, when only considering the SSTA as the predictor, the seasonal prediction skill of summer rainfall anomalies over China is relatively low, with a spatial anomaly correlation coefficient (ACC) of -0.05 averaged during 1981–2000, and the ACCs are even less than -0.5 for the years 1992 and 1993. However, by taking into account more realistic land surface conditions during the hindcast period, the seasonal predictability of summer rainfall anomalies over China is largely increased; the 20-yr averaged ACCs of summer rainfall anomalies over China reach ~ 0.19, with a positive correlation for most years during 1981–2000 (Zhan, 2008).

2.4. *Role of atmospheric teleconnection*

Atmospheric teleconnection refers to a recurring, persistent, and large-scale pattern of atmospheric circulation, which links the climate variability in different regions. The identification of atmospheric teleconnection is of major importance for understanding and predicting a region's climate.

In the last two decades, teleconnection patterns that are related to the EASM have received increasing attention. Results have indicated that the variability of the summer monsoon and the corresponding precipitation are significantly influenced by atmospheric teleconnection from the tropics, the Northern Hemispheric mid-to-high latitudes, and even the Southern Hemisphere. In this section, we review the roles of atmospheric teleconnection over these three regions.

2.4.1. *Teleconnection from the tropics*

At tropical latitudes, there are four teleconnection patterns that have been shown to have an impact on the EASM. One is the PJ or EAP teleconnection pattern (Nitta, 1987; Huang and Li, 1987; Lau, 1992). Observational data, reconstructed data, theoretical work, and modeling analyses have indicated that this teleconnection pattern results from anomalous heating over the tropical western warm pool, and its variability has a close connection to the circulation and rainfall of the EASM (e.g., Nitta, 1987; Huang and Lu, 1989; Huang and Sun, 1992; Lau, 1992; Shi and Zhu, 1993; Huang and Yan, 1999; Han and Zhang, 2009). With a positive-phase (negative-phase) EAP pattern, the EASM-related rainfall is less (more) than normal.

The ENSO, acting as a major source of interannual variability in the tropics, has a profound influence on the tropical climate and even on the climates of some extratropical regions. The EASM is one such climate system subjected to ENSO impact, as has been revealed by many previous studies, from current observational data to historical reconstructed proxy data (Huang and Wu, 1989; Chen et al., 1992; Li, 1992; Shen and Lau, 1995; Zhang et al., 1996; Lau and Weng, 2001). However, ENSO is most active in the winter time; therefore, how does it exert a delayed impact on the following summer's rainfall in East Asia? By investigating the observed evolution of ENSO-related circulation from winter to summer and by conducting a numerical sensitivity experiment, Wang et al. (2000a) pointed out that the EAP teleconnection is responsible for the link between ENSO and the East Asian climate.

Condensation heating in the South Asian monsoon region is an important source of atmospheric variability. Dai et al. (2002) found that the latent heat of condensation of the South Asian summer monsoon can excite a teleconnection pattern, which can result in an in-phase variability of precipitation over India and North China. Recently, Liu and Ding (2008) demonstrated that the onset of South Asian summer monsoon over Kerala in the southwestern coast of the Indian Peninsula can lead to a so-called southern teleconnection of the Asian summer monsoon, which emanates from the western coast of India, across the Bay of Bengal, to the Yangtze River valleys and southern Japan. Via this teleconnection pattern, the date of South Asian summer monsoon onset over Kerala on the southwestern coast of the Indian Peninsula provides a potentially valuable signal for predicting the onset of the Mei-yu over the Yangtze River valleys two weeks later.

2.4.2. *Teleconnection from the extratropical Northern Hemisphere*

Over the extratropical Northern Hemisphere, the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) is the largest hemisphere-scale interannual mode. Signals of the NAO/AO in the East Asian summer climate have been indicated by several studies. Xu et al. (2001) revealed that in a strong (weak) winter NAO year, the onset of the Mei-yu is advanced (delayed). Sung et al. (2006) demonstrated a significantly delayed impact of the winter North Atlantic Oscillation (NAO) on the precipitation of the following EASM. Using 530-yr (1470–1999) reconstructed NAO and eastern China drought and flood indices, Fu and Zeng (2005) also indicated that the winter NAO can influence summer droughts and flooding for the following one to three years in East China. Furthermore, Ju et al. (2005) indicated that the NAO can also modulate the decadal variability of the East Asian summer climate. Thus, the variability of the NAO can provide some useful information for seasonal and long-term prediction of the EASM and corresponding droughts or flooding. In addition, other studies have revealed that the NAO/AO in other seasons is also related to the East Asian summer climate. For example, Gong and Ho (2003) showed that the May AO is highly negatively correlated with the summer rainfall in the Yangtze River valleys. Sun et al. (2008a) and Yuan and Sun (2009) found that the summer NAO can modulate the midsummer air temperature via the excitation of a zonal Rossby wave train along the Asian upper-level jet. However, this impact experienced a decadal shift around the late 1970s, with a strong impact after the late 1970s and a weak impact before. Recently, Sun and Wang (2012) further found that the summer NAO also has a dominant role in the summer precipitation over the mid and high latitudes of East Asia.

The upper-level jet is the major Rossby wave conduit. Along this upper level jet, several zonal teleconnection patterns have been revealed. Using upper-level meridional winds, Lu et al. (2002) identified the existence of a teleconnection pattern in July, which emerges from North Africa to East Asia along the Asian westerly jet in the midlatitudes. Further analysis revealed the possible role of this upper-level teleconnection in linking the EASM to the South Asian summer monsoon, and even to farther westward heat sources over the Atlantic. Enomoto et al. (2003) proposed a “silk road” teleconnection along the East Asian jet. The identification of this teleconnection presents one possible mechanism for the formation of the Bonin high, a predominant subtropical anticyclone near Japan in the summer that is associated with the Mei-yu frontal zone. By synthetically analyzing the summer midlatitude circulation of the Northern Hemisphere, Ding and Wang (2005) found that there is a recurrent circumglobal teleconnection (CGT) pattern, and the two upper-level teleconnection patterns over the Eurasian continent are regional manifestations of the CGT pattern. The CGT pattern is significantly associated with the rainfall and surface air temperature in Western Europe, European Russia, India, East Asia, and North America.

Although the North Pacific is located downstream of East Asia, the teleconnection variability over this region is also important to EASM variability. Zhang et al. (2007) indicated that the boreal winter North Pacific Oscillation (NPO) has a delayed impact on the following summer’s rainfall over the Huaihe River valleys, with a strong (weak) NPO corresponding to less (more) rainfall. Lian (2007) suggested that the preceding winter NPO shows a negative correlation with the EASM, resulting in a dipole pattern of anomalous summer rainfall over eastern China.

Recently, two kinds of teleconnection patterns over the Asian continent and the North Pacific region have been revealed. Zhao et al. (2007) pointed out that the upper-level summer air temperature over the Asian continent and the North Pacific co-varies out of phase. They named this pattern the Asia–Pacific Oscillation and found that this teleconnection has an impact on the Asian summer climate. In investigating the lower-level circulation variability over the Asia–North Pacific region, Sun et al. (2008b) identified the Arabian Peninsula–North Pacific Oscillation (APNPO). This teleconnection essentially reflects the co-variability of the North Pacific high and the South Asian summer monsoon. The APNPO is closely related to the Asian summer monsoon circulation in the upper and lower levels, the moisture transportation, and rainfall on both interannual and decadal time scales. In addition, the APNPO is found to have a persistent feature from spring to summer, which provides potentially valuable information for Asian summer monsoon predictions.

2.4.3. *Teleconnection from the Southern Hemisphere*

Although the EASM occurs over the Northern Hemispheric subtropics, a number of recent studies have indicated that Southern Hemispheric teleconnection patterns are also important in the variability of the EASM. In investigating the role of the Mascarene high and the Australian high in the variability of the EASM, Xue et al. (2003) found that these two highs are closely related to the variability of the Antarctic Oscillation (AAO). Thus, they proposed the hypothesis that the AAO may be an important far-reaching external forcing for the year-to-year variability of the EASM. Some later studies confirmed this hypothesis, revealing the existence of a positive relationship between the boreal spring AAO and summer rainfall in the Yangtze River valleys (Gao et al., 2003; Nan and Li, 2003; Xue et al., 2004; Fan, 2006) and a negative relationship between the AAO and summer precipitation in central North China (Wang and Fan, 2005). In addition to the AAO, Wang and Fan (2006) suggested that the upper-level meridional teleconnection of zonal wind between the middle and high latitudes in the Southern Hemisphere is negatively correlated to the EASM circulation on an interannual scale. Zhu et al. (2009) compared the AAO–EASM link in the NCAR/NCEP reanalysis with that in the ERA40 reanalysis, and a similar relationship was found.

Different from the tropical and Northern Hemispheric teleconnection patterns, the possible mechanism underlying the impact of the Southern Hemispheric teleconnection pattern on the EASM is quite complicated. Up to this point, four kinds of mechanisms have been proposed. Xue et al. (2003) suggested that the Southern Hemispheric teleconnection patterns influence the EASM via changing the cross-equatorial flows. Wang (2005) revealed that the meridional wind shows a circum-Pacific teleconnection pattern, which could be one way to couple the Southern and Northern Hemisphere's climate. Wang and Fan (2006) suggested that the meridional teleconnection in the zonal wind field, with its main part in the Eastern Hemisphere, from the mid and high latitudes in the Southern Hemisphere to the tropical region, is responsible for the link between the Southern Hemispheric upper-level zonal wind teleconnection and the EASM. These three possible mechanisms are all related by a simultaneous connection between the Southern Hemispheric teleconnection and the East Asian climate. For the seasonal delayed impact of the boreal spring AAO on the EASM, Sun et al. (2009) proposed that an anomalous AAO can affect the convection activity over the Maritime Continent, via the excitation of anomalous meridional circulations along the central South Pacific and two meridional teleconnection wave train patterns. Thereafter, the anomalous convection propagates northward along the seasonal cycle and then changes the western Pacific subtropical high in the following seasons, consequently impacting the EASM's rainfall.

The identification of the above atmospheric teleconnection patterns has greatly deepened our understanding of EASM variability and vastly improved EASM prediction.

3. Seasonal prediction of precipitation and monsoons

3.1. *Two-tier prediction approaches*

3.1.1. *Methods*

The two-tiered method can save computer resources and was thus developed quite early in China (Zeng et al., 1990). To make real-time dynamical seasonal predictions in a two-tiered fashion, the SST is predicted by a coupled atmospheric–ocean general circulation model (CGCM) in the first step. Then, an AGCM is forced with the predicted SST given by the first step. Because systematic errors in the predicted SST can be corrected in a statistical way, adverse impacts on the atmosphere predictions that arise from errors in the SST can be minimized.

Focusing on climate anomalies in the summer and winter as well as the spring, the integrations start from different dates in February and October for seasonal prediction and interannual prediction, respectively, in China. Usually, the predicted SST is available over the tropical Pacific, and therefore, a linear combination of the observed SSTA in the initial month and the predicted monthly SSTA are used as the lower boundary conditions of the AGCM. The role of the observed (predicted) SSTA is gradually decreased (increased) in the tropical Pacific in the integration. Over other oceanic regions, the observed SSTA in the initial month is maintained throughout the integration process.

3.1.2. *SST forecast using air–sea coupled general circulation models*

Forecasting of the tropical Pacific SST has been performed since the early 1990s in China by using dynamical models or mathematical statistics models. Mathematical statistics has evolved significantly in recent years (e.g., Ding et al., 1998). However, even more achievements have been made through dynamical prediction methods (Zhou et al., 1998; Wu and Ni, 1999; Zhou and Li, 2000; Shi et al., 2001; Zhou and Zeng, 2001). Several ENSO prediction systems have been established in China since 1999, such as the IAP ENSO forecast system (Zhou et al., 1999; Zhou and Zeng, 2001), established by using the Tropical Pacific–Global Atmosphere Coupled Model, incorporated with an initialization scheme in which only the observed or analyzed SSTA is inserted into the coupled model. The National Climate Center (NCC) set up a simplified ENSO prediction model (Zhao et al., 2000), and the IAP established a probabilistic ENSO ensemble prediction system based on an intermediate coupled model (ICM) developed by Keenlyside and Kleeman (2002) and Zhang et al. (2005a). In general, the prediction skill for the SST gradually decreases with time. As for the dynamical model, the prediction is more reliable than that achieved by means of persistence predictions, if the integrated time is longer than three months, which highlights the importance of ocean data assimilation. Zhang et al. (2006) concluded that the incorporation of SST assimilation with ARGO (the broad-scale global array of temperature/salinity profiling floats) observation data is greatly beneficial for the prediction skill of the summer rainfall anomaly in China. Zheng et al. (2006) found that prediction skills can be significantly improved by assimilating SST observations into an intermediate coupled model. In addition, the accuracy of ENSO simulation is disturbed to a large degree by the "climate drift". Recently, a regressive correction method was presented with the primary goal of improving ENSO simulations in a regional coupled

GCM; it was shown that it is superior to the anomaly coupling both in reducing the coupled model climate drift and in improving the ENSO simulation in the tropical Pacific Ocean (Fu and Zhou, 2007).

More recently, dynamical predictions of SST have experienced new achievements in China. For example, using the parameterization proposed by Zhang et al. (2005), Zhu et al. (2013) established a hybrid coupled model by embedding an SSTA model in an OGCM. Such an embedded approach has proved to be effective in improving ENSO simulations and forecasts (Zhu et al., 2009), and its skill is notable in predicting the whole process of the 1997/98 El Niño, which has not been represented well by many forecast systems (Landsea and Knaff, 2000). Moreover, to overcome the shortcomings of the ICM in some ENSO cases (such as the 2007/08 La Niña event), a coupled assimilation scheme was preliminarily developed to be capable of assimilating the atmospheric data into the ENSO ensemble prediction system to improve the initial atmospheric state (Zheng and Zhu, 2010). An 11-yr retrospective forecast comparison showed that the prediction skill of assimilating wind observations was better than that of assimilating SST observations. The assimilation of wind observations for the 2007/08 La Niña event triggered better predictions, while that of SST observations failed to provide an early warning for that event.

3.1.3. *Ensemble atmospheric forecast*

The earliest experimental extraseasonal prediction of summer monsoon rainfall anomalies by GCMs in China was carried out by Zeng et al. (1990) at the IAP. Verifications showed that, in general, the model possesses relatively high prediction skill in eastern China, especially for the Yangtze River and northern China, but it is insufficient for northeastern and northern China (Wang, 1997; Zeng et al., 1997). Modifications of the surface albedo parameterization (Lin and Zeng, 1997), the horizontal resolution (Zhang et al., 2004), and the correction system (Zhao et al., 1999) have resulted in improvements in seasonal climate prediction. As for the summer rainfall anomaly in 1998, patterns in most parts of China have been successfully predicted by the system in advance (Lin et al., 1998; Chen and Lin, 2006).

Based on the original two-level AGCM mentioned above, a nine-level AGCM was developed in the late 1990s (Zeng et al., 1987; Zhang, 1990; Liang, 1996). The resolution was 5° in longitude by 4° in latitude, with nine vertical levels with a top at 10 hPa. The model has been used in real-time extraseasonal prediction for summer climate anomalies in China since 2002 (Lang et al., 2004a). The drought conditions over northern northeast China and the Yellow River valleys and positive rainfall anomalies over eastern northeast China, South China, and most parts of western China are well captured by the model.

There have been some successful cases of real-time seasonal prediction of summer precipitation in China and monsoons via the dynamical approach. However, the overall skill of GCM-based seasonal precipitation prediction in China thus far is generally low. Considering that interactive ocean–atmosphere coupling is neglected in the two-tier method, a one-tier approach was proposed and applied to seasonal climate prediction.

3.2. ***One-tier approach***

Supported by the National 9th Five-Year Development Plan (1996–2000), the first generation of a dynamical climate model prediction operation system was established at the NCC in 2001 (Ding et al., 2004). The seasonal prediction model system consists of the Coupled Global Atmosphere–Ocean Model (CGCM/NCC) and the Global Ocean Data Assimilation. The CGCM consists of a T63L16 AGCM (Dong, 2001) and L30T63 OGCM (Zhao et al., 2000). The T63L30 AGCM and L30T63 OGCM are coupled through a daily flux anomaly coupling scheme (Yu and Zhang, 2000). The observational data used in this system comprise both the Globl Temperature-Salinity Profile Program (GTSPP) data (from 1981) and ARGO data (from 1998; Liu et al., 2005b).

Since the spring of 2003, four-season climate prediction produced by dynamical climate models has been in operation (Li et al., 2005). Two years later, monthly-moving seasonal climate products were released at the beginning of each month with a lead time of 0–6 months. Results from 20-yr hindcasting experiments and routine operation of seasonal climate prediction since 2003 show that this system has variable capability of seasonal prediction from year to year in East Asia.

With the development of climate system models and earth system models, two one-tier prediction systems were established at the IAP based on version 3.0 and version 4.0 of the Community Climate System Model (CCSM) developed by the NCAR and a self-designed initialization system. These prediction systems are hereafter referred to as PCCSM3 and PCCSM4, respectively (Liu and Wang, 2014[a]; Ma and Wang, 2014). PCCSM3 is composed of an ocean–atmosphere coupled model that consists of complete air–sea interaction and two initialization systems for the ocean component, one being based on observational SST, similar to Zhou et al. (1999) and Zhou and Zeng (2001), and the other based on NCEP Climate Forecast System Reanalysis (CFSR) data, which can import deep ocean information. A detailed discussion on the performance of PCCSM3 is available in Liu and Wang (2014)[a]. PCCSM4 is based on CCSM4, the later version of CCSM3, with a mixed-layer ocean model that involves complete air–land interaction, partial air–sea interaction, and an ensemble initialization scheme (Ma and Wang, 2014). Retrospective summer prediction experiments have been carried out and demonstrate that both PCCSM3 and PCCSM4 possess good prediction skill in terms of summer climate, especially so for SST and over the tropical zone. In addition, PCCSM3 and PCCSM4 show good capability in simulating the year-to-year variability of the Asian summer monsoon (data not shown). Both PCCSM3 and PCCSM4 have begun real-time summer climate prediction since 2013.

[a]Liu, S., and H. J. Wang, 2014: Extra-seasonal short-term prediction systems based on CCSM3 and their evaluation. *Int. J. Climatol.*, under review.

Precipitation forecasting for the rainy season (JJA) is a crucial task for short-term climate prediction in China. Results show that among 160 stations, there are 69 stations with ACCs between predictions and observation that are above zero, accounting for 43.12% (Ding et al., 2002). Therefore, the accuracies of the prediction are generally low, but might be good in some particular years over eastern China. For real-time prediction of the summer climate in 2006, the predictions of summer rainfall anomalies are quite similar to observations (data not shown).

The temperature in West China (such as Xinjiang, Tibet, Qinghai, Gansu, Ningxia, and Shaanxi), North China, the regions between the Yangtze and Yellow rivers, and the southeast part of Northeast China, can in part be successfully predicted, with the central values of the ACCs reaching or exceeding the 90% significance level. Among the 160 stations in China, 77 stations' ACCs of temperature are greater than zero, which accounts for 48.12% of the total.

In order to effectively improve numerical prediction skill, the so-called "dynamical analogue prediction" approach has been recently investigated (Ren, 2006). Based on the atmospheric analogy principle, information from historical analogue data is utilized to estimate the model errors (Ren and Chou, 2006; Gao et al., 2006). When applied to extraseasonal prediction experiments on an operational atmosphere–ocean CGCM, results showed that it can reduce the prediction errors and successfully improve predictive skill (Ren, 2006).

In addition, some statistical downscaling methods have been applied, which also result in improved skill of seasonal climate prediction in China (e.g., Chen, 2008). This is discussed in more detail in the following section.

3.3. *Downscaling and correction of model results*

As a simplification of a realistic climate system, the GCM inevitably has model errors resulting from the parameterization of physical processes, the effects of unresolved scales, and imperfect boundary conditions. In particular, model errors are considerable for simulations of precipitation and monsoons, due to their intricate mechanisms. Therefore, statistical downscaling or model error correction is essential for dynamical seasonal prediction in operation.

Model error correction is an approach to combine both statistical and dynamical methods together. It is a model output statistics technique, which regards the GCM as a black box and reduces the model error based on a certain statistical relation between model output fields and historical observed data. The model error correction is not only much easier to implement than the advancement of the model parameterization of physical processes and dynamical cores, but it is also much cheaper than increasing the model resolution. Commonly used correction methods include mean bias correction, regression analysis, coupled field techniques, analogy analysis, magnitude correction of predicted interannual variation, and statistical downscaling.

Zeng et al. (1994, 1997) outlined four methods for correcting model error: mean bias correction, maximum similarity, minimum difference, and a coupled pattern technique based on EOF. The maximum similarity and minimum difference are actually two methods for deriving the coefficients of a regression equation and thus belong to a regression scheme. Some studies have used the mean bias correction method to reduce the model error of the IAP GCM (Zhao et al., 1999; Lang, 2003; Chen, 2003) and improve the forecast skill of summer seasonal rainfall over China.

One shortcoming of the mean bias correction method is that the magnitude of the corrected anomalies is much smaller than the observation due to the weak interannual variation of the original simulation (Wang et al., 2000b). In order to overcome this shortcoming, some effective methods have been developed to correct the magnitude of the predicted interannual variation, which multiply the year-to-year or seasonal variation by the ratio of their observed to predicted standard deviation or standard difference (Wang et al., 2000b; Lang, 2003).

Li et al. (2005) introduced a coupled pattern technique based on singular value decomposition analysis (SVD) (Ward and Navarra, 1997) and EOF (Feddersen et al., 1999) to correct the model error in the IAP GCM. The EOF correction method is a combination of the minimum difference and the coupled pattern technique based on EOF in Zeng et al. (1994, 1997). Since the summer rainfall over China is mostly subtropical monsoon rainfall, the chaotic component is greater than that of tropical rainfall, due to the larger contribution of the internal atmospheric process (Wang et al., 1997; Lang et al., 2004b). Therefore, Li (2008) introduced a double cross-validation method to obtain the prior information about the feasibility of the correction method and to determine the number of truncation modes of SVD and EOF, which improved the seasonal forecast skill significantly. In addition, Li (2008) explained the phenomenon pointed out by Feddersen et al. (1999) that the post-processed results were not sensitive to the choice of methods based on the SVD and EOF. The significant improvement of forecast skill achieved by the coupled pattern technique suggested that there was a shift in the spatial pattern of variability of summer rainfall over China in the IAP GCM, which resulted in a substantial drop in the skill score.

Analogy correction is also a widely used model error correction method. The analogy scheme always assumes that a similar spatial pattern of the predictand for the target year has already occurred in past years. Based on the fact that different model error patterns of the IAP GCM for summer rainfall over China appear in ENSO warm years, cold years and normal years, separately, Chen and Lin (2006) developed a method to estimate the model error in the target year. Ren and Chou (2007) proposed an analogue correction method based on the assumption that the errors in the predicted results with similar initial conditions are the same. In addition, due to the high spatial pattern correlation between summer rainfall anomalies over the East Asian and western Pacific region (EAWM) and tropical region and successfully predicted tropical precipitation, Wang and Fan (2009) developed a correction method with the predicted tropical precipitation as an analogical index. This new scheme can substantially improve the forecast skill of summer rainfall with six models in the Development of a European Multimodel Ensemble System for Seasonal to Interannual Prediction (DEMETER) system.

Recently, the statistical downscaling technique, which is based on the assumption that atmospheric variability on local scales is conditioned, though not determined, by large scales (von Storch et al., 1993; von Storch, 1999), was introduced to correct model error. Statistical downscaling correction methods aim at specifying the local field (the predictand, e.g., the precipitation or its model error) statistically from a large-scale field (the predictor) that is skillfully predicted by the dynamical model. The choice of predictor depends on the predictand and should satisfy two conditions. First, it must be possible to accurately specify the predictand from the predictor. Second, the predictor should be well predicted by the dynamical model. Large-scale fields such as geopotential height, sea level pressure, air and surface temperature, velocity, and tropical SST have been used as predictors to improve the forecast skill of precipitation (Zhang et al., 2005; Ren, 2008; Zhu et al., 2008; Chen, 2008; Ke et al., 2009; Kang et al., 2009; Li et al., 2009).

In statistical downscaling correction schemes, the statistical relation between large-scale fields and local prediction can be identified by coupled pattern techniques (Zhang et al., 2005), analogy analysis (Ren and Chou, 2007), regression analysis (Chen, 2008; Ke et al., 2009; Kang et al., 2009; Sun and Chen, 2012; Liu and Fan, 2013; 2014; Liu and Li, 2014), and Bayesian schemes (Li et al., 2009). The predictands include the summer rainfall and its model error. For the former, only the large-scale fields are used. In this case, the corrected rainfall fields obtained by statistical models with large-scale fields as predictors are regarded as more valuable than those achieved with the rainfall field simulated by a nonlinear GCM as predictors. This is usually true in view of the poor forecast skill of the GCM for summer rainfall over China. A new scheme proposed by Wang and Fan (2009) achieved a largely improved hindcast of summer precipitation over China. In their scheme, they attempted to make adequate use of tropical summer precipitation predictability to reinforce the extratropical precipitation predictability in China, and their results were encouraging. The new scheme of Wang and Fan (2009) is based on the fact that the forecast skill of local fields in the GCM is usually related to the different states of large-scale fields.

Besides statistical downscaling, the dynamic downscaling method using a high-resolution regional climate model can be applied to regional climate prediction. Over East Asia where the topography is complex, a high-resolution regional climate model could be more capable of depicting the small-scale weather systems and capturing local climate details, due to the more reasonable terrain and higher resolution compared to a GCM (Yu et al., 2010). The extreme flooding over the middle–lower reaches of the Yangtze River valleys in the summer of 1998 was selected as a case to investigate the performance of the Weather Research and Forecasting model (WRF) in retrospective summer precipitation prediction (Ma et al., 2014). The results were encouraging. The WRF model not only gave a better hindcast for the exclusive rainfall over the middle–lower reaches of the Yangtze River valleys on the seasonal scale, but also for the two occurrences of Mei-yu rainfall, which was the main characteristic of the 1998 summer climate on the sub-seasonal scale.

Moreover, a rare catastrophic flood occurred in central eastern China in 2003, and it was not predicted in advance by any of the prediction departments in China except for the NCC using the regional climate model (Ding et al., 2006). The flood and drought distribution of the summer rainfall in eastern China derived from the regional climate model is quite consistent with observations.

3.4. *Development of new statistical prediction models for summer precipitation*

Current operational skill for summer precipitation in China, with both statistical and dynamical model methods, is quite limited. Recently, a year-to-year incremental approach was proposed for forecasting summer rainfall over the middle–lower reaches of the Yangtze River valleys (RYRV) (Fan et al., 2008). In this prediction procedure, the year-to-year increase or decrease (represented by DY) of RYRV is firstly forecasted to yield a RYRV or the percentage anomalies of the RYRV. Thus, the statistical forecast model for the DY of RYRV is established first and then applied to forecast the RYRV. Five predictors of the DY of RYRV include the DY of the March–April–May (MAM) mean AAO index, the index of the DY of the Ural circulation in MAM, the index of the DY of the East Asian circulation in MAM at 500 hPa, the DY of the meridional wind shear between 850 hPa and 200 hPa in MAM over Indo-Australia, and the index of the winter DY of the southern Pacific sea level pressure. The model captures the interannual variability of the observed percentage anomalies of the RYRV well, with a correlation coefficient between the observed and modeled percentage anomalies of the RYRV of 0.79 during the training period of 1965–96 (32 years), with a RMSE of 20%. The model hindcast for 1997–2006 shows a high level of accuracy for the percentage anomalies of the RYRV, with an RMSE of 18%. It even reproduces the upward and downward trends of the percentage anomalies of the RYRV, respectively, during the periods from 1985 to 1998 and 1999 to 2006. In particular, the model successfully reproduces the abnormal precipitation observed from 1997 to 1999, with relative errors below 10%.

The year-to-year increment was also applied to forecasting summer rainfall over North China (RNC) (Fan et al., 2009). Fan et al. (2009) identified only five predictors for the DY of the RNC, including the DY of the DJF North East Asia sea level pressure circulation, the DY of the MAM North Pacific circulation at 500 hPa, the DY of the intensity of the June South Asian high, the DY of the intensity of the June polar vorticity over the Northern Hemisphere, and the DY of the June Niño3 index. Results demonstrated that the correlation coefficient between the observed and simulated percentage anomalies of the RNC is 0.8 during the training period of 1965–99, with an RMSE of 18%. It was noted that the model reproduces the downward trend of percentage anomalies of the RNC. The model shows good prediction capacity for the hindcast period of 2000–06, with an RMSE of 21%. The model captures the abnormal drought year in 2002, with a relative error of 10% for the precipitation prediction. Therefore, it appears that the year-to-year increment approach has potential to significantly improve the operational forecast skill of summer rainfall over China due to its advantages of: (1) using merely five or six predictors that can explain 60%–80% of the interannual variances of a predictand; and (2) capturing the decadal trend of a predictand.

Liu and Fan (2012b) also applied the year-to-year increment prediction approach to develop an effective statistical downscaling scheme for summer rainfall prediction at the station-to-station scale in southeastern China. The independent sample test and the cross-validation test showed that the downscaling scheme yields better predicted skill for summer precipitation at most stations over southeastern China than the original GCM outputs, with greater correlation coefficients, as well as lower RMSEs.

4. Seasonal prediction of the climate background for dust weather and typhoon activity

4.1. *Climate background of dust weather*

Dust weather is quite frequent in North China in the winter and spring, resulting in air pollution and climatic consequences. Recently, dust weather anomalies have dramatically changed on seasonal, interannual, and decadal timescales (Wang and Dong, 1996; Zhou and Zhang, 2003; Wang et al., 2012). This is related to many land surface processes as well as atmospheric circulation. Thus, the prediction of dust weather frequency (DWF) is a challenging but nevertheless worthwhile task.

Dust weather in North China has been revealed to be closely related to surface wind velocity, humidity, and surface air temperature. On seasonal and interannual timescales, surface wind and precipitation are regarded as having the most important roles in DWF (Ye et al., 2000; Zhang and Ren, 2003). In addition, the preceding SST anomalies in the Pacific, the ENSO cycle, and climatic factors in the northern middle and high latitudes (e.g., geopotential height at 500 hPa, polar vortex intensity, AO, and westerlies in the northern high latitudes) are also documented as significantly influencing the DWF in China (Zhao et al., 2004a; Kang and Wang, 2005). Recently, a significant negative correlation between the AAO and spring DWF in North China was reported (Fan and Wang, 2004), which provides a new important potential predictor for DWF prediction.

In 2003, a GCM-based numerical prediction method for spring DWF was proposed and tested by Wang et al. (2003). The prediction was realized according to the dynamically predicted anomalous cold air intensity, precipitation, surface air temperature, etc., in winter and spring. Encouraging results were obtained by performing a real-time seasonal prediction experiment utilizing the IAP GCM. Subsequently, real-time predictions for the spring DWF have been performed every year with a lead time of several months. A comparison of the prediction with the observation shows general agreement for four years but disagreement for two years.

With the goal to improve the prediction, Lang (2008) developed a new method by considering major predictors that come from either the preceding observed atmosphere or from the GCM output by applying multiple linear regression techniques. The predictors identified include the seasonal mean anomalous surface air temperature, precipitation, the AO, AAO, SO, near surface meridional wind, and the Eurasian westerly index in the preceding winter and current spring.

Based respectively on the observed data and corresponding forecast experimental data, two prediction models (model-I and model-II, hereafter) were set up for the spring DWF using regression analysis. Validation of the models indicates that the correlation coefficient between the observed and modeled time series is larger than 0.93 for the calibration period of 1955–2001 for both models. An examination of the retrospective forecasts shows that both models possess high prediction skill for the spring DWF in North China. However, there are two deficiencies embedded in model-I. One is a time limitation that may arise in the real-time prediction because the DJF mean observational data are used in the prediction, and the other is that the synchronous climate signal in the spring is not taken into account. However, in general, the prediction skill of the spring DWF in North China could be largely reinforced if these two models, especially model-II, were applied in practice.

Besides the sophisticated influencing processes and factors, the spring dust weather in China possesses regional characteristics. Although much progress has been made in frequency prediction in China, the prediction for synoptic spring dust weather in China is still difficult. New prediction methods are urgently needed in future studies, such as a regional climate model to make more reliable predictions of both the DWF and individual dust events.

4.2. *Climate background of typhoon activity*

Typhoon activity significantly influences China. It is important and difficult to forecast interannual typhoon activity in the WNP. Major scientific achievements associated with seasonal forecasts of WNP typhoon activity are reported in this subsection. One aspect is the relationship between typhoon activity and atmospheric circulation, and the other is the development of statistical and dynamical prediction models of typhoon activity.

4.3. *Factors associated with typhoon activity*

The selection of predictors is based on the relationship between typhoon activity and atmospheric circulation. Xie et al. (1963) indicated that 80% of typhoons develop in the eastern part of the equatorial convergence zone over the western Pacific. They further identified that when the equatorial westerly is enhanced and extended northward and eastward, the typhoon genesis frequency is increased. Ding et al. (1977) further provided a synoptic conceptual model for the formation of multiple typhoons in the ITCZ, and they emphasized the role of interaction of the tropical circulations of both hemispheres in the development of the ITCZ. Dong and Zhang (1979) suggested that there is a stronger jet at the middle-low level before the formation of typhoons in the ITCZ. In this sense, the strengthened jet at the middle-low level on both sides of the ITCZ could be an indicator for the formation of typhoons in the ITCZ. Chen (1965) suggested that the movement of typhoons is led by three to seven days by the high-middle latitude circulation over East Asia. Tao et al. (1962) pointed out that there are meridional and zonal flow patterns over the tropical and subtropical area in Asia, which cause distinct characteristics of typhoon activity through the position of the zonal wind belt over the Northern Hemisphere, the distribution of long waves, and the locations of subtropical highs and the ITCZ. Xu and Gu (1978) further indicated that only when both the upper- and lower-level zonal-dominated circulations synchronously turn into meridional-dominated circulation over the tropical western Pacific do multiple typhoons and stronger typhoons occur.

Previous studies have also suggested that tropical and subtropical circulations in the Southern Hemisphere play an important role in the development of typhoons (Li, 1956; Tao et al., 1962, Ding et al., 1977; Xu and Gu, 1978; Wang and Leftwich, 1984). These studies speculate that outbreaks of cold air along with enhanced low-level cross-equatorial flow near Australia would result in an enhanced ITCZ, which favors the development of typhoons over the WNP. These studies were based on case studies and provide potential indicators of medium-range weather forecasts for typhoon activity. By employing long-term datasets, it has been indicated that the ENSO and stratospheric Quasi-Biennial Oscillation (QBO) can influence the interannual variability of typhoon activity over the WNP via changes in thermal and dynamical conditions over the typhoon genesis region (Pan, 1982; Ding and Wright, 1983, Li, 1985; Dong and Zhong, 1989; Chan, 1995). Therefore, ENSO is one of the main predictors for seasonal prediction models for typhoon activity over the WNP (Chan et al., 1998, 2001).

However, the interannual variability of typhoon activities is much more complicated than previously recognized. Thus, the search for other predictors of typhoon activities is an essential aspect in research on the variability and predictability of typhoon activities. In this context, the role of high-latitude atmosphere modes has been stressed recently.

The AAO is an extratropical annular mode in the Southern Hemisphere. Recent analysis has indicated that the AAO has close relationships with the DWF in North China and summer rainfall over North China and the Yangtze River valleys (Gao et al., 2003; Fan and Wang, 2004; Wang and Fan, 2005; Fan, 2006; Sun et al., 2009). Wang and Fan (2007) showed that the WNP typhoon frequency (WNPTF) is also significantly negatively correlated with the AAO in June–July–August–September (JJAS) in the period 1949–98. Based on the above studies, a positive phase of the JJAS AAO corresponds to a larger magnitude of vertical zonal wind shear, anomalous low-level anticyclonic circulation, anomalous high-level cyclonic circulation, and lower SSTs in the major typhoon genesis region, thus providing an unfavorable environment for typhoon genesis, and vice versa. Through the meridional teleconnection in the high troposphere existing primarily in the Pacific sector, the convective activities over the equatorial region of the western Pacific are connected to the AAO, and in turn are connected to the convective activities in the WNP, which are associated with typhoon activities.

The NPO is a major mode in the interannual atmospheric variability over the North Pacific, as indicated by a seesaw pattern between the high- and low-latitude sea-level pressure variability. Wang et al. (2007a) discussed the relationship between the NPO and typhoon activity, as well as hurricane frequencies. The correlation coefficient between the NPO index in JJAS and the WNPTF is 0.37 for the period 1949–98. The NPO is also correlated with the annual hurricane number in the tropical Atlantic at -0.28 for the same period. The variability of the NPO is found to be concurrent with changes in the thermal and dynamical conditions of the WNPTF and the annual hurricane number via atmospheric teleconnections.

Fan (2007) further suggested that the sea ice cover in the North Pacific both in DJF and in MAM is negatively correlated with the annual WNPTF during the period 1965–2004. Anomalous sea ice cover may modulate the WNPTF through variations in the NPO or through meridional teleconnections in the high troposphere existing primarily in the Pacific sector.

Zhou et al. (2008) reported that the spring Hadley Cell is negatively correlated to the summer WNPTF. In addition, the teleconnection pattern over the extratropical Asian-Pacific region, which can give rise to anomalous large-scale atmospheric circulations such as the western North Pacific subtropical high, the South Asian high, and westerly jets, is identified as co-varying with the WNPTF (Zhou and Cui, 2008).

4.3.1. *Development of statistical models for typhoon activity prediction*

Chan et al. (1998) developed an operational statistical forecast model for seasonal tropical cyclone activity over the WNP and the South China Sea using the projection pursuit regression technique. Predictors include monthly values of indices representing the ENSO and environmental conditions over East Asia and the WNP for the months from April of the previous year to March of the current year. However, the scheme partially failed in 1997 and 1998, during which a warm and a cold ENSO event occurred, respectively. Chan et al. (2001) improved the scheme by covering new predictors related to ENSO and updated the scheme to include April and May predictors.

Fan (2007) considered the influence of high-latitude circulation, including newly identified predictors such as sea ice cover over the North Pacific and the NPO in the winter–spring. Multi-linear regression was applied to establishing a forecast model for the WNPTF by using the datasets of 1965–99. The forecast model shows a high correlation coefficient (0.79) between the model-simulated and the actual typhoon frequencies for the period of 1965–99. The forecast model also exhibits reasonable hindcasts for the typhoon frequencies for the years 2000–06. Therefore, this work demonstrates that the new predictors are significant for the prediction of the interannual variability of the WNPTF. Cross-validation of the model performance demonstrated the high forecast skill of the model established.

Later, Fan and Wang (2009) proposed a new approach to forecasting the WNPTF. In their work, the year-to-year increase or decrease in typhoon frequency is first forecasted to yield a net typhoon frequency prediction. This new approach has been successfully applied in establishing forecast models of the summer/spring rainfall over the Yangtze River valleys and North China, the temperature in North China, and the EASM (Fan et al., 2008, 2009; Fan and Wang, 2009; Fan, 2012; Fan et al., 2012). Results demonstrate that the new approach can capture not only the interannual variability but also the linear trends of a predictand, showing high prediction capability.

Only five predictors were used in the model set up by Fan and Wang (2009), including winter sea ice cover over the North Pacific and other indices of thermal and dynamical conditions over the WNP. The model performs with reasonable accuracy for the periods of calibration and validation. The model successfully captures the larger typhoon frequency anomalies in the WNP during 1997 and 1998 and the smaller anomalies of the WNPTF during 2002–07. The cross-validation test of the prediction model showed that the new approach and the prediction model result in better prediction skill, as compared to models established based on the typhoon frequency itself. Thus, it appears that this new approach has the potential to improve the operational forecast skill for typhoon frequency in the WNP.

Sun and Chen (2011) developed a statistical downscaling method to predict the WNPTF using six predictors from DEMETER CGCMs during 1974–2001. The prediction skill of the statistical downscaling method is much better than that of the raw CGCMs. Similar improvement can also be found in the prediction of the number of landfalling Chinese typhoons (Sun and Ahn, 2011). In addition, the multi-model ensemble has the best prediction performance. Therefore, combining a multi-model ensemble and statistical downscaling greatly improves the CGCM prediction skill.

4.3.2. *Dynamical approach for typhoon activity prediction*

Wang et al. (2006) carried out a real-time numerical experiment on the climate background conditions over the WNP associated with typhoon activity for 2006 by using the IAP GCM. They reasonably predicted less than normal typhoon genesis in 2006 according to the prediction of the climate background for the WNPTF, including reduced convective activity, an increased magnitude of vertical zonal wind shear, and low-level divergence over the WNP.

Lang and Wang (2008) further evaluated the capability of the IAP GCM to forecast the climate background for typhoon activity over the WNP. They focused on the vertical shear of zonal wind, outgoing longwave radiation, and divergence fields in the lower and upper troposphere during the summer, which are related to the thermal and dynamical conditions for typhoon genesis. After analyzing their 34-yr (1970–2003) ensemble hindcast experiment results, it was found that the temporal correlation coefficients between the hindcast and observation were 0.70 and 0.62 for the vertical shear of zonal wind and the divergence field, respectively, in the key region of the WNP. These results suggested that the model possesses good potential skill for predicting the large-scale climate background for WNP typhoon activity.

5. Summary and future prospects

Frequent flooding in South China and serious droughts in North China often cause significant damage to human life, the nation's economy, and public security. Such disasters have recently resulted in economic losses of about 20 million Euros per year in China. In addition, the issue of water supply has become increasingly serious in North China, where the economy and society are undergoing rapid development and the population and level of urbanization are increasing at present, and are predicted to continue to increase over the next 30 years. Therefore, short-term climate prediction will be a continuous focus for atmospheric research in China. This is even more important when we consider that the frequency of climate extremes in China will likely be reinforced under the global warming background, based on the observed climate variability in the 20th century and GCM-projected climate change in the 21st century.

Despite tremendous social demands, short-term climate prediction for the country is scientifically a difficult issue, basically because the link between the climate variability and the tropical oceanic variability is complicated, unstable, and generally weak, as well as the fact that the internal variance in the mid- and high-latitude atmosphere is large. In addition, large uncertainty remains in understanding the roles of various land surface processes, such as soil moisture, underground water tables, snow and sea ice cover etc., in short-term climate variability in China.

Therefore, GCM-based seasonal climate predictions, either via the "two-tiered" or "one-tiered" approach, have limited skill, even when the state-of-the-art GCM is employed. The spatial correlation coefficient between the simulated and observed JJA mean precipitation anomalies in China south of 40°N is less than 0.2 on average for the years of 1979–2001 for all models in the DEMETER program of Europe (Wang and Fan, 2009). There have also been validations of domestic models for seasonal prediction in China, and similar results have been obtained.

There have been numerous analyses and modeling studies aimed at understanding various processes and factors responsible for the seasonal climate variability in China. Besides the local elements, some remote factors have been identified. Among these, snow cover over the Tibetan Plateau and Eurasia, sea ice cover in the Northern Hemisphere, the SST in the tropical ocean, the NAO, AAO, and cross-equatorial flow in the Indian-Pacific sector are the most notable. Studies of these aspects have helped to establish more rational and effective forecast models for the seasonal climate variability in China.

However, much effort has been devoted to developing new techniques to improve seasonal climate prediction, particularly for the summer precipitation. These endeavors involve dynamical and statistical downscaling, year-to-year incremental forecasting, and new statistical models that adopt new sets of predictors including preceding observational information and/or GCM output.

A successful case in dynamical downscaling was achieved by the NCC in its seasonal precipitation prediction for the year 2003 (Ding et al., 2006). However, there has been no reports thus far to show an improved prediction skill based on multi-year dynamical downscaling seasonal forecasts. Regardless, such an effort would be worthwhile, and the results will likely be promising.

Statistical downscaling and correction techniques developed for climate prediction in China have achieved significant improvements for precipitation forecasting. In a recent new scheme developed by Wang and Fan (2009), the precipitation anomalies of the most similar year and the most dissimilar year, judged by the spatial anomaly pattern similarity between the observed and modeled summer precipitation in the tropical Eastern Hemisphere, are used to compose new predicted precipitation anomalies in East Asia and the western Pacific region. This new scheme was tested by using the DEMETER multi-model hindcasts from Europe, and significant improvement was obtained by applying the new scheme for all six models and the multi-model ensemble for the years of 1979–2001. Thus, the development and application of new downscaling techniques may produce substantially increased forecast skill in operational seasonal climate prediction.

Another successful new technique is related to the selection of the prediction objective. Traditionally, the anomaly of a quantity as compared to its multi-year average is adopted as the predictand. Fan et al. (2008) and Fan and Wang (2009) proposed to substitute the "anomaly" by the "year-to-year increment" for the prediction objective and re-established forecast models for the year-to-year increment. Applications in the seasonal forecast of summer rainfall in the Yangtze River valleys and central North China, as well as in the seasonal prediction of the WNP typhoon frequency, have demonstrated the apparent advantage of this new technique. All of the applications show improved forecast skill and decreased forecast errors.

Correct simulation of local soil moisture and snow cover over the Tibetan Plateau and Eurasia has been demonstrated to be significant for improving the seasonal prediction for precipitation as well as other quantities. A study by Zhan and Lin (2011) documented an example of improved seasonal prediction skill in the Yangtze and Huaihe river basins for the spring of 2008 by better describing the initial soil moisture.

With all of the above progress that has been achieved and problems that still remain, future work in the context of seasonal climate prediction in China should focus on several aspects such as process-based studies, GCM improvement, downscaling techniques, new statistical models based on the identification of new predictors and new processes, new integration schemes for seasonal prediction, and the development of various data assimilation schemes for land surface and oceanic processes. Multi-model ensembles always give high scores of seasonal prediction. Thus, the design of new schemes associated with the method of multi-model ensemble prediction is another important research focus in the future.

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