

Seasonal Prediction of the Global Precipitation Annual Modes with the Grid-Point Atmospheric Model of IAP LASG*

WU Zhiwei^{1,2}(吴志伟) and LI Jianping^{1†}(李建平)

¹ LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

² Graduate School of the Chinese Academy of Sciences, Beijing 100049

(Received June 13, 2008; revised September 9, 2008)

ABSTRACT

A right annual cycle is of critical importance for a model to improve its seasonal prediction skill. This work assesses the performance of the Grid-point Atmospheric Model of IAP LASG (GAMIL) in retrospective prediction of the global precipitation annual modes for the 1980–2004 period. The annual modes are gauged by a three-parameter metrics: the long-term annual mean and two major modes of annual cycle (AC), namely, a solstitial mode and an equinoctial asymmetric mode.

The results demonstrate that the GAMIL one-month lead prediction is basically able to capture the major patterns of the long-term annual mean as well as the first AC mode (the solstitial monsoon mode). The GAMIL has deficiencies in reproducing the second AC mode (the equinoctial asymmetric mode). The magnitude of the GAMIL prediction tends to be greater than the observed precipitation, especially in the sea areas including the Arabian Sea, the Bay of Bengal (BOB), and the western North Pacific (WNP). These biases may be due to underestimation of the convective activity predicted in the tropics, especially over the western Pacific warm pool (WPWP) and its neighboring areas. It is suggested that a more accurate parameterization of convection in the tropics, especially in the Maritime Continent, the WPWP and its neighboring areas, may be critical for reproducing the more realistic annual modes, since the enhancement of convective activity over the WPWP and its vicinity can induce suppressed convection over the WNP, the BOB, and the South Indian Ocean where the GAMIL produces falsely vigorous convections. More efforts are needed to improve the simulation not only in monsoon seasons but also in transitional seasons when the second AC mode takes place. Selection of the one-tier or coupled atmosphere-ocean system may also reduce the systematic error of the GAMIL prediction. These results offer some references for improvement of the GAMIL seasonal prediction skill.

Key words: seasonal prediction, global precipitation, annual cycle, climate model

Citation: Wu Zhiwei and Li Jianping, 2009: Seasonal prediction of the global precipitation annual modes with the grid-point atmospheric model of IAP LASG. *Acta Meteor. Sinica*, **23**(4), 428–437.

1. Introduction

A Model's performance in simulating and forecasting seasonal mean states is closely related to the model's capability in predicting seasonal anomalies (Sperber and Palmer, 1996; Slingo et al., 1996; Zhang and Li, 2007; Li and Zhang, 2008). Kang et al. (2002) showed a clear relationship between the model predictive performance in climatology and that in anomalies for summer 1997 and winter 1997/98 by using 11 Atmospheric General Circulation Models (AGCMs). Over Southeast Asia and the tropical western North

Pacific (WNP) regions, those models that better simulated the climatological precipitation can produce more realistic precipitation anomalies (Kang et al., 2002; Wang et al., 2004b). Gadgil and Sajani (1998) found that realistic simulations of the seasonal variation of the rain belt may also contribute to successful reproduction of the Indian summer rainfall interannual variation. Sperber et al. (2001) showed that errors in the climatological mean are likely to result in errors in the magnitude and location of subseasonal precipitation simulation, which compromises the dynamical seasonal prediction. Therefore, a right annual cycle is

*Supported by the National Natural Science Foundation of China under Grant No. 40605022, the "973" Project of the Ministry of Science and Technology of China under Grant No. 2006CB403600, and the Special Research Program for Public Welfare (Meteorology) under Grant No. GYHY200706005.

[†]Corresponding author: ljp@lasg.iap.ac.cn.

of great importance for improving a model's prediction skill. Our analysis will primarily focus on precipitation, because precipitation plays an essential role in determining the global general circulation and hydrological cycle (Matsuno, 1966; Charney, 1971; Webster, 1972; Gill, 1980; Wang and Ding, 2008; Wu and Li, 2008). The latent heat energy released in precipitation also plays a vital role in balancing radiative heat loss. Thus, a global analysis of precipitation is extremely important (Wang and Ding, 2006).

The largest annual variation of precipitation occurs in the monsoon domain, namely, wet summer and dry winter (e.g., Ramage, 1971; Li and Zeng, 2002; Wu et al., 2006, 2009a, b; He et al., 2006). Based on this fact, Wang and Ding (2008) put forward a simple objective metrics to gauge the annual variation of precipitation. The metrics consists of three major components: the annual mean and two leading modes of annual cycle (AC). Wang and Ding (2008) defined the two dominant AC modes by using the multi-variable empirical orthogonal function analysis of the climatological monthly mean precipitation and 850-hPa winds. They have shown that the first two leading modes account for 71% and 13% of the total annual variance, respectively. Both modes are statistically distinguishable from each other and from the other modes. The first mode represents a solstitial global monsoon mode, whereas the second mode reflects an equinoctial asymmetric mode.

The main objectives of the present study are to: 1) assess how well the model we used captures the annual modes; 2) to determine how the model performs in reproducing the annual modes and how it is related to the model's seasonal prediction skill; 3) to offer some references for the future model improvement. Section 2 describes the main features of the climate model and its experimental design for retrospective forecasts. In Section 3, the long-term annual mean of predicted precipitation is validated against the observation. In Section 4, the dominant AC modes of precipitation are evaluated between the prediction and observation. The last section gives conclusions and discussion.

2. Model, data, and methodology

The model used in this study is the Grid-point Atmospheric Model of IAP (Institute of Atmospheric Physics) LASG (the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics) (GAMIL), which was developed in LASG, IAP, Chinese Academy of Sciences (CAS). This model also participated in the "Climate Prediction and Its Application to Society" (CliPAS) project aimed at supporting the Asia-Pacific Economic Cooperation (APEC) Climate Center (APCC) for seasonal climate prediction and application (Wang et al., 2008). The GAMIL model has a horizontal resolution of $2.8^\circ \times 2.8^\circ$ and 26 vertical levels. The dynamical core is designed in LASG/IAP using the semi-implicit finite difference scheme with exact effective energy conservation, mass conservation, and terrain reduction (Wang et al., 2004a). The physical package mainly comes from the National Center for Atmospheric Research (NCAR) Community Atmosphere Model, Version 2 (CAM2), in which an improved Tiedtke convective scheme (Tiedtke, 1989) has replaced the original convective parameterization (Li et al., 2007).

Our analysis employs the GAMIL two-tier hindcast data for the period 1979–2004. The hindcast was done four times a year, targeting for a 6-month prediction initialized from 1 February, 1 May, 1 August, and 1 November, respectively. Note in a two-tier approach (Bengtsson et al., 1993), SST is first predicted by using a coupled model and then the atmospheric anomalies are predicted by using an atmospheric model forced by the predicted SST.

In the present study, we will focus on evaluating the GAMIL seasonal forecasts with one-month lead time. The Global Precipitation Climatology Project (GPCP) data (Adler et al., 2003) are used for verification.

Wang and Ding (2008) suggested a simple three-parameter metrics to gauge the precipitation annual variation which includes the long-term annual mean and two dominant AC modes. The annual mean here is defined by a 25-yr mean precipitation for the

1980–2004 period. The first AC mode reflects the global monsoon mode and its spatial pattern can be represented extremely well by the difference between June–July–August–September (JJAS) and December–January–February–March (DJFM) mean precipitation, whereas the second mode reflects an equinoctial asymmetric mode and its spatial pattern can be very well depicted by the difference between April–May (AM) and October–November (ON) mean precipitation. Hereafter, we will use the pattern of JJAS minus DJFM and that of AM minus ON to represent the first and second AC mode, respectively.

To assess the difference between the observation and prediction, the method of the standard deviations of differences (SDD) (Chou et al., 2004) is adopted. To obtain an SDD field, the difference between the observation and prediction should be calculated first year by year and grid by grid. Then SDD values are

computed grid by grid within the hindcast period. Finally, an SDD field is produced. High SDD value areas denote large year-to-year prediction biases in the hindcast period, and vice versa. Note that SDD alone cannot prove that the simulation is larger or smaller than the observation. Some other parameters have to be included to reflect this. In this paper, mean biases (simulation minus observation) are used to show the sign difference as a complement to the SDD method. If mean biases are positively correlated with high SDD values, a larger-than-observation situation occurs. If mean biases are negatively correlated with high SDD values, a less-than-observation situation exists.

3. Prediction of long-term annual mean precipitation

Figure 1a shows the observed pattern of long-term

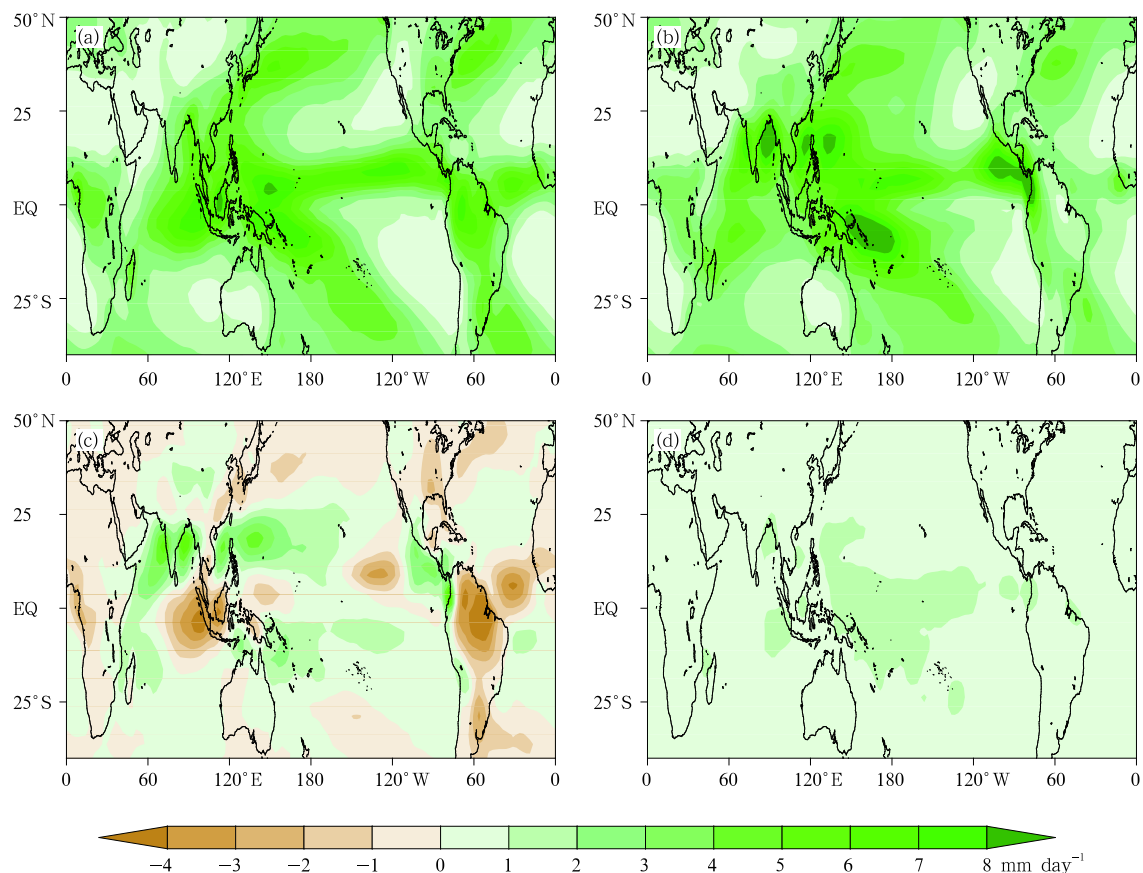


Fig. 1. The climatological mean of annual precipitation (mm day^{-1}) in the (a) GPCP observation and (b) GAMIL prediction. (c) The mean bias defined by the difference between (b) and (a). (d) The standard deviations of differences (SDD) between GPCP and GAMIL (Chou et al., 2004).

annual mean precipitation. As many previous studies have discussed in detail (e.g., Annamalai et al., 1999; Matsumoto and Murakami, 2002; Hung et al., 2004; Chang et al., 2005; Goswami et al., 2006; Wang and Ding, 2008), it exhibits significant meridional and zonal asymmetries in the tropics. The tropical Eastern Hemisphere receives more precipitation than the tropical Western Hemisphere, whereas the tropical Northern Hemisphere receives more precipitation than the tropical Southern Hemisphere because the mean intertropical convergence zone (ITCZ) is located in the Northern Hemisphere. The South Pacific convergence zone (SPCZ) reduces the meridional asymmetry in the Western Hemisphere, while in the Eastern Hemisphere the precipitation is nearly symmetric around the equator. In addition, the major precipitation zones in the extratropical Pacific and Atlantic tilt eastward and poleward in association with the oceanic storm tracks.

It can be seen from Figs. 1a and 1b that major

features of the climatological annual mean precipitation of the GPCP observation are basically reproduced by GAMIL. These features include the ITCZ, SPCZ, the equatorial-South Indian Ocean convergence zone, and the major precipitation zones in the extratropical Pacific and Atlantic. The pattern correlation coefficient (PCC) between the GAMIL prediction and GPCP observation reaches 0.77, exceeding the 99.9% confidence level based on the student-*t* test.

The magnitude of the GAMIL prediction tends to be greater than the observation in most of the tropical monsoon domains. It can be inferred from Fig. 1c that the GAMIL tends to overestimate the annual precipitation over the Arabian Sea, the Bay of Bengal (BOB), and the WNP, but it underestimates precipitation over the Maritime Continent, the western Pacific warm pool (WPWP) area, and the equatorial America and its surrounding areas. Note that the SDD field (Chou et al., 2004) between the observation and

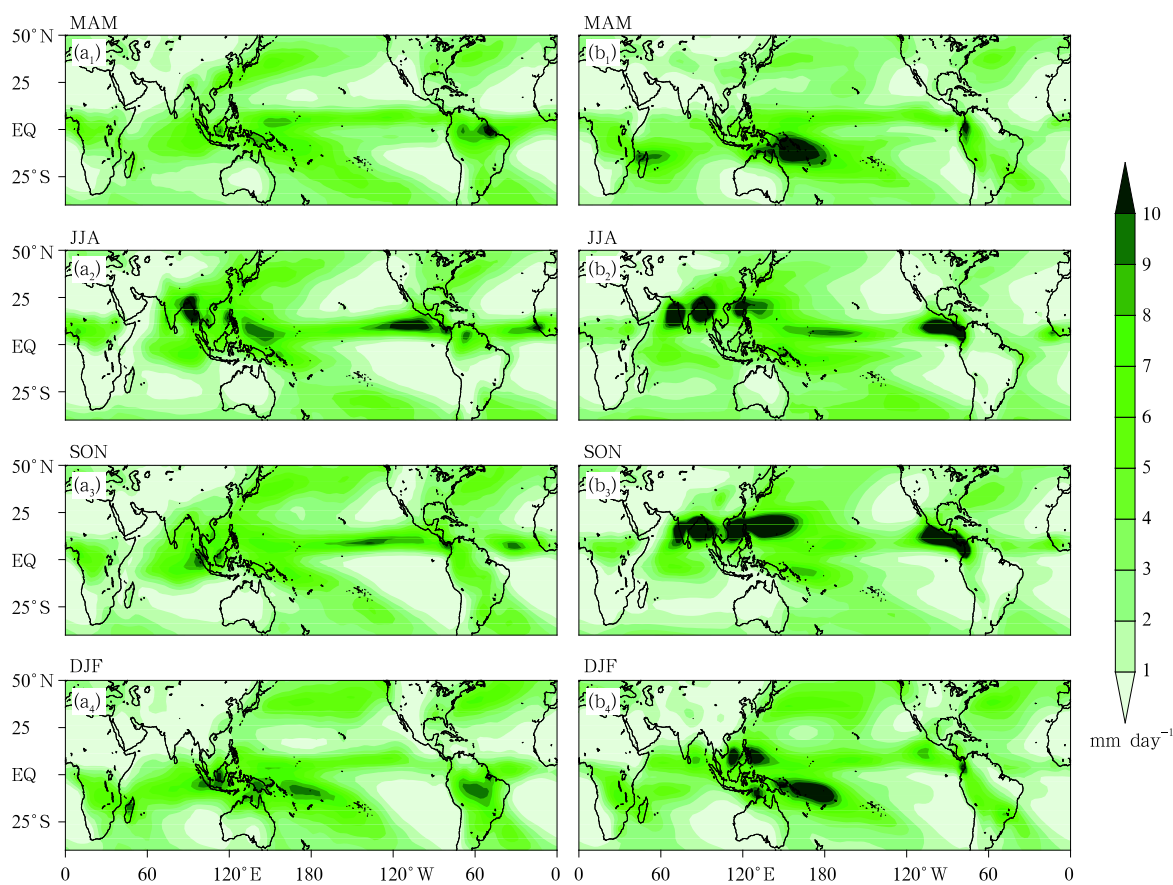


Fig. 2. The climatological mean of seasonal precipitation (mm day⁻¹) in the GPCP observation (a; left panels) and GAMIL prediction (b; right panels).

prediction (Fig. 1d) has a spatial pattern different from that of the mean bias (Fig. 1c). The maximum SDD values are located in the ITCZ region and are centered at the WPWP area (Fig. 1d) where mean biases exhibit negative values (Fig. 1c). The high SDD value takes place in the region where the GAMIL prediction has a more remarkable temporal variation difference with the GPCP observation. As mentioned earlier, if mean biases are positively associated with high SDD values, it denotes a larger-than-observation situation; if mean biases are negatively associated with high SDD values, it indicates a less-than-observation situation (see Section 2). The maximum SDD values centered at the WPWP area are associated with negative mean biases, which indicates the simulated convective activity is underestimated compared with the observation in terms of the annual mean. Note that the overestimation of the annual mean precipitation over the Arabian Sea, the BOB, the WNP, and the

South Indian Ocean is concurrent with the precipitation underestimation in the ITCZ and WPWP areas (Figs. 1c and 1d).

In addition to the annual mean precipitation, the seasonal precipitation is also basically reproduced. The PCCs between the GAMIL prediction and GPCP observation reach 0.69 (MAM), 0.71 (JJA), 0.63 (SON), and 0.75 (DJF), respectively, and all exceed the 99.9% confidence level based on the student-*t* test (Fig. 2). Note that PCCs in MAM and SON (transitional seasons) are lower than those in JJA and DJF (monsoon seasons). Larger discrepancies emerge over the Arabian Sea, the BOB, and the WNP with an overestimation of seasonal precipitation in JJA, SON, and DJF, and an underestimation in MAM (Fig. 3a). Also underestimated is seasonal precipitation over the Maritime Continent, the equatorial America and its vicinity. The high SDD values (Fig. 3b) associated with negative mean biases (Fig. 3a) are primarily

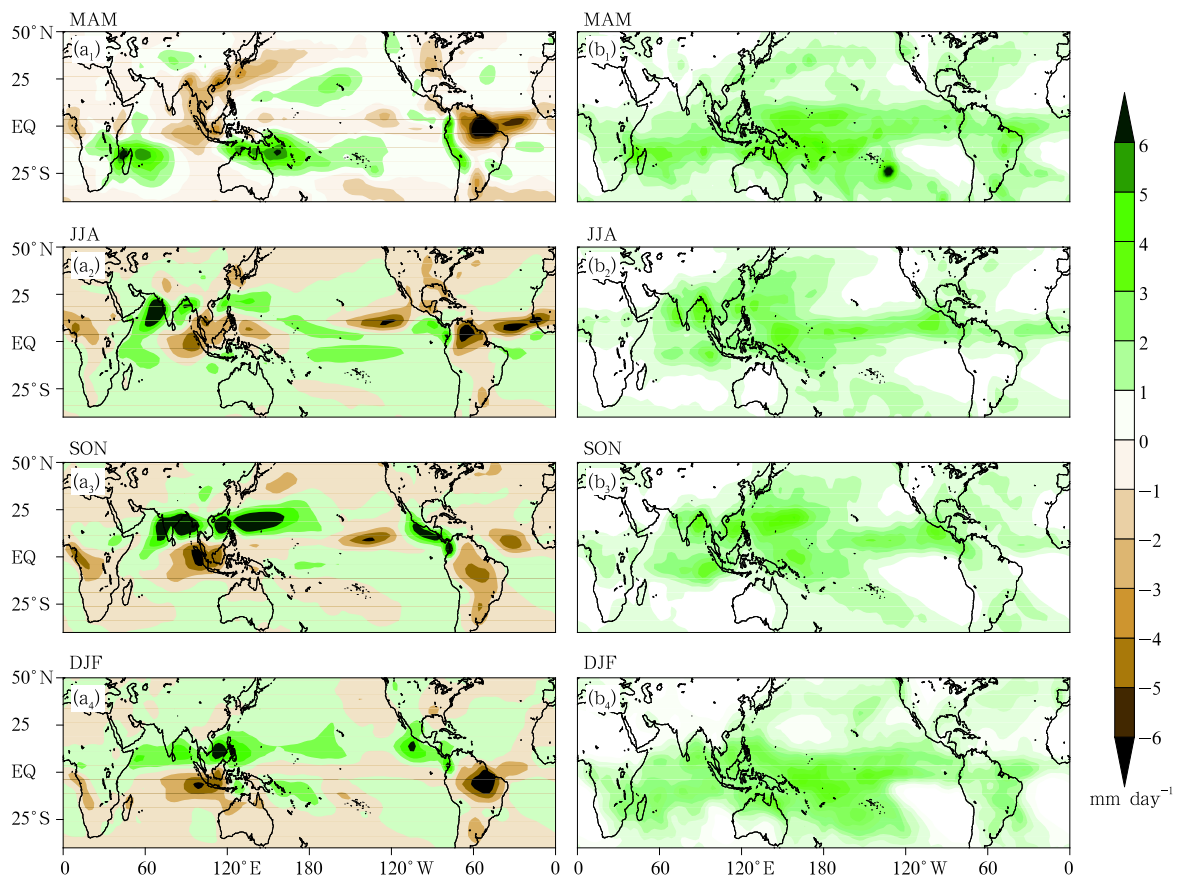


Fig. 3. The mean bias (a; left panels) and SDD (b; right panels) of the seasonal mean precipitation (mm day^{-1}) between the GPCP observation and GAMIL prediction.

located in the Maritime Continent region where larger temporal variation difference between the observation and prediction exists (Fig. 3b). Similar to the annual mean, the overestimation over the Arabian Sea, the BOB, and the WNP is associated with the underestimation of the deep convective activity over the WPWP and neighboring areas, especially in JJA.

4. Prediction of the two dominant AC modes

As mentioned in Section 2, we used the patterns of JJAS minus DJFM and AM minus ON to represent, respectively, the first (Fig. 4) and second AC mode (Fig. 5) (Wang and Ding, 2008). Figure 4a shows the observed first AC mode whose spatial pattern displays a contrast between the Northern Hemisphere and Southern Hemisphere although the asymmetry is not a mirror image about the equator. The longitudinal locations of the precipitation between the

Northern Hemisphere and Southern Hemisphere differ, mainly due to the differences in land distribution and topography between the two hemispheres, which reflects the major global monsoon systems including the Asian-Australian monsoon, the African monsoon, and the American monsoon. This mode is defined as a solstitial mode by Wang and Ding (2008).

Figure 5a presents the asymmetric patterns between the two transitional seasons, i.e., the spring-fall asymmetry for short. The spring-fall asymmetry is one of the fundamental features of the seasonal variation in the tropical circulations, and especially noted is the asymmetric location of the spring and fall ITCZ (Lau and Chan, 1983; Meehl, 1987). In April and May, heavy precipitation occurs along the coast of Southeast Asia, from the BOB through southern China to Okinawa, Japan. This enhanced rain belt reflects the establishment of the planetary-scale Asian summer monsoon during May (e.g., Wang and LinHo,

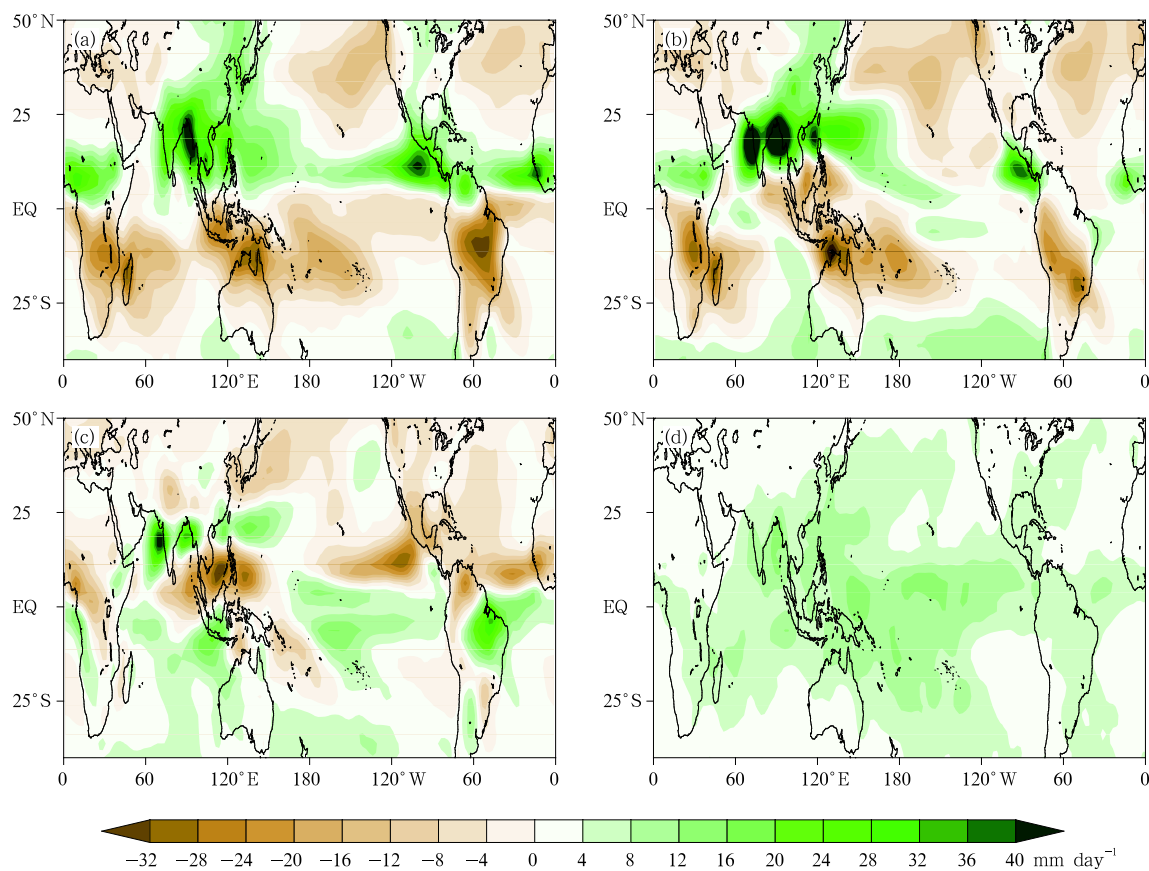


Fig. 4. Spatial patterns of the first AC mode (color shadings; mm day⁻¹) obtained from the GPCP observation (a), GAMIL prediction (b), and the corresponding mean bias (c) and SDD (d) between them.

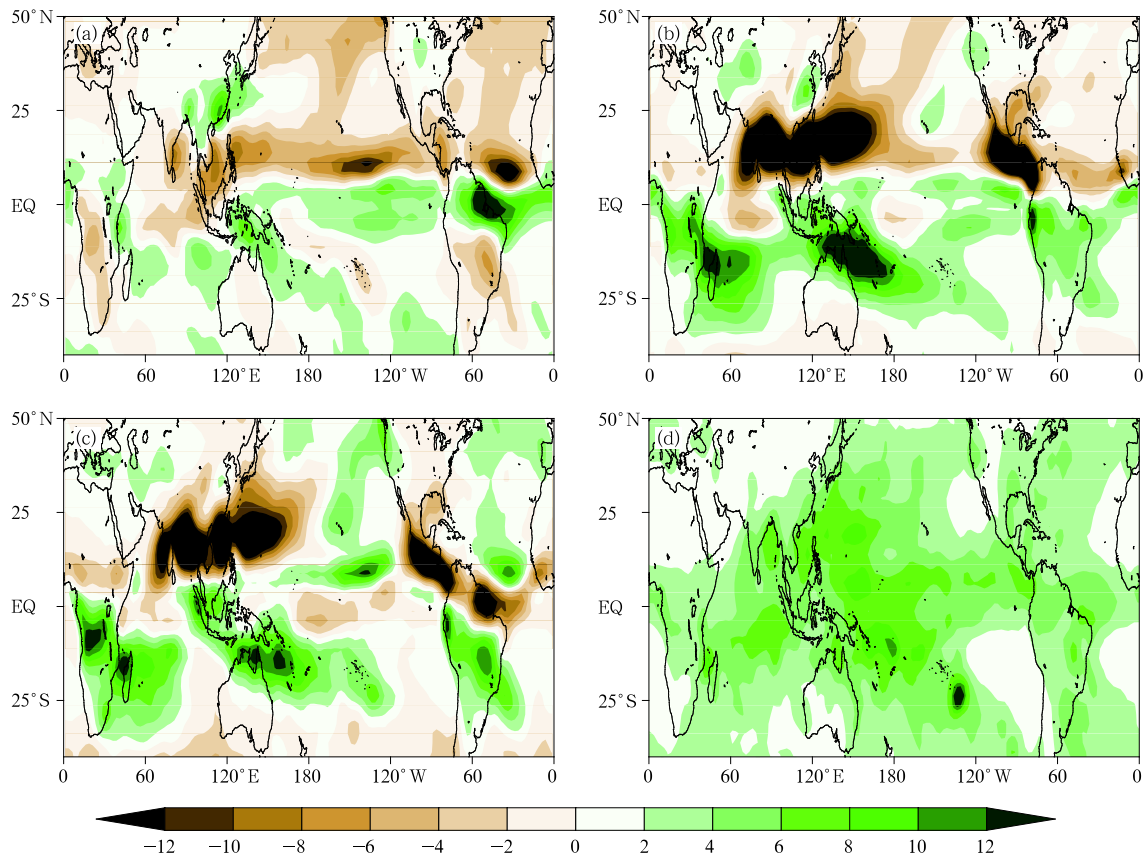


Fig. 5. As in Fig. 4, but for the second AC mode.

2002). During the boreal fall, strong precipitation remains over the Philippine Sea due to the large ocean thermal inertia, which delays the retreat of the rainy season and prolongs tropical cyclone activities in the region. The mode is defined as an equinoctial asymmetric mode by Wang and Ding (2008).

The GAMIL model is basically able to capture the major features of the first AC mode (Fig. 4b). The PCC between the prediction and observation reaches 0.67, exceeding the 99.9% confidence level based on the student-*t* test. The Asian-Australian monsoon and the African monsoon are better reproduced than the American monsoon in general. Large discrepancies primarily exist in the American monsoon domain and the joint area of Asia and Indian-Pacific Ocean including the Arabian Sea, the BOB, the Maritime Continent, and the WNP (Fig. 4c). High SDD values are located in the ITCZ, the SPCZ, and the South Asian monsoon regions, and centered at the WPWP area (Fig. 4d). Similar to the annual mean, the dis-

crepancies and high SDD values may reflect temporal variation bias of the convective activity between the observation and the prediction over the WPWP and surrounding areas. It also implies that not only spatial locations but also temporal variations of deep convective activity in the tropics, especially around the WPWP region, might greatly affect the prediction skill of the first AC mode (the solstitial monsoon mode).

GAMIL cannot realistically reproduce the second AC mode compared with the first AC mode, which suggests that more efforts are needed to improve the simulation in transitional seasons. The mean bias (Fig. 5c) exhibits three major features. First, the strengthening of the spring-fall asymmetry over the Indian Ocean is related to underestimation of AM-ON precipitation difference over the North Indian Ocean and its overestimation over the South Indian Ocean. Second, the enhancement of the spring-fall asymmetry over the East Asia-WNP and the Maritime

Continent-northern Australian regions is basically resulted from the negative bias over the East Asian-WNP region and the positive bias over the Maritime Continent-northern Australian region. Third, the spring-fall ITCZ bias is mainly due to the underestimation over the equatorial eastern Pacific. These biases are quite likely attributed to the failure of reproducing the convective activity over the joining area of Asia and Indian-Pacific Ocean where high SDD values exist (Fig. 5d). Chang et al. (2005) have discussed this spring-fall asymmetry in detail. They attributed the spring-fall asymmetry to a combination of asymmetric wind-terrain interaction and low-level divergence asymmetry, which are both induced by different land-ocean thermal inertia over the Asian-Australian monsoon region. In light of this, the peculiarity of the land-sea distribution in the Maritime Continent-northern Australian region may greatly affect the second AC mode prediction, which is such an important factor that a climate model should not neglect.

5. Conclusions and discussion

Thus far, ENSO is the primary source of predictability for global seasonal climate anomalies. Getting the annual cycle right is extremely critical for models in simulating and predicting accurate teleconnection and climate anomalies away from the ENSO region. To gauge the precipitation annual modes, this paper used a three-parameter metrics: the annual mean and two major AC modes. The patterns of JJAS minus DJFM and AM minus ON are used to represent the first and second AC mode, respectively. The performance of GAMIL, a model that participated in the APCC/CliPAS project, is assessed with respect to its seasonal prediction of precipitation annual modes, based on the GASMIL one-month lead retrospective hindcast product for the 1980–2004 period. The results demonstrate that the GAMIL one-month lead prediction has basically captured the major patterns of the long-term annual mean as well as the first AC mode (the solstitial monsoon mode), but has deficiencies in reproducing the second AC mode (the equinoctial asymmetric mode). The magnitude of the GAMIL prediction tends to be greater than the GPCP observa-

tion, especially in the sea areas including the Arabian Sea, the BOB, and the WNP.

The overestimation of precipitation over the Arabian Sea, the BOB, and the WNP may be associated with the underestimation of the convective activity of the model in the WPWP and surrounding areas, because the enhancement of the convective activity over the WPWP and surrounding areas can induce suppressed convection over the WNP, the BOB, and the South Indian Ocean (Wang et al., 2000).

To improve the GAMIL skill in seasonal prediction of precipitation annual modes, a more accurate parameterization of convection in the tropics, especially in the Maritime Continent, the WPWP and adjacent areas may be critical. In light of the fact that GAMIL cannot realistically capture the second AC mode, more efforts are needed to improve the simulation in transitional seasons. In fact, deficiencies in the simulations of the transitional season might be common characteristics in most of the current atmospheric models (e.g., Zhang and Li, 2007). In addition, selection of a one-tier (air-sea coupling) system may also reduce the amplitude of systematic error of the prediction and enhance the predictability, because the annual harmonic in equatorial sea surface temperature is primarily wind driven, while air-sea interaction strongly affects the semianual harmonic (e.g., Robertson et al., 1995; Stockdale et al., 1998; Yang and Anderson, 2000).

In this paper, we focus on the performance of GAMIL in predicting global precipitation annual modes. However, what determines the structure and dynamics of the annual cycle of the coupled atmosphere-ocean-land system? How to remedy the major weaknesses of GAMIL in simulation of the principal modes of global precipitation AC? These are still outstanding issues and need further investigations.

Acknowledgements. The authors acknowledge Prof. Bin Wang (University of Hawaii) and the anonymous reviewers for helpful discussion and comments.

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