Improved simulation of the East Asian winter monsoon interannual variation by IAP/LASG AGCMs

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\textbf{ABSTRACT}

The simulation of the East Asian winter monsoon (EAWM) has been a challenge for climate models. In this study, the performances of two versions of the AGCM developed at the IAP, versions 1 and 2 of the Grid-point Atmospheric Model of the IAP/LASG (GAMIL1 and GAMIL2), are evaluated in the context of mean state and interannual variation. Significant improvements are shown for GAMIL2 in comparison to GAMIL1. The simulated interannual variability of the EAWM, measured by the regional average of 1000 hPa meridional wind over East Asia, has evidently improved; the correlation coefficient with reanalysis data changes from 0.37 in GAMIL1 to 0.71 in GAMIL2. The associated interannual precipitation anomalies are also improved, in terms of both spatial pattern and magnitude. Analysis demonstrates that the improvements result from the better simulation of the El Niño-related Philippine Sea anticyclone (PSAC) in GAMIL2. The improved moist processes, including the stratiform condensation and evaporation in GAMIL2, lead to a reasonable atmospheric heating associated with El Niño in the tropical Pacific, which further drives the PSAC as a Rossby-wave response.

\textbf{1. Introduction}

The East Asian winter monsoon (EAWM) is one of the most active regional climate systems in boreal winter. The intense variability of the EAWM can bring severe cold surges and heavy snowfall, which may cause serious damage over East Asia, such as the persistent low temperature and icy weather over southern China in January 2008 (Zhou et al. 2009). In addition to regional impacts, as a coupled extratropical–tropical system, the EAWM also has substantial impacts on far away regions through changes in large-scale deep convection over the equatorial western Pacific, or changes in the Hadley and Walker circulations (Chang and Lau 1980, 1982; Huang, Zhou, and Chen 2003). Therefore, understanding the mechanisms of EAWM changes and improving its predictability have been important topics for the Asian climate research community (Ding 1994; Chen, Yang, and Huang 2005; Huang et al. 2012).

The EAWM is characterized by a cold Siberian–Mongolian high, strong northerlies at the surface, a broad East Asian trough at 500 hPa, and an enhanced East Asian jet stream in the upper troposphere. It is difficult to measure all of the EAWM’s characteristics using a single index because of the difference in the EAWM variability between extratropical and tropical East Asia (Wang and Chen 2010; Wang et al. 2010). The interannual variability of the EAWM can be separated into a northern mode and southern mode using EOF analysis of the 2-m air temperature (Wang et al. 2010). The northern mode is characterized by enhanced surface pressure over central Siberia, related to the Arctic Oscillation (Gong, Wang, and Zhu 2001; Wang et al. 2010; Chen et al. 2013). The southern mode is mainly attributed to the Philippine Sea anticyclone (PSAC), associated with El Niño forcing (Zhang, Sumi, and Kimoto 1996; Jin and Zhou 2005).
Numerical climate models are useful tools to study the variability of the EAWM. Wei et al. (2014) examined the climatology of the EAWM in 41 fully coupled atmosphere–ocean models from CMIP5 and found that the biases of surface air temperature and precipitation are improved in CMIP5 models compared with CMIP3 models. The interannual variabilities of the EAWM-related circulations are successfully reproduced in CMIP5 multimodel ensembles; for example, about half of CMIP5 models successfully capture the observed ENSO–EAWM relationship (Gong et al. 2014). Jiang et al. (2015) evaluated 77 coupled global climate models in CMIP3/CMIP5 and revealed an improvement in the performance of models from CMIP3 to CMIP5 with respect to temperature in China, but an underestimation of the strength of the EAWM as manifested by southerly wind anomalies.

Much effort has been devoted to the development of climate models at the LASG, IAP, Chinese Academy of Sciences (see Zhou, et al. 2014b for a summary). FGOALS-g2 (Li, et al. 2013a) has shown reasonable performance in many aspects among both Chinese (Zhou, et al. 2014a) and international (Bellenger et al. 2013) CMIP5 models. However, the performance of FGOALS-g2 in simulating the EAWM remains unknown. In this study, we begin to address this knowledge gap by assessing the AGCM component of FGOALS-g2, the Grid-point Atmospheric Model of the IAP/LASG (GAMIL). By comparing AMIP runs of GAMIL driven by observational SST, we aim to evaluate the performance of two versions of GAMIL in simulating the EAWM mean state and interannual variation. We also hope to understand the physical processes that have led to the improvements.

2. Model and data description

Two versions of the IAP/LASG AGCM (GAMIL1 and GAMIL2) are used in this study. They employ the same horizontal (128 × 60) and vertical (26 Ω-layers) resolution (Li et al. 2012). The main differences between the two versions are their cloud-related processes, including the deep convective parameterization, convective cloud fraction, and microphysical schemes (Li, et al. 2013a, 2013b). For the deep convective scheme, the CAPE adjustment closure in GAMIL1 (Zhang and McFarlane 1995) is replaced by a free-tropospheric quasi-equilibrium closure in GAMIL2 (Zhang 2002). For nonconvective cloud processes, a two-moment cloud microphysical scheme (Morrison and Gettelman 2008; Shi et al. 2010) is applied in GAMIL2 instead of the one-moment scheme (Rasch and Kristjánsson 1998) in GAMIL1.

The AMIP experiments from GAMIL are performed with the same forcing data recommended by CMIP5, such as the solar constant, greenhouse gases, and HadISST data-set. Only the first member, with the same period from 1979 to 1998, is used for analysis. All the datasets are interpolated into a $2.5^\circ \times 2.5^\circ$ common grid by bilinear interpolation.

The observational and reanalysis datasets include: (1) atmospheric circulation and air temperature from NCEP-2 (Kanamitsu et al. 2002); (2) heating rate in deep convection, shallow convection, and large-scale condensation from the NCEP CFS Reanalysis (CFSR) (Saha et al. 2010); (3) precipitation data from the GPCP (Adler et al. 2003); and (4) SST data from ERSST.v3b (Smith et al. 2008).

3. Results

3.1. Climatology of the EAWM simulated by the IAP/LASG AGCMs

We assess the performance of the models in simulating the EAWM with a focus on the surface climate. The climatology of 1000-hPa wind, SLP and 2-m temperature derived from the simulations and NCEP-2 reanalysis (hereafter referred to as ‘observation’ to facilitate the discussion) are shown in Figure 1. In the observation (Figures 1(a)), a salient structure of the Siberian–Mongolian high is evident at the surface, which induces strong northerlies from 60°N down to the equator. Northwesterlies prevail toward the subtropical Pacific, north of 30°N, and turn westward along the coast of East Asia into the South China Sea. The above features are reproduced well by the two versions of GAMIL (Figure 1(b) and (c)). We further assess the performance of the models in simulating the 2-m temperature, 500-hPa geopotential height, and 300-hPa zonal wind is better than that of precipitation, SLP and 1000-hPa meridional wind (V1000). Quantitative comparison suggests that GAMIL2 performs better than GAMIL1 in simulating the climatology of precipitation, SLP, and V1000.

3.2. Interannual variability of the EAWM simulated by the IAP/LASG AGCMs

Following Ji et al. (1997), an EAWM index is defined as the 1000-hPa meridional wind averaged within the box (10°–30°N, 115–130°E) over East Asia. The interannual variation of the EAWM is reproduced well in both GAMIL1 and GAMIL2 (Figure 2(a)). The correlation coefficients of the EAWM index between the observation and the two models indicate significant improvement from GAMIL1 (0.37) to GAMIL2 (0.71). The interannual variability of the EAWM is dominated by El Niño, as demonstrated by the significant correlation coefficient of −0.75 between the EAWM index
and Niño3.4 index in the observation. Note that in Table 1 the correlation coefficient between the Niño3.4 index and EAWM index is ~0.59 for GAMIL1 and ~0.64 for GAMIL2, demonstrating El Niño’s forcing of the interannual variability of the EAWM.

To show more robust evidence, we further examine the interannual EAWM anomalous patterns by regressing the observed EAWM index onto the precipitation and 1000-hPa wind anomalies (Figure 2). In the observation (Figure 2(b)), associated with a high EAWM index, there is a cyclone over the Philippine Sea, with enhanced northeasterly winds over South China. Correspondingly, the precipitation exhibits a dipole pattern, with negative anomalies extending from continental South China to the south of Japan and positive anomalies over the western Pacific.

Both models reproduce the cyclone and dipole rainfall patterns well. However, the Philippine Sea cyclone in GAMIL1 is weaker than that in the observation and is shifted more eastward (Figure 2(c)). Accordingly, the anomalous precipitation dipole pattern is weak and shifts eastward. Compared with GAMIL1, the performance of GAMIL2 is improved in this regard, along with a better simulation of the precipitation anomaly pattern and its magnitude (Figures 2(d) and (e)). Since the EAWM index is significantly negatively correlated with Niño3.4 index (Table 1), the cyclonic circulations associated with the positive EAWM index shown in Figure 2 are actually indicative of the impact of anticyclonic circulation over the Philippine Sea in El Niño-year winters (Zhang, Sumi, and Kimoto 1996). We further examine the PSAC simulated by the two versions of GAMIL.

The establishment of the PSAC in boreal winter associated with El Niño events is remotely driven by the warm SST anomalies in the central-eastern Pacific and enhanced by the local cold SST via wind–evaporation–SST feedback (Wang, Wu, and Fu 2000). To understand the response of

Figure 1. Climatology of 1000-hpa winds (vectors; m s⁻¹), SLP (contours; hPa), and 2-m temperature (shading; °C) in winter (December–January–February), derived from (a) the observation (NCEP-2), (b) GAMIL1, and (c) GAMIL2. (d) Taylor diagram: The observation is considered as the reference (REF); the angular (vertical) coordinate is the pattern correlation coefficient (ratio of standard deviation) between the model and observation. The nearer the distance between a number and REF, the better the performance of the corresponding model.
over the equatorial central Pacific (western North Pacific) to
El Niño are weakly simulated by GAMIL1 (Figures 3(c) and
(d)), whereas significant improvement is seen in GAMIL2
(Figures 3(e) and (f)). The improvement of the simulation
of the PSAC from GAMIL1 to GAMIL2 ultimately results in a
better simulation of the EAWM interannual variation.

But why does GAMIL2 better reproduce the PSAC? Since in
the AMIP-type simulation both the central equatorial Pacific
warming and the local colder SST in the western Pacific
are prescribed as the observation, the improved response
should result from the improved sensitivity of the model
to El Niño-related SST forcing, the anoma-
lies of precipitation, 1000-hPa wind and 500-hPa vertical
velocity are regressed onto the Niño3.4 index (Figure 3). In
the observation (Figures 3(a) and (b)), in response to the
warming SST, positive precipitation anomalies and anom-
alous upward motion are seen over the equatorial central
Pacific, whereas the western North Pacific witnesses nega-
tive precipitation anomalies along with anomalous sinking
motion. The PSAC induced by the Rossby-wave response in
the lower troposphere (Wang, Wu, and Fu 2000) and local
anomalous sinking motion significantly affects the EAWM.
In comparison to the observation, the positive (negative)
responses of precipitation and upward (sinking) motion
over the equatorial central Pacific (western North Pacific) to
El Niño are weakly simulated by GAMIL1 (Figures 3(c) and
(d)), whereas significant improvement is seen in GAMIL2
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should result from the improved sensitivity of the model
to the SST forcing. In comparison to GAMIL1, cloud-related
processes, including deep convective parameterization, the

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**Figure 2.** (a) Normalized EAWM index (1000-hPa meridional wind averaged within the box (10–30°N, 115–130°E)) derived from the
observation (NCEP-2; black line), GAMIL1 (red line), and GAMIL2 (blue line). Green line: normalized (−1) × Niño3.4 index. (b–e) Regression
coefficients of the December–January–February 1000-hPa winds (vectors; m s⁻¹) and precipitation (shaded; mm d⁻¹) with respect to the
EAWM index derived from (b) the observation (NCEP-2), (c) GAMIL1, (d) GAMIL2, and (e) the difference between GAMIL2 and GAMIL1.

**Table 1.** Time correlation coefficients among the EAWM index (EAWMI) derived from GAMIL and the observation (NCEP-2), and the
Niño3.4 index.

|                  | GAMIL1 EAWMI | GAMIL2 EAWMI | Niño3.4 index |
|------------------|--------------|--------------|---------------|
| NCEP2 EAWMI      | 0.37         | 0.71         | −0.75         |
| Niño3.4 index    | −0.59        | −0.64        | 1.0           |
convective cloud fraction and microphysical schemes, are much improved in GAMIL2 (Li, et al. 2013a). Associated with the enhanced stratiform condensation and evaporation in GAMIL2, the climatology of annual mean water vapor (or relative humidity), cloud fraction, and in-cloud liquid water path, are also improved (Li, Wang, and Zhang 2014). In Figure 4, we examine the regression coefficients of the vertically integrated heating rate with respect to the Niño3.4 index. Clearly, the heating rate simulated by GAMIL1 is too weak in comparison to the observation, while the result of GAMIL2 is
greatly improved and closer to the observation. The improved moist physical processes in GAMIL2 lead to a more reasonable anomalous atmospheric heating associated with El Niño forcing in the tropical Pacific, which further drives a better PSAC as the Rossby-wave response. The improved simulation of the PSAC further results in more reasonable wind anomalies over the East Asian continent.

A previous study of GAMIL suggested that improved simulation of the tropical mean climate is associated with an improved representation of the tropical climate anomalies related to El Niño events (Li, Wang, and Zhang 2014). Our analysis finds that the EAWM simulated by GAMIL2 is better than that by GAMIL1, suggesting a connection between the EAWM mean states and the interannual variation. Further work based on multi-model intercomparisons is needed to clarify the issue.

4. Summary

The climatology and interannual variability of the EAWM simulated by two versions of the IAP/LASG AGCM, GAMIL1 and GAMIL2, are evaluated in this study. The physical processes that dominate the model performance are analysed. The main findings can be summarized as follows:

(1) The two versions of GAMIL reasonably simulate the climatological pattern of the winter monsoon over the East Asian continent, including the 2-m temperature, SLP, and V1000. The performance for the upper troposphere (500-hPa geopotential height and 300-hPa zonal wind) are better than that for precipitation, SLP, and V1000. GAMIL2 shows better performance than GAMIL1 in simulating the climatology of precipitation, SLP, and V1000.

(2) The interannual variability of the EAWM simulated by GAMIL2 is significantly improved compared to GAMIL1, as evidenced by change in correlation coefficient from 0.37 to 0.71. The improvement is also evident in the surface wind anomalies and the dipole rainfall pattern and its magnitude. The improved simulation of monsoon anomalies derives from the better simulation of the PSAC associated with El Niño forcing. The improved moist processes in GAMIL2, including stratiform condensation and evaporation, have led to a reasonable atmospheric heating associated with El Niño forcing in the tropical Pacific, which further drives the PSAC as a Rossby-wave response.

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