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Simulation of the East Asian Subtropical Westerly Jet Stream with GFDL AGCM (AM2.1)

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Abstract The present study validated the capability of the AM2.1, a model developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), in reproducing the fundamental features of the East Asian Subtropical Westerly Jet Stream (EASWJ). The main behaviors of the EASWJ are also investigated through the reanalysis of observational NCEP/NCAR data. The mean state of the EASWJ, including its intensity, location, structure, and seasonal evolution is generally well-portrayed in the model. Compared with the observation, the model tends to reproduce a weaker jet center. And, during summer, the simulated jet center is northward-situated. Results also demonstrate the model captures the variability of EASWJ during summer well. The results of the empirical orthogonal function (EOF) applied on the zonal wind at 200 hPa ($U200$) over East Asia for both the observation and simulation indicate an inter-decadal shift around the late 1970s. The correlation coefficient between the corresponding principle components is as great as 0.42 with significance at the 99% confidence level.

Keywords: East Asian Subtropical Westerly Jet Stream, seasonal evolution, GCM

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1 Introduction

Throughout the year, over the subtropical East Asia, a notable, narrow, and strong westerly belt, often referred to as the East Asian Subtropical Westerly Jet Stream (EASWJ) and featuring large horizontal and vertical wind shear in the upper troposphere and lower stratosphere, exists. Previous studies have indicated that the EASWJ is one of the most important components of the East Asian monsoon system, with crucial influences on the weather and climate over East Asia.

Large efforts have been made to investigate the seasonal features and formation of the EASWJ and its variations and association with climate variability over East Asia on interannual and decadal scales. Accompanying the transition of atmospheric circulation during the pre-onset to post-onset period of the East Asian monsoon, the EASWJ exhibits notable seasonal evolutions of intensity and location (Yeh et al., 1959; Tao and Chen, 1987; Lau et al., 1988; Ding, 1992; Liang and Wang, 1998; Yang et al., 2002; Liao et al., 2004; Zhang et al., 2006). Yeh et al. (1959) and Tao and Chen (1987) revealed that the EASWJ experienced two seasonal northward jumps in early May and late July and retreated southward in October. This seasonal evolution corresponded to the seasonal climate variability over East Asia and played an essential role in the onset and withdrawal of the East Asian Mei-yu season. On both the interannual and decadal time scales, the shift of the EASWJ may trigger anomalous atmospheric circulation, which would affect the water transport and divergence background and, thus, create anomalous rainfall patterns over the East Asian summer monsoon region (e.g., Liao et al., 2004; Lu, 2004; Yu et al., 2004; Kuang and Zhang, 2005; Lin and Lu, 2005; Zhou and Yu, 2005; Zhang et al., 2006; Kuang et al., 2007; Yu and Zhou, 2007; Zhang et al., 2008).

As a critical component of the East Asian monsoon climate systems, the EASWJ has attracted increasing inquiry into the mechanism responsbile for its formation (Yang and Webster, 1990; Hou, 1998; Zhang et al., 2006) and its association with other climate systems (Yang et al., 2002; Lu, 2004; Lin and Lu, 2005). Zhang et al. (2006) stated that the location change of the westerly jet core is associated with the meridional temperature contrast in the troposphere, and that the diabatic heating changes are the primary factors determining the seasonal evolution of the westerly jet core over East Asia. Lin and Lu (2005) analyzed the relationships of summer and subseasonal movements between the EASWJ and the South Asian High, the Western Pacific Subtropical High, and the convection over Western Pacific. Furthermore, evidence showed that the EASWJ was accompanied by a teleconnection-like wave-train that was propagating within and interacted with the jet. The teleconnection showed remarkable correlation to climate variability along its path, such as in East Asia and North America (e.g., Lu et al., 2002; Ding and Wang, 2005; Sato and Takahashi, 2006; Huang et al., 2011).

The studies described above provide a better perspective on the East Asian monsoon system and reveal the considerable significance of understanding the EASWJ in

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its context. Currently, numerical models are widely employed as powerful tools in climate studies to describe the physical characteristics and the mechanisms that influence climate. Reasonable performance of the numerical models in reproducing current state of global and regional climate is the bases for the development of future models and their research applications. Several studies contributed to the model's performance on the EASWJ. For example, Zhang et al. (2008) analyzed the main features of the EASWJ simulated by the two versions of the CCSR/NIES/FRCGC (Center for Climate System Research/the National Institute for Environmental Studies/the Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science of Technology) climate system models, which called Model for Interdisciplinary Research On Climate (MIROC); they suggested that reasonable reproductions of the meridional heat transport gradient and the surface diabatic heating are the key challenges for improving the EASWJ simulation by the MIROC model. Likewise, Guo et al. (2008) evaluated the performance of the two atmospheric models developed by IAP/LASG in the simulation of the major characteristics of EASWJ, which are named Grid-point Atmospheric Model of IAP/LASG (GAMIL), and Spectral Atmospheric Model of IAP/LASG (SAMIL), respectively.

Recently, the AM2 model (Global Atmospheric Model Development Team (GAMDT), 2004), a state-of-the-art climate model developed at Geophysical Fluid Dynamics Laboratory (GFDL), has been used widely in studies of the Asian-Pacific-Australian and West African monsoons (Kang et al., 2002a, b; Lu and Delworth, 2005; Zhou et al., 2009). These studies indicated that it performed well in capturing the leading modes of these monsoons and that it was one of the three best models in AMIP2 (An extension of the original Atmospheric Model Intercomparison Project) in capturing the interannual variability of rainfall in Asian-Australian monsoon regions. The AM2.1, a newly released version by GFDL, however, is not as widely employed as the AM2 is to study the Asian monsoon. Li et al. (2008) used the AM2.1 and CAM3 (NCAR (the National Center for Atmospheric Research) Community Atmospheric Model) to investigate the effects of observed changes in sea surface temperature (SST), greenhouse gases, and aerosols on East Asian climate from 1950–2000, and found that both models induce most of the observed weakening of the East Asian Summer Monsoon circulation when forced with the SSTs.

Despite this, model performance in simulating the EASWJ has not been investigated. Therefore, following Zhang et al. (2008) and Guo et al. (2008), the present study explored the performance of the AM2.1 in the simulation of EASWJ, aiming to provide some useful reference for employing the model in further studies of Asian monsoon.

2 Model description and experiment design

The AM2.1 model, developed on the basis of version AM2, is the atmospheric component of the coupled ocean-atmosphere GCM CM2.1 in the CMIP3 (Phase 3 of the Coupled Model Intercomparison Project) archive. It employs the finite-volume atmospheric dynamical core (Lin, 2004) and has a horizontal resolution of 2° latitude by 2.5° longitude and 24 vertical levels. AM2.1 uses a hybrid coordinate in the vertical range from approximately 30 m above the surface up to 3-hPa (approximately 40 km). It also includes multi-species three-dimensional aerosol climatology, a fully prognostic cloud scheme, and a moist turbulence scheme. The coupled land model component, LM2.1, is based on the land dynamics model described by Milly and Shmakin (2002), with 11 soil/vegetation types and 18 soil layers with total soil depth 6 m (see Anderson et al., 2004; Delworth et al., 2006).

In the present study, two sets of experiments were designed. The first evaluates the model's climatic performance in simulating the EASWJ, which was integrated for 20 years and forced by the climatological monthly mean SST derived from 49-year monthly mean SSTs (1950–98) in the NCEP (the National Centers for Environmental Prediction) Reynolds Historical Reconstructed SST. The second experiment represents a real run experiment integrated for 44 years and forced by monthly mean SSTs from 1950–93 to investigate the model's ability to capture the variability of the EASWJ. In this study, the outputs of the last 43 years are utilized for comparison with the observations. The observational dataset used in this paper is the monthly atmospheric data from 1951 to 1993 with a horizontal resolution of 2.5°×2.5°, drawn from NCEP/NCAR reanalysis (Kalnay et al., 1996).

3 Results

3.1 Seasonal distribution structure of the EASWJ

To evaluate the model's performance in simulating the EASWJ, the vertical and horizontal structures of the zonal wind (U) in the Northern Hemisphere were analyzed both for simulation and observation. Figure 1 shows the latitude-height seasonal distributions of zonal averaged U for AM2.1 and observation between 100–150°E, respectively. Over East Asia, the low and upper atmosphere is dominated by the westerly in winter (December-January-February, DJF). The center of the maximum speed is located at the 200-hPa level around 30°N with speed beyond 60 m s^{-1}. The distribution in spring (March-April-May, MAM) shows similar features to that in winter but with a weaker westerly center at the 200-hPa level. In summer (June-July-August, JJA), the tropical troposphere to the south of 20°N exhibits a tilted structure between the upper and lower level with a strong easterly for the upper level and a weak westerly for the lower atmosphere. The extra-tropical troposphere is dominated by the strong westerly, having a maximum speed center of approximately 20 m s^{-1} at the 200-hPa level around 42.5°N. The distribution for autumn (September-October-November, SON) resembles that of summer except that the westerly is strengthened in the mid-latitude, the easterly is weakened in the upper tropical troposphere, and the maximum speed center retreats southward. The simulated seasonal

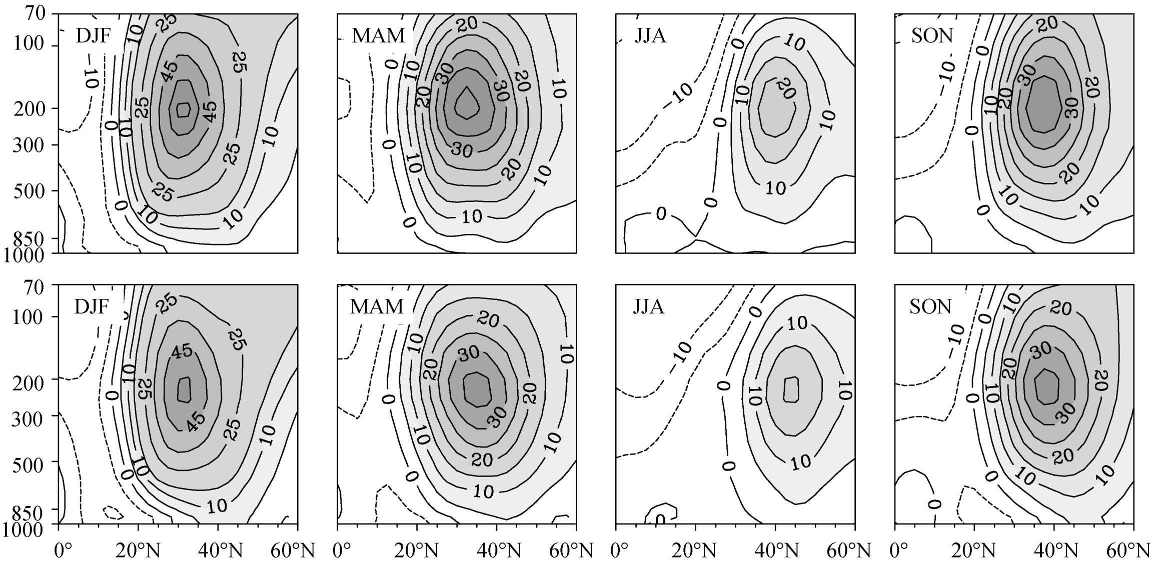

Figure 1 The latitude-height distribution of zonal averaged zonal wind (m s^{-1}) between 100–150°E, for the observation (top panel) and AM2.1 model (bottom panel). Shading denotes the value above 10 m s^{-1}.

westerly jet stream agrees well with the observation data in the locations and vertical structures. The model tends to reproduce a weaker jet center during the four seasons however, and the simulated location of jet center in summer is shifted northward.

The westerly jet stream is a remarkable feature at the 200-hPa level in the Northern Hemisphere with a clear annual cycle and movements of the jet center, especially in the meridional direction (Fig. 2). Figure 2 depicts the simulated and observed seasonal structures of the zonal wind at the 200-hPa level (*U*200). For the observation, the upper-tropospheric jet stream is zonally oriented within the mid-latitude around 20–50°N all through the year. The features in winter, spring, and autumn similarly feature centers of different maximum speeds northeast -southwestwardly located over East Asia and Western Pacific regions. The maximum speeds are about 65, 45, and 40 m s^{-1}, respectively. The distribution feature of *U*200 in summer differs from the other three seasons: the intensity of the zonal wind is strikingly weakened with a maximum speed of about 30 m s^{-1}, and the maximum speed center moves westward to the Eurasian continent compared with its location in winter and spring. In the annual cycle of the EASWJ, it is clearly observed that the jet center moves northward from DJF through MAM to JJA and then retreats southward in SON. The simulated seasonal features of *U*200 are comparable to main features in the observation except for simulation deficiencies in reproducing weakened jet centers which are similar to those in Fig. 1. Additionally, for the simulated summer EASWJ, the main belt of westerly jet is northward situated, especially over the exit of the EASWJ.

3.2 Sub-seasonal evolution of the EASWJ

Previous studies revealed that the meridional displacement of the EASWJ is coherent to the path of the East Asian summer and winter monsoons (Lu, 2004; Lin and Lu, 2005). Its displacement is closely related to the movement of the monsoon rainfall over East Asia especially in summer.

Figure 3 illustrates the latitude-time distribution of climatological *U*200 averaged between 100–150°E, with dashed lines representing the westerly jet axis. The movement of the EASWJ center exhibits a clear annual cycle. First, the jet axis is located approximately at 32°N in January, moves southward slightly in winter, moves distinctly northward in spring, reaches its highest meridional degree (about 46°N) in late July and early August, then moves southward swiftly, and returns to 32°N at the end of the year. Two sudden jumps in late March and late July also appear in observation and in the model. The simulated *U*200 and the center of the EASWJ follow the observation data in the winter half-year, but during the summer half-year, the simulated centers are found to the north of observed positions from May to September and especially in July.

3.3 The variability of summertime U200 over East Asia during 1951–93

Previous studies revealed that the meridional movement of the *U*200 showed close relation to climate variability over East Asia, especially in summer. In this section, we perform the EOF analysis on the JJA *U*200 over the region 20–60°N, 100–150°E to investigate the model's capability in simulating the variability of the EASWJ during summer. During 1951–93, the first leading mode accounts for 33% of total variance in the observation and 30% of the total variance for the simulation. The leading mode is characterized by a meridional tripole structure with an easterly anomaly center between 25–40°N for the observation (Fig. 4a) and westerly anomalies at the two flanks. The model results reveal a similar

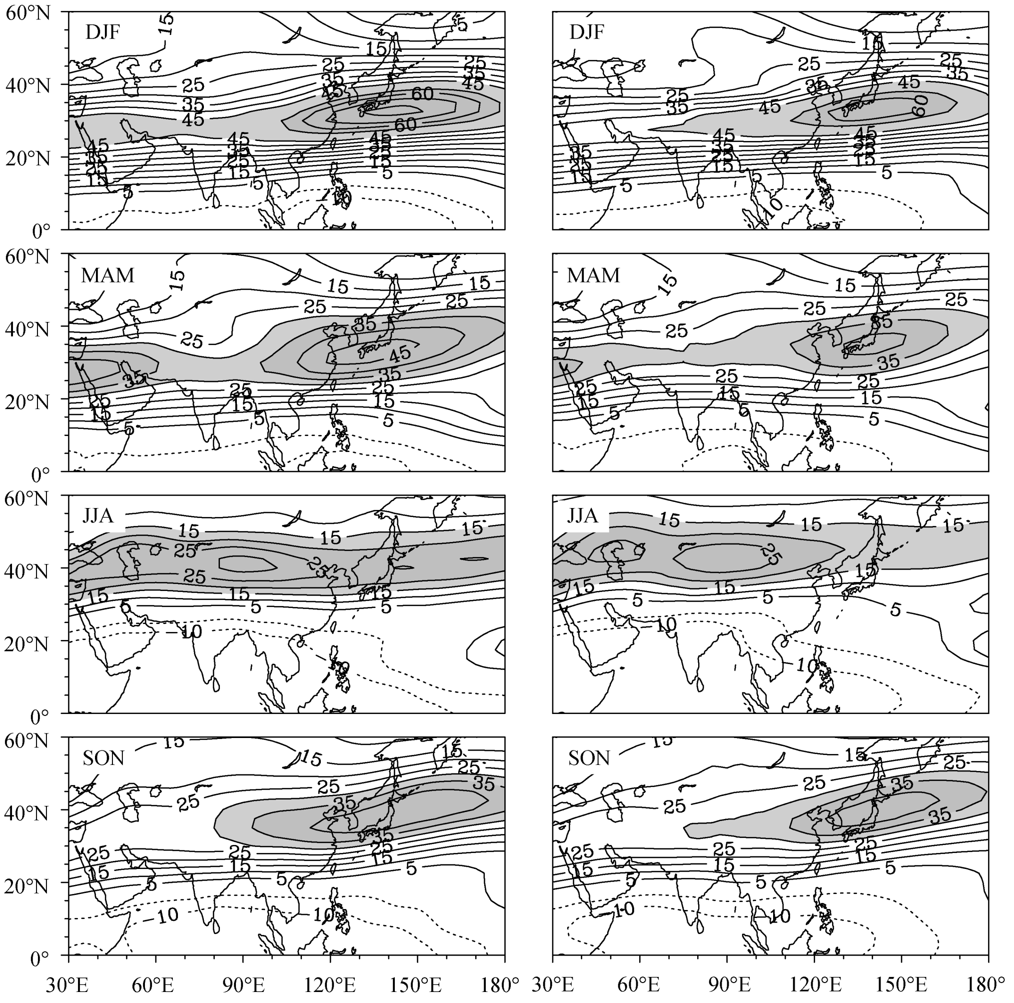

Figure 2 The seasonal mean state of *U*200 (m s^{-1}) for the NCEP/NCAR reanalysis (left panel) and AM2.1 model (right panel). Shading delineates the values above 45, 30, 15, and 30 for DJF, MAM, JJA, and SON, respectively.

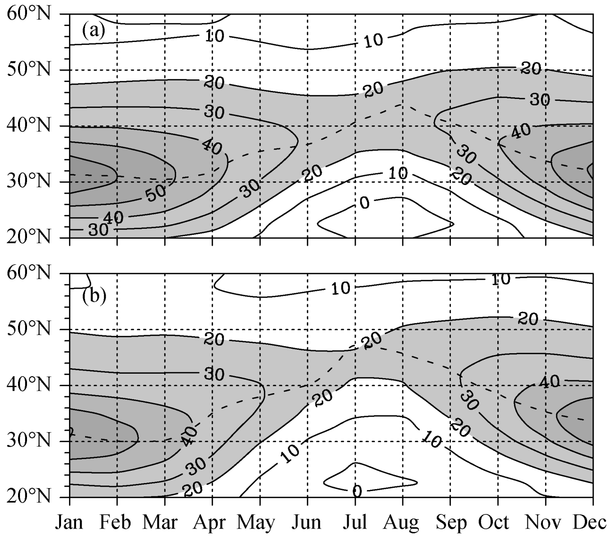

Figure 3 The latitude-time cross distribution of *U*200 (m s^{-1}) averaged between 100–150°E, (a) for the NCEP/NCAR reanalysis and (b) simulation. The area with value of *U*200 exceeding 20 is shaded, and the dot-dashed line denotes the EASWJ core, which is defined as the climatic locations of the jet stream axis at 200 hPa.

structure to that shown in Fig. 4a but the easterly anomaly moves northward with its center between 30–45°N (Fig. 4b). This may be due to the northward location of the center of the simulated *U*200 over East Asia. The corresponding principal components (PC1) for the observation and simulation are depicted in Figs. 4c and 4d. There is a correlation coefficient between them is as great as 0.42 with significance at the 99% confidence level. Remarkably, both the observational data and the model achieve an inter-decadal shift of JJA *U*200 around the late-1970s, a result in keeping with the earlier finding by Kwon et al. (2007) and Lin et al. (2010).

4 Conclusion and discussion

In this paper, the performance of AM2.1 in reproducing the EASWJ has been evaluated through the comparison of the model output against the observation. The model proves to be capable of capturing the main features of the EASWJ. Encouraging results have been found in the simulation of the seasonal vertical distribution of the zonal averaged zonal wind, the seasonal patterns of the zonal wind at the 200-hPa level, and the seasonal and

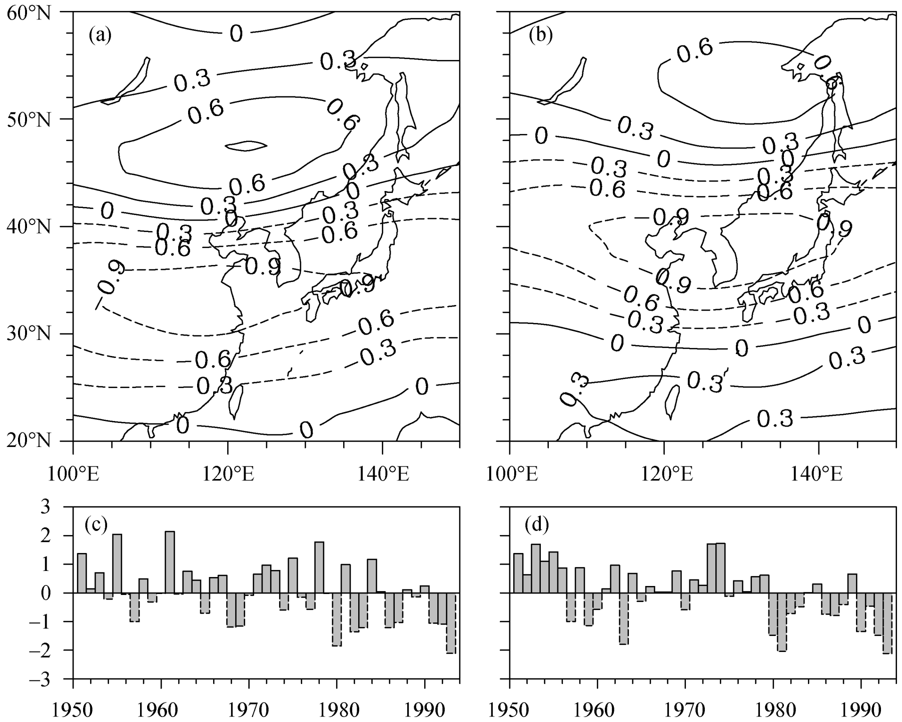

Figure 4 The first EOF mode (EOF-1) of JJA *U*200 over the region 20–60°N, 100–150°E (a) for the NCEP/NCAR reanalysis and (b) the simulation and the corresponding PC (PC-1) (c) for the NCEP/NCAR reanalysis and (d) the simulation.

subseasonal evolutions of the EASWJ. The model shows clear deficiencies in simulation of the intensity and location of the westerly jet core; namely, it reveals that the simulated westerly jet intensity is weaker and that during summertime the position of the westerly jet core is located northward. Results also show the model is capable of reproducing the variability of the summer *U*200 over East Asia during 1951–93 and is able to capture the inter-decadal shift of climate around the late-1970s.

Possible causes for the biases of the intensity and location of the simulated EASWJ center are also investigated (figures not shown). Results show strong similarity with the findings of Zhang et al. (2006, 2008) and Guo et al. (2008) in that the location and intensity of the EASWJ center is closely related to the intensity and position of the meridional temperature gradient (MTG) center. The simulated MTG has a weaker intensity, and its core is located northward in comparison with the observation. Thus, the weaker intensity and northward-shifted jet core of the EASWJ is reproduced in the model. This may be related to the inappropriately resolved topography of the Tibetan Plateau and parameterization schemes in the calculation of heating from the heating release of atmospheric radiation, cloud radiation, and convective condensation in the model, none of which was covered in the present study.

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