

Simulated Asian–Australian monsoon with a spectral element atmospheric general circulation model

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Abstract. A low-top version of SEMANS (Spectral Element Model with Atmospheric Near Space resolved) has been used to carry out numerical simulation on characteristics of Asian-Australian Monsoon (A-AM) in the work. The simulation results are validated with ERA-Interim reanalysis dataset and precipitation data from satellite remote sensing. It's shown that the model can reproduce the major climatic features of A-AM with stronger easterly in the tropical Eastern Pacific, and a weaker northerly component in the Northern Hemisphere. The simulated precipitation rate is larger and the double ITCZ (Inter-Tropical Convergence Zone) in the tropical Eastern Pacific in the northern spring is not reproduced. A due to the absence of variation longer than a year in the bottom boundary conditions, the model cannot reproduce the relationships between the monsoon indexes and the surface air temperature in the broad area near the equator.

1. Introduction

The area dominated by monsoon is the key region where the atmosphere gets momentum and water vapor, and the activities of monsoon have direct connections with variations of global general circulation, weather, and climate [1]. Asian-Australian Monsoon (A-AM) is the largest monsoon circulation system on the earth, and it influences the weather and climate of China to a great extent. With reanalysis datasets, Chinese researchers have performed many studies, such as the relationship between the westerly jet stream (and the front associated with it) over the northern China and the low frequency variation of summer Australian Monsoon [2]. Alongside the feature of water vapor transportation in the A-AM region [3], the climatic characteristics of flow field structure and the evolution of the summer A-AM subsystems [4]. The quasi-biennial oscillation of water vapor sink in the A-AM region [5], and the relationships between A-AM and the summer precipitation of Yangtze River [6]. Numerical modeling is a necessary means to carry out scientific research. With the numerical model, the influence of surface land situation on A-AM has been investigated [7]. Forced with observed sea surface temperature, atmospheric general circulation model (AGCM) can reproduce some characteristics of interannual variabilities associated with A-AM and ENSO [8,9], whereas the ability of prediction of Indian summer precipitation is weak. This may be due to that the contribution of ENSO to interannual variability is comparable to the strength of regional perturbation caused by the inner perturbation of numerical model, which is independent of sea surface temperature anomaly [10]. Some researchers discussed the connections of the ability of reproducing climatic precipitation with that of reproducing interannual variation in numerical simulation [11,12]. Wang et al. (2004) [13] and Zhou et al. (2009) [14] evaluated the capacity of the atmospheric model in reproducing the interannual



variation of A-AM, showing that AGCMs share similar weakness in some aspects such as modeling the pattern of abnormal precipitation. To deduce differences in the monsoon simulations run with observed sea surface temperatures and with ocean–atmosphere coupling, Meehl et al.(2012) [15] studied the Asian–Australian Monsoon regimes and processes in CCSM4 (Community Climate System Model, version 4). The ability of CCSM4 as well as its atmospheric component CAM (Community Atmosphere Model) to simulate the Asian summer monsoon, focused particularly on the inter-model comparison and the role of air–sea interaction, were also examined by Islam et al. (2013) [16]. Xue et al. (2015) [17] reviewed the major progress that has been made in monsoon studies in China.

In numerical modeling, both the discretization method and the parameterization of physical processes influence the results. In current AGCMs, finite difference and spectral approximations are mostly used to discretize the equations describing the movement of the atmosphere, and finite element and finite volume discretizations are also used in a few ones. The finite difference has the merit of being intuitive and easy to implement for parallel computing. It has the disadvantage of low accuracy and slow convergence to the real solution. The spectral expansion used in AGCM usually adopts spherical harmonic function as the basis. Since the approximated function is calculated in the whole domain of computation, the local error will be propagated to a broad area. Furthermore, the implementation of parallel computation algorithm based on the idea of area division is difficult. However, the spectral method is still popular in atmospheric modelling since it gives higher precision compared to other traditional methods. Compared to the spectral method, the finite element method divides the computation domain into many elements, in each of them, different local approximation function is used. When the finite element method is used, the division of computation domain can be very flexible. So it is suitable for the problem with complex geometry. Although the finite element method has the merit of versatility, it is less precise than the spectral method. A finite volume method constructs discrete scheme based on the idea of regional integration and the finite difference method can thus be seen as one particular case of it. Compared to the finite difference method, the finite volume method can be used to construct discrete schemes much more flexibly and the constructed schemes can meet the constraint of integration relations better. The finite volume method has similar drawbacks as that of the finite difference method. The spectral element method combines the accuracy of the spectral method and the flexibility of finite element method [18]. It has more advantages than each method. The basic idea of spectral element method is to decompose the computation domain into finite elements and then get the solution within each element with the spectral method. So the spectral element method possesses the merits of the finite element method and the spectral method. It is desirable to use spectral element AGCM to perform a numerical study of monsoon.

There are connections between the variations of different atmospheric levels. To explore the influence of middle atmosphere on the simulation of monsoon, twin experiments with low and high top models should be setup. As a first step, a low top version of a Spectral Element Model with Atmospheric Near Space resolved (SEMANS) [19] is used to perform numerical study on the A-AM in the work. The model and design of a numerical experiment will be given in section 2. Simulation results and analysis will be presented in section 3. In the last part, the conclusion will be given (section 4).

2. Numerical model, datasets and design of experiment

The low top version of SEMANS [19] is used in the work. The spectral element approximation and finite difference method are used in the horizontal and vertical respectively in SEMANS. The model uses quadrilateral element [20, 21], although triangular element may also be used in many applications [22]. To solve the polar problem, which is unavoidable when the longitude-latitude grids are used, a cubed sphere projection is used in SEMANS. To improve the calculation accuracy of pressure gradient at high levels of the atmosphere, a mixed p - σ coordinate in the vertical, is adopted in the model.

The data for low boundary conditions, initial values, and comparison in the analysis are all from the ERA-Interim [23], which is a widely used reanalysis dataset from ECMWF (European Centre for

Medium-Range Weather Forecasts). The global precipitation at one-degree daily resolution from multi-satellite observations [24] for 1997-2007 is also used.

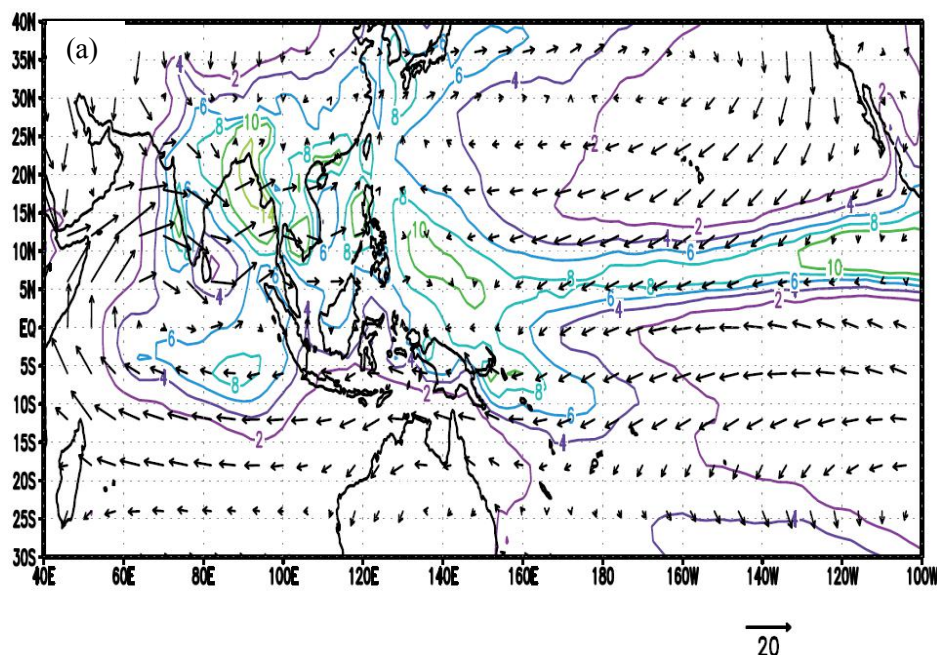
In the experiment, each projected cube face is decomposed into 81 elements, and an interpolation polynomial of 8 degrees is used for spectral approximation in each local element [19]. The atmospheric state on 00:00:00 GMT, January 1, 1997, is used for the initial values. The low boundary conditions (land surface temperature, sea surface temperature, sea ice concentration, albedo, snow thickness and so on) are means of years from 1997 to 2007 with seasonal variations considered whereas interannual variations not. In the vertical, the model atmosphere is divided into 28 layers, with about 5 layers within the planetary boundary layer. The model top situates at the 0.4hPa.

Schemes of physical processes used are identical to that of SEMANS. The model has been integrated for 20 years, and monthly mean model results saved for analysis. During the integration, global mean total energy (sum of sensible heat, potential energy, latent heat for phase change between cloud water and cloud ice, latent heat for phase change between vapor and cloud ice) and air mass (represented by surface air pressure) are monitored every step. There is no strange apparent value found in these variables.

3. Simulation results and analysis

3.1. Winds and precipitations in summer and winter

The simulated and observed precipitation in summer (mean of June, July, and August) is given in Figure 1. It's shown that the model reproduced the precipitation extrema associated with the south Asian monsoon region, ITCZ (Inter-Tropical Convergence Zone) and SPCZ (South Pacific Convergence Zone) with the amount of precipitation bigger than that of observation. The simulated precipitation in the East China is a bit smaller than the observed. The model simulated the low-level southerlies from the Arabian Sea and Bengal Bay to the South Asia and the two extrema of precipitation associated with them well. The model also reproduced the intense precipitation center in the South China Sea adjacent to the Indonesia. Compared to the result from the reanalysis dataset, the simulated easterly over the tropical eastern Pacific Ocean is stronger. Besides, the simulated subtropical high circulation in the Pacific Ocean is weak, and its location is northward, giving a contribution to the smaller northerly component in the tropical Pacific Ocean.



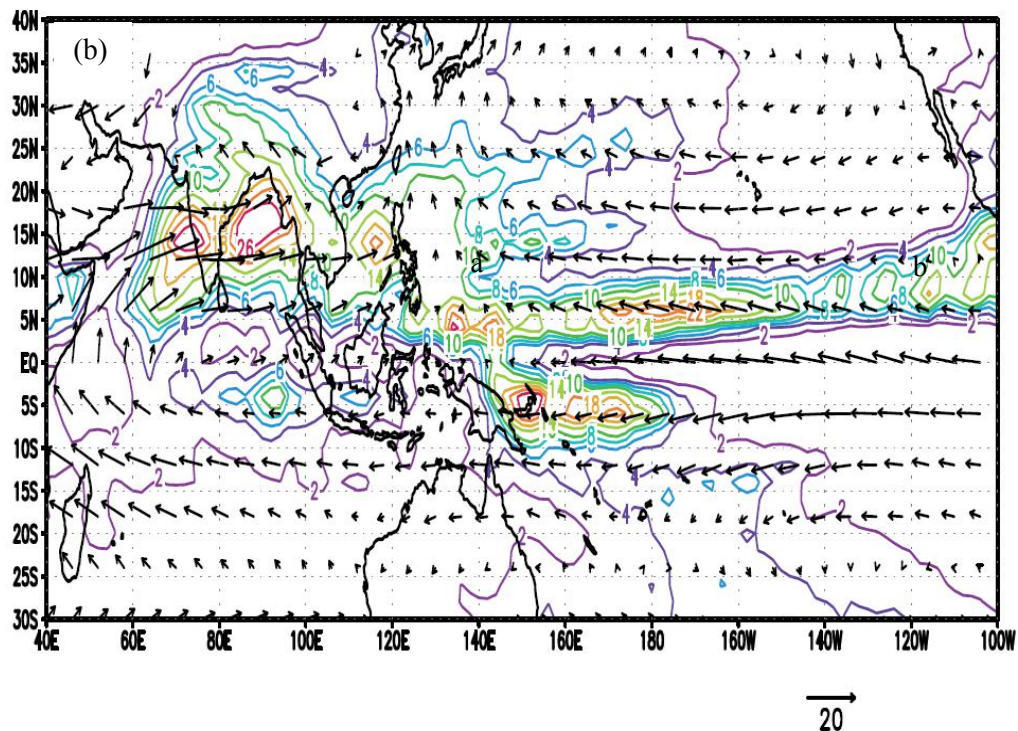
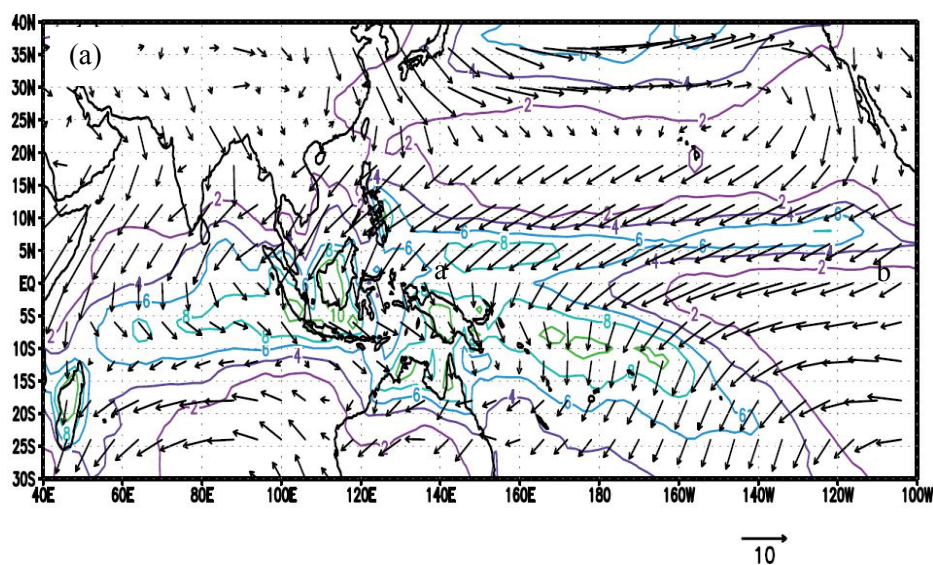


Figure 1. Averaged precipitation rate and the wind at 850 hPa in summer from (a) reanalysis and (b) simulation. Contour interval for precipitation rate is 2 mm/day.

In winter (mean of December and subsequent January and February), the model reproduced the principal feature of precipitation in tropical Indian-Pacific Ocean. The intense precipitations in ITCZ, SPCZ and over the Indonesian and Australian were all reproduced well (see Figure. 2). But the model produced a false precipitation center in the South China Sea and the simulated northerly component in the tropical easterly zone is weak. Also, the location of the simulated transition region from easterly to westerly in the subtropical Pacific Ocean is much northward, and the simulated northerly component in the Arabian Sea and Bengal Bay is weak (compare Figure 2b. to Figure 2a.).



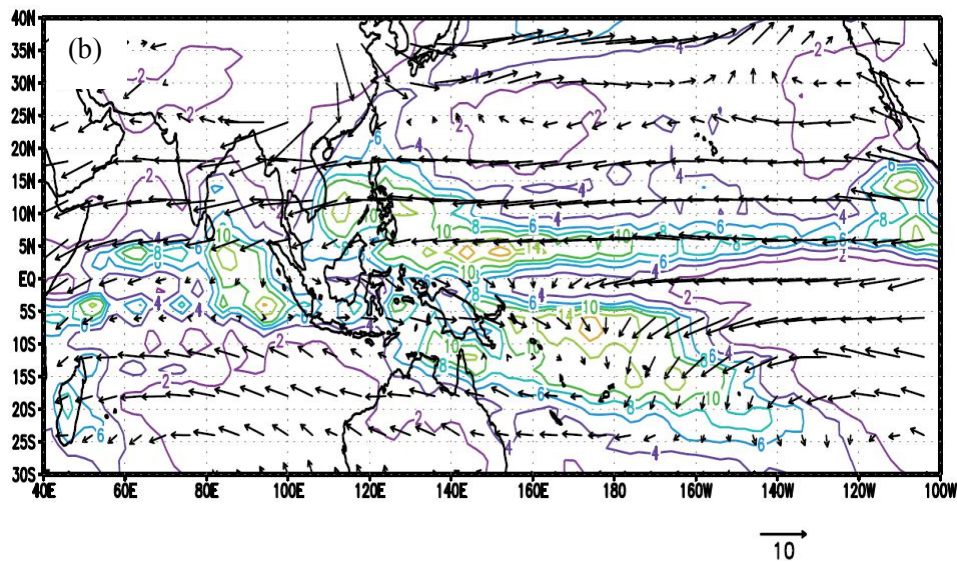
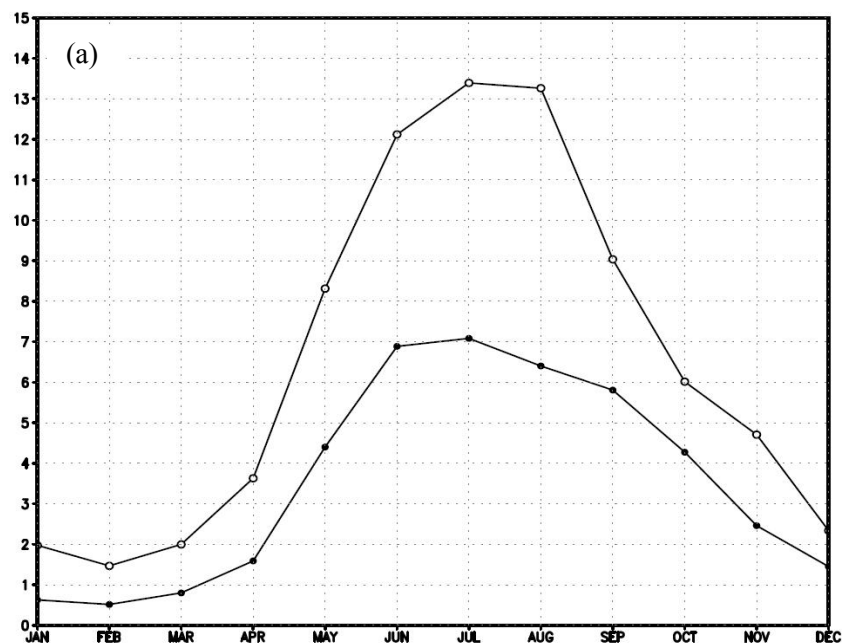


Figure 2. Same as Figure 1 except for winter.

3.2. The annual variation of precipitation

To analyze the precipitation feature in regions of the Indian monsoon and the Northwest Pacific, two zones, one for the Indian monsoon (60°E-105°E, 7°N-27°N) and another for the Northwest Pacific (105°E-150°E, 7°N-22°N), are selected. The variations of areally averaged precipitation rate in the two regions are shown in Figure 3. It can be seen that the simulated precipitation rate in the Indian monsoon, is bigger (this is consistent with the results in Figure 1 and Figure 2), and the bias is the biggest in summer with a value of difference over 5 mm/day. From February to May, the simulated areal averaged precipitation rate is close to observation for the Northwest Pacific region. But in other months, the model produced bigger precipitation, which is also consistent with the results in Figure 1 and Figure 2.



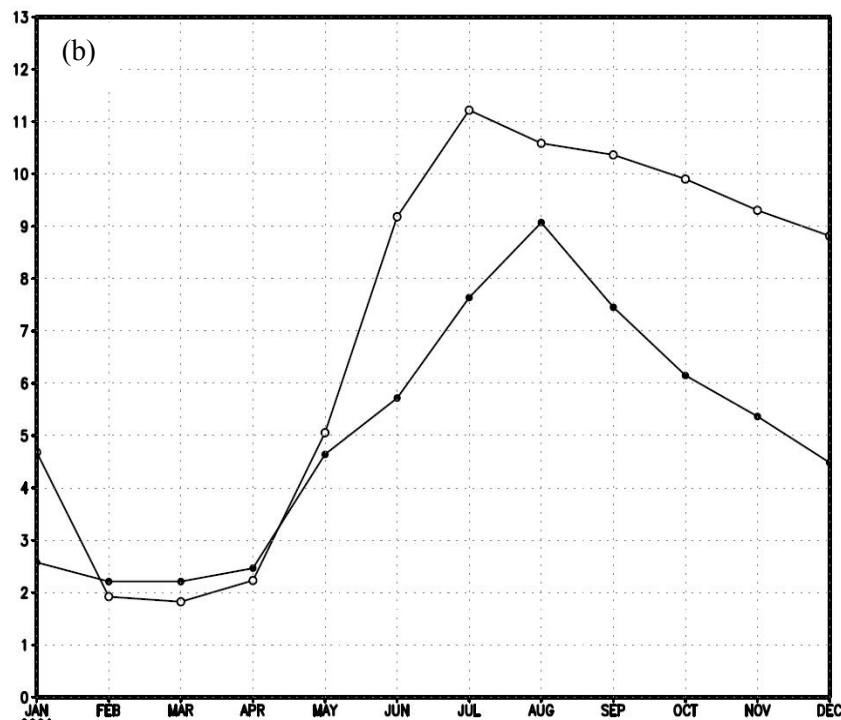
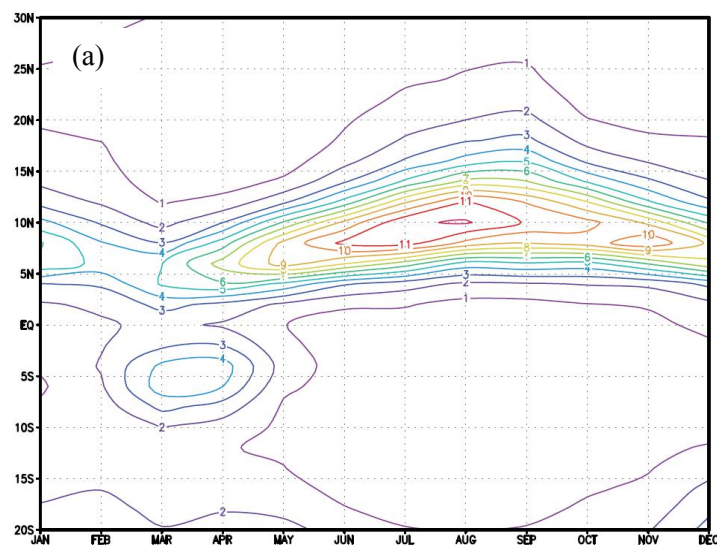


Figure 3. Annual variation of areally averaged precipitation rate for (a) Indian Monsoon region and (b) Northwest Pacific Ocean region. The solid circle and empty circle denote result from observation and simulation respectively. The unit of the vertical axis is mm/day.

From the distribution of zonal mean precipitation rate from 150°W to 100°W (Figure 4), it can be seen that there are extreme ITCZ precipitation north of the equator in the second half year with the most significant value in August and the second biggest value in November. There is double ITCZ precipitation bestriding the equator in March and April. This is consistent with the result from the Xie and Arkin (1996) dataset [25]. The model only reproduced the ITCZ precipitation north of the equator and the simulated occurring time of intense precipitation does not match that of observation.



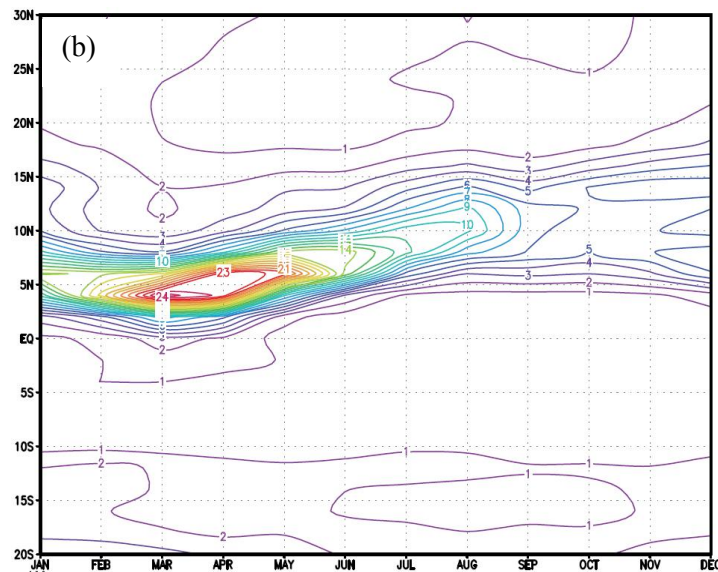
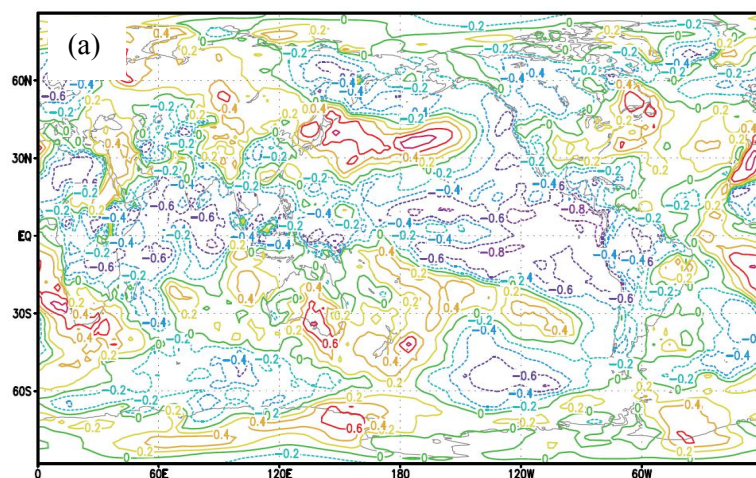


Figure 4. Annual variation of zonal mean precipitation rate over the eastern Pacific Ocean from (a) observation and (b) simulation. The contour interval is 1 mm/day.

3.3. Influences of A-AM on the global atmosphere

To analyze the influences of A-AM on the global atmosphere, correlations between the index of circulation of South Asian monsoon, the global surface air temperature in the northern summer (see Figure 5), the index of precipitation of Australian monsoon, and global surface air temperature in the northern winter (see Figure 6); are calculated respectively. Here, the index of circulation of South Asian monsoon, is defined as the averaged zonal wind difference over the area (0° - 20° N, 40° - 110° E), between the 850hPa and the 200hPa [26]. The index of precipitation of Australian monsoon is defined as the precipitation rate averaged over the area (15° S- 0° , 110° - 150° E) [27]. In most areas near the equator and south of India the two correlations are negative (see figures 5a and 6a). The model could not reproduce these relationships. This is due to that the low boundary conditions such as sea surface temperature and land surface temperature of the model do not include the variation longer than a year. The A-AM is the effect of complicated interactions between the ocean, land, and atmosphere. Among them, ENSO is the primary element determining the interannual variability of A-AM. So, the correlations in other areas will not be analyzed.



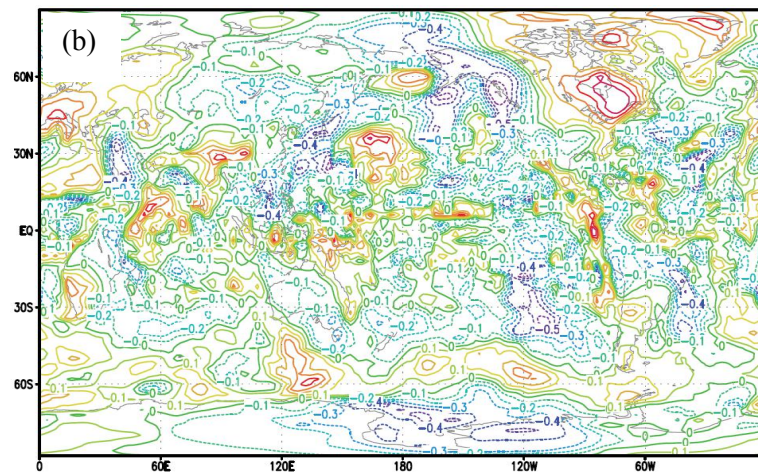


Figure 5. Correlation between circulation index of South Asian monsoon and the global surface air temperature in the northern summer from (a) reanalysis dataset and (b) simulation.

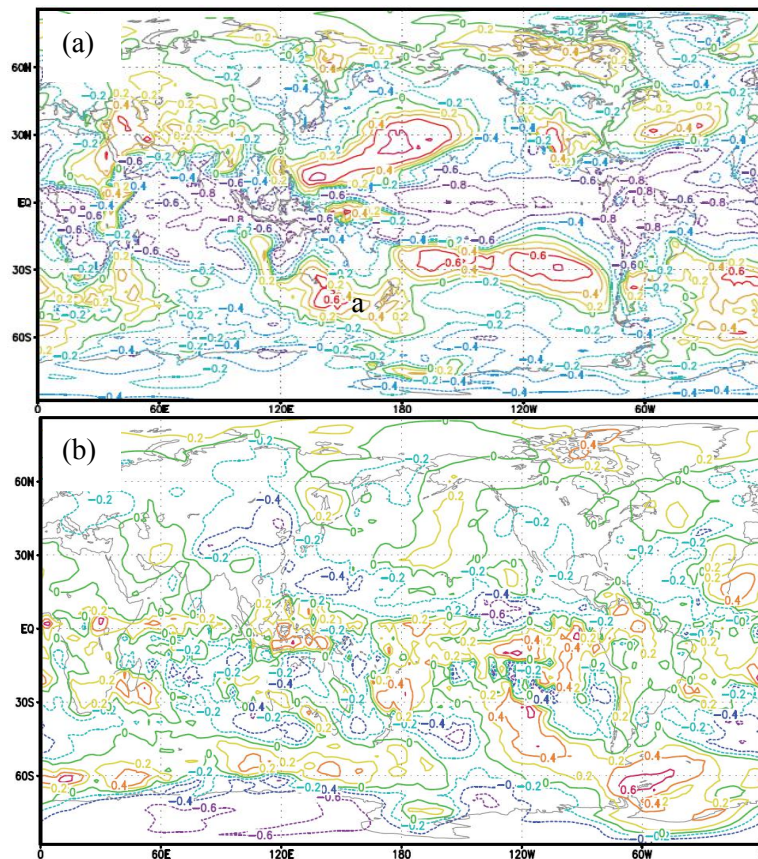


Figure 6. Same as Figure 5. but for the precipitation index of Australian monsoon in the northern winter.

4. Conclusion

A numerical experiment on Asian-Australian monsoon has been carried out with a global spectral element atmospheric general circulation model. Reanalysis dataset ERA-Interim and precipitation dataset from satellite observation has been used to validate the simulation results. It's shown that the model can reproduce the principal climatic features of Asian-Australian monsoon with stronger

easterly over the eastern tropical Pacific Ocean and weaker northerly over the northern tropical ocean. The reproduced precipitation rate is bigger than the observed in general, and the feature varies in different regions. Due to the exclusion of variation longer than a year, the model cannot reproduce the negative correlation between the monsoon index and the surface air temperature in the most area near the equator.

Acknowledgments

The work is sponsored by the Natural Science Foundation of China (Grant No. 41276190) and the China Special Fund for Research in the Public Interest (Grant No. GYHY201506011). The ERA-Interim reanalysis datasets are downloaded from the ECMWF data server website.

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