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A GCM with cloud microphysics and its MJO simulation

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Abstract

The present study examines the Madden and Julian oscillation (MJO) appearing in a general circulation model (GCM) with full representation of cloud microphysics at 50 km horizontal resolution, and the MJO is compared with those of GCMs with conventional convective parameterizations. The present coarse-resolution GCM requires modifications of several parameters of cloud microphysics and an additional vertical mixing process in the lower troposphere to simulate the MJO reasonably well. The GCM with cloud microphysics only produces the relatively small-scale precipitation scattered in the tropic. The shallow convection added in the GCM helps moisten the lower troposphere and enhances low-level moisture convergence, and thus large-scale cloud clusters are generated effectively, resulting in a better simulation of MJO.

Background

A number of studies have demonstrated that the MJO simulation with a current general circulation model (GCM) depends on the convective parameterization (e.g., Lin et al. 2006; Lee et al. 2008; Frierson et al. 2011). Although moist physical parameterizations have been improved substantially in recent years, most of recent GCMs still have problems in simulating the MJO, as evaluated by Hung et al. (2013) with the CMIP5 models. To overcome the limitation of parameterized convection, recent studies have used full representation of cloud microphysical processes, so called "explicit convection", in regional and global models. Moncrieff and Klinker (1997) showed that explicit convection results in a more realistic simulation of superclusters than parameterized convection does. Holloway et al. (2013, 2015) performed the MJO simulations with the parameterized and explicit convection with varying horizontal mesh sizes and found better performance with explicit moist physics.

The superparameterized GCM, where a cloud resolving model (CRM) is embedded in each grid box in a GCM (Iorio et al. 2004; DeMott et al. 2007), has been shown to simulate the MJO reasonably well with computational efficiency (Benedict and Randall 2009; Zhu et al. 2009). The superparameterization, however, does not consider the interaction between clouds in neighboring GCM grids. Satoh et al. (2005), on the other hand, expressed the cloud microphysical processes explicitly in a GCM, which is so called "NICAM", using GCM state variables. It has been reported that the NICAM model reproduces the eastward propagation of the observed MJO and typhoon genesis reasonably well (Miura et al. 2007; Oouchi et al. 2009; Miyakawa et al. 2014; Kodama et al. 2015). However, this approach requires heavy computing resources due to a very high horizontal resolution. With a coarse-resolution GCM with cloud microphysics, Yoshizaki et al. (2012) and Takasuka et al. (2015) also obtained an MJO-like signal, although their simulations were performed under idealized aquaplanet conditions. It is noted that the simulated MJO is very sensitive to the horizontal structure of SST (Kang et al. 2013), and a good MJO simulation under an idealized condition may not warrant a good MJO simulation in a realistic configuration of land and SST conditions. Also as seen in Fig. 1 of Yoshizaki et al. (2012), the precipitation characteristic simulated by an NICAM model with a resolution of about 100 km is somewhat different from that of the model with a

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resolution of order of 10 km. Holloway et al. (2012) demonstrate that a high-resolution GCM with explicit cloud microphysics does not necessarily simulate a good MJO, rather it depends on the vertical distribution of simulated moisture anomalies in the MJO time scale, particularly in the lower troposphere. There have been several studies which indicate that the vertical distribution of moisture is a key issue for a good simulation of MJO (e.g., Holloway et al. 2013; Kim et al. 2014).

In the present study, we examine the quality of MJO simulation using a relatively coarse-resolution GCM with a cloud microphysics again. Noted is that the present cloud microphysics, as introduced in "Models" section, is somewhat different from that of NICAM, and the present GCM with a horizontal resolution of 50 km includes a parametrization of shallow convection in addition to full representation of cloud microphysics. A shallow convective parameterization is added since a coarse-resolution GCM produces a large bias in low-level moisture field with a cloud microphysics alone, as shown by Kang et al. (2015). The present study demonstrates that good simulations of the mean low-level moisture and its anomalies with MJO time scales are important for simulating the MJO reasonably well, which can be obtained by adding a shallow convective parameterization in the GCM with a cloud microphysics. "Models" section describes the models utilized, "Climatology and MJO simulated by GCMs with cloud microphysics" section shows the precipitation climatology and the MJO simulated by the models, and summary and concluding marks are given in "Summary and conclusion remarks" section.

Models

The cloud microphysics used in the present model is taken from the Goddard Cumulus Ensemble Model developed at the Goddard Space Flight Center of National Aeronautic Space Administration (Tao et al. 2003). The cloud microphysics includes the Kessler-type two-category liquid water scheme and the three-category ice-phase scheme, developed by Lin et al. (1983) and Rutledge and Hobbs (1983, 1984). Based on the sensitivity experiments of microphysical processes to the horizontal resolutions for 1 and 50 km, Kang et al. (2015) have developed a modified cloud microphysics suitable for the 50 km resolution to overcome a resolution dependency of cloud microphysics (Weisman et al. 1997; Grabowski et al. 1998; Bryan et al. 2003; Jung and Arakawa 2004; Pauluis and Garner 2006; Arakawa et al. 2011; Bryan and Morrison 2012). The major parts of modification are for the condensation process and for the terminal velocity. The original CRM condensation formula is replaced with the large-scale condensation formula of Le Trent and Li (1991), except that the relative humidity criterion for condensation is 95 % in the present GCM. The coefficient in the terminal velocity formula adapted is a half of the original value. The details are described in Kang et al. (2015).

The atmospheric GCM (AGCM) used in this study is a Seoul National University model. The model has a finite volume dynamical core with a hybrid sigma–pressure vertical coordinate developed by Lin (2004), represented by 50 km horizontal resolution and 20 vertical levels. The convective parameterizations include a deep convection scheme based on the bulk mass flux formula (Kim and Kang 2012) and a large-scale condensation scheme based on Le Trent and Li (1991). Also included is a diffusion-type shallow convection scheme described by Tiedtke (1984). The planetary boundary layer scheme is a non-local diffusion scheme of Holtslag and Boville (1993). Radiation processes are parameterized by the two-stream k-distribution scheme developed by Nakajima et al. (1995). Land surface processes are represented by the land surface model of Bonan (1996). A detailed description of the physical parameterizations of the model can be found in Lee et al. (2001) and Kim and Kang (2012), and the simulation quality of the model can be found in Kim and Kang (2012).

The modified cloud microphysics was implemented in an SNU GCM, in which the conventional parameterizations (both convective and large-scale condensation schemes) were replaced by the modified cloud microphysics of the CRM described above. The GCM with the modified cloud microphysics will be referred as to the "CM-GCM", where the cloud microphysics are expressed explicitly using GCM state variables, and therefore, the cloud hydrometers are treated as prognostic variables in the GCM. The GCM with modified cloud microphysics is described in more detail in Kang et al. (2015). Noted is that the present GCM does not use a sub time interval for the cloud microphysics calculation but the time interval of model integration is reduced to 900 s for all GCM and microphysics variables except the terms with the terminal velocity computed every 20 s. Although the time interval is changed, the present model results are not much different from those of Kang et al. (2015). The horizontal resolution of the CM-GCM is 50 km and the model was integrated for 2 years with the climatologically varying SST prescribed.

Climatology and MJO simulated by GCMs with cloud microphysics

The climatological mean state of precipitation simulated by CM-GCM is shown in Fig. 1b along with the observed one in Fig. 1a. The distribution of simulated precipitation over the tropic is characterized by the

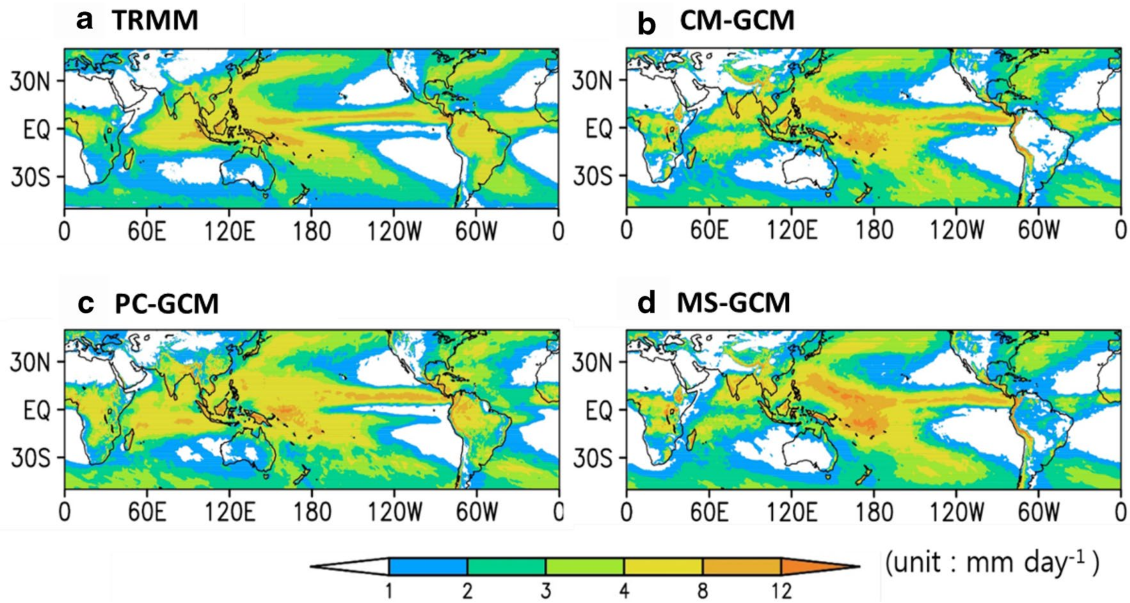

Fig. 1 Annual mean precipitation from **a** TRMM, **b** GCM with modified cloud microphysics, **c** GCM with parameterized convection, and **d** GCM with modified cloud microphysics and shallow convection. The TRMM data were interpolated to model horizontal resolution

heavy precipitation over the western Pacific and the Inter Tropical Convergence Zone (ITCZ) in the Pacific and Africa and the dry regions over the eastern subtropical Pacific and Atlantic Oceans. Those characteristics are similar to the observation. However, the observed heavy precipitation over the eastern tropical Indian is not clearly seen in the simulated precipitation, and the simulated precipitations in the extratropical storm track regions in the Pacific and Atlantic oceans and tropical South America are weaker than the observed. The simulated precipitation with CM-GCM is compared to the simulated one with parameterized convection, which will be referred to PC-GCM. The weak precipitation over the eastern Indian Ocean is also seen in Fig. 1c, indicating that this bias may be related to the mechanisms other than the precipitation processes. It is noted that there is some improvement with CM-GCM compared to PC-GCM in terms of precipitation intensity and its location in the tropics, particularly the western Pacific. Although there are differences between the observed and simulation precipitation, the GCM with the modified cloud microphysics appears to simulate the annual mean precipitation, which is not far from observation and not worse than that of the GCM with conventional parameterizations.

Kang et al. (2015) showed that the low-resolution GCM with the modified cloud microphysics produces a relatively weak vertical velocity in the precipitation area, resulting in weak vertical transport of moisture and the moisture trapped in the PBL. As a result, the bias of cloud water content of the GCM with the cloud microphysics only is large near the lower troposphere, as seen in their study. Thus, to increase the vertical mixing in lower troposphere, a diffusion-type shallow convective scheme similar to Tiedtke (1984) was incorporated in the CM-GCM. The main difference between the present parameterization and the Tiedtke's parameterization is the coefficients that determine the magnitude of diffusion at each layer. The coefficient has the largest value near the top of PBL at 800 hPa and is decreased gradually with the height and becomes zero near 500 hPa. Hereafter, the GCM with the modified cloud microphysics and the shallow convection is referred to as "MS-GCM". The 2-year mean precipitation simulated by the MS-GCM is shown in Fig. 1d. Comparison of this figure with Fig. 1b indicates that there is not much difference between the two figures except that the precipitation intensity is slightly increased in case of adding the shallow convection. It is also noted that the weak precipitation over the Indian Ocean in the CM-GCM is even weaker in the MS-GCM. This weaker precipitation could be resulted from the strong coupling between the low-level moisture circulation and precipitation, which is enhanced by adding the shallow convection. However, the vertical structure of annual mean moisture bias shown in Fig. 2 (blue line) is much improved compared to that of the GCM with the cloud microphysics only (red line) and that of the PC-GCM (black line).

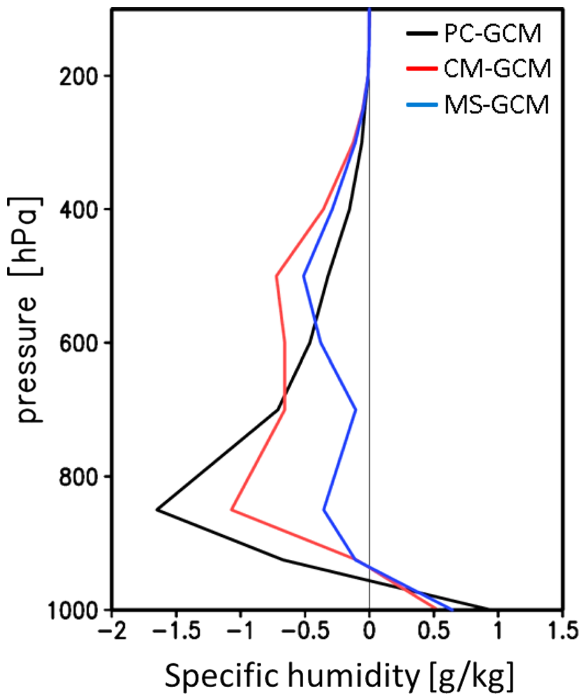

Fig. 2 Bias of annual mean specific humidity from GCM with parameterized convection (*black*), GCM with modified cloud microphysics (*red*), and GCM with modified cloud microphysics and shallow convection (*blue*). The specific humidity is horizontally averaged over the tropics (30°S–30°N)

Now, we examine the transient behaviors of precipitations simulated by various models described above. Figure 3 shows the longitude-time (hovmöller diagram) daily mean precipitation averaged over 10°S–10°N for a 4-month period (1 January–1 May) of the second year of the integration. Again, the TRMM data are used as observation (Fig. 3a). The observation shows strong eastward propagation of heavy precipitation with 20- to 100-day periods and relatively weak westward propagation of precipitation for shorter periods. Whereas, the PC-GCM shows the westward propagation more distinctive than the eastward propagation, although some signal of eastward propagation can be seen with a relatively fast time scale compared to the observed (Fig. 3b). The GCM with the modified microphysics only (CM-GCM) appears to simulate the eastward propagation, but the phase speed is relatively fast, and the precipitation is scattered all over the tropics without a large-scale organized convective system (Fig. 3c). The MS-GCM, on the other hand, produces slower eastward propagation with more organized convection (Fig. 3d) than the model without the shallow convection. There may be several reasons for this improvement by adding the shallow convection. One of important reasons is due to moistening effect in the troposphere for the MJO time scale, as discussed in "Background" section. Figure 4 shows the vertical profile of 30- to 90-day filtered specific humidity composite when the area average of 30- to 90-day filtered precipitation over the Indian Ocean region (60°E–90°E and 10°S–10°N) is positive and bigger than one stsandard deviation. The moisture anomalies for both PC-GCM and CM-GCM are much weaker than the observed for the whole troposphere, but the moisture anomaly profile of MS-GCM is close to the observed one particularly in the lower troposphere. It is noted that the MS-GCM (with shallow

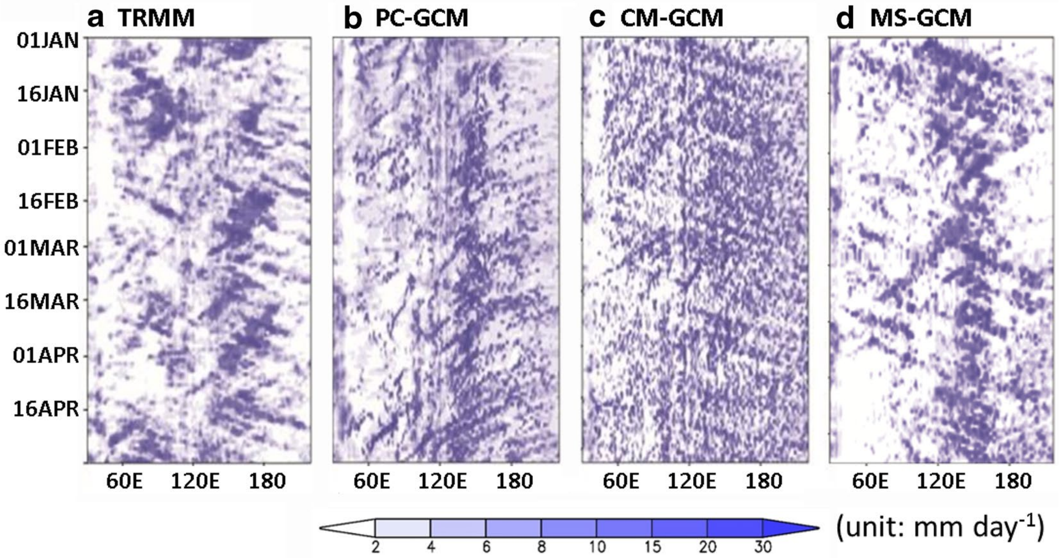

Fig. 3 Longitude-time diagram of the daily mean precipitation averaged over 10°S–10°N from **a** TRMM, **b** GCM with parameterized convection, **c** GCM with modified cloud microphysics, and **d** GCM with modified cloud microphysics and shallow convection

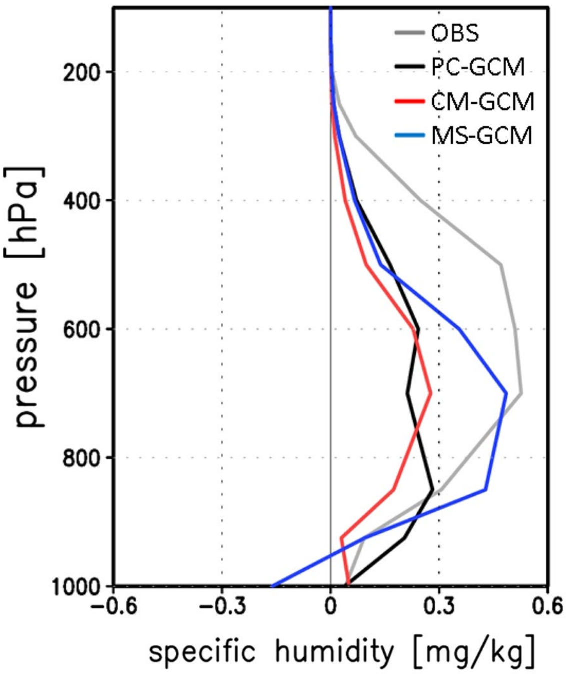

Fig. 4 Vertical profile of 30- to 90-day filtered specific humidity composite when the area average of 30- to 90-day filtered precipitation over the Indian Ocean (60°E–90°E, 10°S–10°N) is positive and larger than one standard deviation from observations (*gray*), GCM with parameterized convection (*black*), GCM with modified cloud microphysics (*red*), and GCM with modified cloud microphysics and shallow convection (*blue*)

convection) produces the negative moisture anomalies near the surface, indicating that the shallow convection plays an important role for transporting the moisture near the surface to the lower troposphere for the precipitation anomalies of the MJO time scale. The horizontal distribution of lower troposphere specific humidity anomalies for the MJO phase with convection center in the Indian Ocean are shown in Fig. 5 for the observation (Fig. 5a), the PC-GCM (Fig. 5b), the CM-GCM (Fig. 5c), and the MS-GCM (Fig. 5d). In the observation, relatively large positive anomalies of specific humidity in the lower troposphere locate in the precipitation anomaly region over the Indian Ocean and are extended to the region over Indonesian subcontinent, the region of east of the MJO precipitation anomalies. Therefore, the eastward propagation of the MJO is initiated by moistening the lower troposphere in the east of the MJO center which contributes to gradual development of organized deep convection to the east (Sperber 2003; Kiladis et al. 2005). Such an observed pattern is poorly simulated by the PC-GCM with convective parameterization. As in Fig. 5b, the positive specific humidity is much weaker than the observed in the Indian Ocean and moistening in the Indonesian subcontinent is not clear. As seen in Fig. 5c, the cloud microphysics appears to amplify the local specific humidity anomalies in the Indian Ocean, but they are confined in the Northern tropical region. By adding the shallow convection in the CM-GCM, on the other hand, the low-level humidity anomaly pattern and intensity over and to the east of the Indian Ocean become close to that of the observed counterparts. In particular, the meridional structure of the moisture anomaly is broader than that of CM-GCM, which may contribute to slow down the MJO propagation speed as suggested by Kang et al. (2013). The present results support previous studies which indicate the important role of low-level moisture in the MJO simulation (Holloway et al. 2013; Kim et al. 2014) and demonstrate that not only the cloud microphysics but also the shallow convection plays important roles in simulating realistic MJO simulation in the present coarse-resolution GCM.

Summary and conclusion remarks

The present study is aimed to describe the MJOs simulated by various configurations of GCM with cloud microphysics at 50 km horizontal resolution. In this model, the convective parameterizations are replaced by the cloud microphysics, which is expressed in terms of GCM state variables. A major issue of developing such a coarse-resolution GCM is to develop a modified version of cloud microphysics suitable to the coarse horizontal resolution. The modification was done based on sensitivity studies for the parameters of the important processes sensitive to the model resolution, particularly the condensation process and the terminal velocity. It was also demonstrated that additional vertical mixing is needed in the present coarse-resolution model with cloud microphysics (Kang et al. 2015). Therefore, a shallow convection scheme similar to that of Tiedtke (1984) is implemented in the CM-GCM. It is demonstrated that the present GCM with the modified cloud microphysics and the shallow convection are able to simulate the observed precipitation characteristics: its climatology and intra-seasonal transient behavior, particularly the MJO. It may be important to note that the present model evaluation based on AGCM may be limited because the ocean–atmosphere coupled process affects the MJO simulation over the oceans, particularly in the western Pacific (Wang et al. 2005; Martin and Schumacher 2012). Therefore, a coupled ocean–atmosphere GCM with the cloud microphysics may be necessary to be developed to tune the parameters mentioned above and to reevaluate rigorously the MJO simulation with the coupled model to be developed.

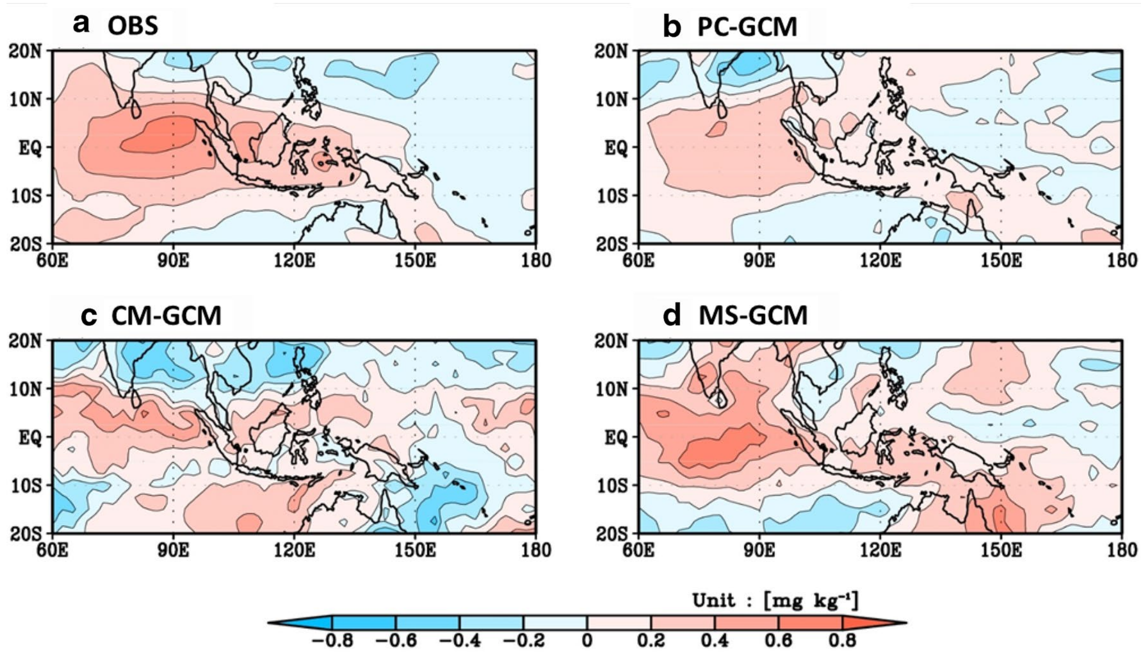

Fig. 5 Composite map of 30- to 90-day filtered specific humidity averaged over the lower level (850–700 hPa) when the area average of 30- to 90-day filtered precipitation over the Indian Ocean (60°E–90°E, 10°S–10°N) is positive and larger than one standard deviation from **a** observations, **b** GCM with parameterized convection, **c** GCM with modified cloud microphysics, and **d** GCM with modified cloud microphysics and shallow convection

Authors' contributions

ISK conceived the original idea of the paper and wrote the final manuscript. MSA and YMY made computations and analysis for the paper. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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