A parameter sweep experiment on the influence of vertical structure of environmental flows on deep moist convection

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1. Introduction

There are some observational evidences of the influence of the equatorial quasi-biennial oscillation (QBO) on the tropical moist convective systems (e.g., Collimore et al., 2003; Liess and Geller, 2012). Modulation of the Madden-Julian Oscillation (MJO) by the QBO in boreal winter is a hot subject in recent years (Yoo and Son, 2016; Nishimoto and Yoden, 2017). Motivated by these, we have investigated modulation of moist convection and its organization associated with a QBO-like oscillation obtained in a two-dimensional minimal model framework of nonhydrostatic cloud-system resolving model (Yoden et al., 2014; Nishimoto et al., 2016; Bui et al., 2017). Yoden et al. (2014) re-examined an internal oscillation dynamically analogous to the QBO, which was firstly obtained by Held et al. (1993) as a radiative convective quasi-equilibrium state in the minimal model framework under a periodic lateral boundary condition without Coriolis effects. They showed the robustness of the QBO-like oscillation, which is not sensitive to the choice of model configuration such as domain size and horizontal resolution, or boundary conditions such as prescribed zonal wind at the top and sea surface temperature.

Nishimoto et al. (2016) studied the modulation of moist convection associated with the QBO-like oscillation, and found alternative appearance of two types of convection, squall-line type and back-building type, depending on the vertical shear of zonal mean zonal flow near the surface. Wave characteristics and vertical momentum transport processes of convectively generated gravity waves were also analyzed by time-space spectral analysis for piece-wise time intervals to show their dependence on the vertical structure of environmental flow fields. Bui et al. (2017) performed a new series of low-level nudging experiment with reduced zonal mean zonal wind toward zero from the surface to a certain level, in order to investigate the influence of vertical structure of environmental flow on deep moist convection, by separating the vertical shear effect of the mean zonal flow near the surface from that around the cloud top near the tropopause. The obtained results reveal that the QBO-like oscillation modulates the moist convection via two mechanisms related to the vertical shear. Large values of the shear near the surface enhance the longevity and intensity of the moist convective systems by separating the updraft and downdraft. On the other hand, large values of the shear near the cloud top tend to disrupt the convective structure and lead to weakening moist convection, although this mechanism seems to be secondary.

In this study, we further perform a parameter sweep experiment by using the nudging technique in a two-dimensional parameter space; the vertical shear of environmental flow near the surface, $dU/dz|_{z\sim 0}$, and the mean zonal wind at the top boundary placed at the lower stratosphere, $U|_{z\sim top}$, in order to investigate the parameter dependence of precipitation characteristics, generation of gravity waves, and role of convective momentum transport under the radiative moist-convective quasi-equilibrium states controlled for each condition.

2. Model description and experiment

The model used here is version 3.4 of the Advanced Research of the Weather Research and Forecasting Model (ARW) (Skamarock et al. 2008). The model is configured to run in a two-dimensional framework in a periodic domain of 640-km width and 5-km horizontal resolution. The initial domain top is 20-km height with 100 vertical levels. The diurnal and seasonal variations of solar radiation are removed by setting the solar declination to the equinox condition and the solar insolation to the daily averaged value ($436 Wm^{-2}$). The Coriolis parameter is set to zero, and the sea surface temperature is fixed to 300K throughout the integration. In the model, convective parameterization is turned off and moist convection is represented explicitly. For cloud microphysics, the WRF single-moment 6-class microphysics scheme (WSM6) is used. Other physics options include the Rapid Radiative Transfer Model (RRTM) longwave radiation, MM5 (Dudhia) shortwave radiation, Yonsei University (YSU) PBL, Monin–Obukhov similarity theory surface layer, and the 1.5-order prognostic TKE closure option for the eddy viscosities.

A traditional Rayleigh damping layer is put near the top boundary (top 5 km) with taking one of the following four values: $U|_{z\sim top}$ = 0, 10, 20, and 30 ms^{-1}. Nudging near the surface is the same as that introduced by Bui et al. (2017);

$$\frac{\partial u(x,z,t)}{\partial t} = -\tau(z)\left[\overline{u(z,t)}^{zonal} - u_0(z)\right] \quad (1)$$

Only the zonal mean zonal wind is nudged to prescribed vertical shear, $dU_0/dz|_{z\sim 0}$ = -30, -20, -10, 0, 10, 20, 30 $ms^{-1}(3km)^{-1}$. The initial zonal wind satisfies the prescribed values in these layers, linearly connected between them. The initial thermodynamic state is constructed by using the climatological profiles of equatorial temperature and moisture from the ERA-Interim dataset (Dee et al. 2011) with an initial perturbation of a small warm bubble in the middle of the domain. In the two-dimensional experimental parameter space (7x4), all runs have 100-day integration period with a 5-min output resolution, and the last 60 days after initial transience are analyzed.

3. Results

Time mean and variable range of the zonal mean zonal wind is plotted to characterize the radiative convective quasi-equilibrium state for the 7x4 parameter space. Time variation of zonal mean daily precipitation also shows systematic dependence on the exprimental parameters. Particularly, the standard deviation of the precipitation is sensitive to $dU_0/dz|_{z\sim 0}$ and then $U|_{z\sim top}$. Figure 1 shows Hovmoeller diagram of 5-min precipitation $p(x,t)$ for the 7x4 parameter space. Two types of convection pattern are confirmed to be dependent on the vertical shear of zonal mean zonal flow near the surface for small or zero $U|_{z\sim top}$; squall-line type for large value of $dU_0/dz|_{z\sim 0}$ whereas back-building type for small or zero value. For large $U|_{z\sim top}$, another feature of back-building type organization appears with longer life time. A new computational algorithm is developed to detect and characterize convective systems. Statistics of the detected convective systems are studied, such as (a) number of total systems detected, (b) life time of systems, (c) system propagation speed, (d) maximum 5-min precipitation, (e) average of 5-min precipitation, and (f) average of ccumulated precipitation. Vertical momentum transports associated with tilted convection and gravity waves are also analyzed following Nishimoto et al. (2016) with separation of convective momentum transport and upward and downward gravity-wave momentum transports.

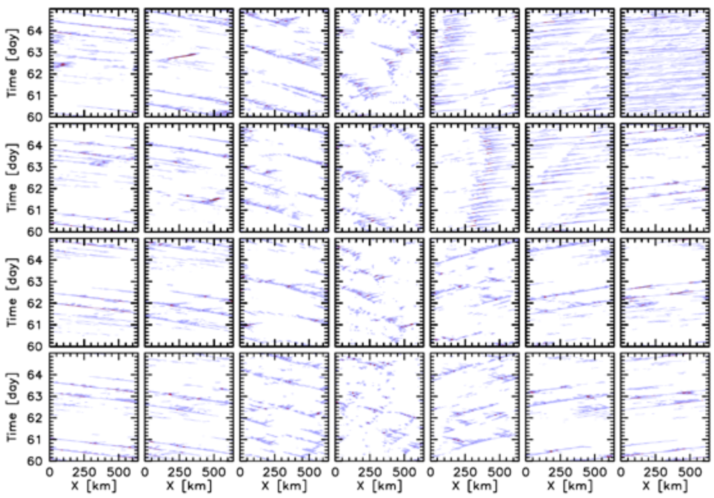

Figure 1　Hovmoeller diagram of 5-min precipitation $p(x,t)$