QBO-Like Oscillation in a Three-Dimensional Minimal Model Framework of the Stratosphere–Troposphere Coupled System

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Abstract

We present a three-dimensional minimal model that produces a self-sustained oscillation reminiscent of the quasi-biennial oscillation (QBO) in a radiative–moist convective quasi-equilibrium state. The computational domain is rectangular (640 km × 160 km) with doubly periodic boundary conditions. After initial transient time, an oscillation with a period of about 300 days emerges in the stratosphere, both in the domain-averaged zonal wind and meridional wind. A synchronization of the zonal and meridional winds is observed and is characterized as an anti-clockwise rotation of a skewed spiral feature with height in the mean horizontal wind vectors. The QBO-like wind oscillations penetrate into the troposphere. Modulation of tropospheric temperature anomalies and precipitation occurs with an irregular period of about 100 days, in which heavy precipitation is associated with positive temperature anomalies. The simulation reveals three types of precipitation patterns: isolated quasi-stationary type clusters, fast-moving back-building type and squall-line type patterns. The quasi-stationary type is newly identified in this three-dimensional model. Intermittent self-organization of convective systems into quasi-stationary type and transition back to the fast-moving back-building type or squall-line type are fundamental characteristics of self-aggregation in the three-dimensional model.

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1. Introduction

The quasi-biennial oscillation (QBO) of the zonal mean zonal wind in the equatorial stratosphere (e.g., https://acd-ext.gsfc.nasa.gov/Data_services/met/qbo/qbo.html) has been recognized for more than half a century since its discovery in 1960's. Theoretical and numerical modeling studies attribute the QBO to the interaction between vertically propagating atmospheric waves and the equatorial zonal mean zonal wind, as reviewed by Baldwin et al. (2001). However, some questions remain: how should the downward propagation speed and oscillation amplitude be quantified, and how should the generation process of wave momentum sources in the troposphere be evaluated?

In order to deepen our understanding on these essential questions, Yoden et al. (2014) (hereafter, YBN14) presented a minimal model of a QBO-like oscillation with a two-dimensional configuration of the stratosphere-troposphere coupled system. The model framework produces an oscillation of the zonal mean zonal wind under a radiative–moist convective quasi-equilibrium state, in which vertically propagating gravity waves are generated internally by moist convection. This QBO-like oscillation resembles the real-world QBO in a dynamic sense, and is notable for the repeated descent of an alternating strong shear layer due to wave-mean flow interactions. The oscillation was shown to be the result of the convergence of the vertical flux of horizontal momentum by means of gravity waves and tilted convective systems (Nishimoto et al. 2016).

However, notable differences exist between this oscillation and the real-world QBO. For instance, this QBO-like oscillation can penetrate down deep into the troposphere. Bui et al. (2017) suggested this could be due to the two-dimensionality of the model that may result in the mixing mechanism being too weak to damp out the oscillation in the troposphere.

Three-dimensional simulations of the QBO use global circulation models with realistic topography or idealized aqua-planet models, as reviewed by Baldwin et al. (2001). There is a gap in understanding the oscillation processes between these three-dimensional models and the minimal two-dimensional model introduced in YBN14. Thus, a three-dimensional model under a radiative–moist convective quasi-equilibrium state on a non-rotating limited-domain with a periodic lateral boundary condition may present some interesting results to fill this gap. There are many such models with a wide range of spatial and temporal domains. However, most experiments with these models have focused on self-aggregation of convective systems in the troposphere, as reviewed by Wing et al. (2017). To the best of our knowledge, three-dimensional limited-domain simulations that produce a QBO-like oscillation in the stratosphere-troposphere coupled system are lacking.

In this study, we present a three-dimensional minimal model on a non-rotating limited-domain that produces a QBO-like oscillation. The model is an extension of the two-dimensional framework of YBN14, with a similar long integration period of 2 years to ensure a radiative-moist convective equilibrium condition. In addition to the phenomenological description of the obtained QBO-like oscillation, low-frequency modulation of moist convective systems linked to the environmental wind shear is also described.

2. Model description

We use the Weather Research and Forecasting (WRF) Model (version 3.4) (Skamarock et al. 2008) with the Advance Research WRF (ARW) dynamical core. We run a three-dimensional model on a non-rotating plane (i.e., no Coriolis effect), with the same zonal domain size as that of YBN14, i.e., 640 km, and 160 km meridional width, with a horizontal grid size of 5 km. The domain top is initially 40 km with 201 vertical levels. The top 5 km is a traditional Rayleigh damping layer to absorb gravity waves. All model settings, including the time-constant solar radiation, radiative transfer schemes, cloud microphysics scheme without any cumulus parameterization, and micro-physics schemes for boundary layer and turbulence, are as given in YBN14.

For the initial wind field condition, the meridional wind is set to zero, and the zonal wind is westerly with 5 m $\mathrm{s^{-1}}$ for a layer of 19−29 km, whereas 0 m $\mathrm{s^{-1}}$ outside a layer of 17−33 km. The initial condition for the temperature field is created uniformly using the climatological profile from the ERA-Interim dataset (Dee

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et al. 2011). The sea surface temperature (SST) is kept at 27°C throughout the simulation.

The simulation time is 2 years with a time increment of Δt = 5 s, and the history outputs are produced every 24 hours. In addition, we rerun five sub-periods of 4 days to produce high-resolution temporal outputs every 5 minutes.

3. Results

3.1 A QBO-like oscillation

Figure 1 shows the time-height sections of (a) the domain-averaged zonal wind (hereafter, mean zonal wind), (b) the domain-averaged meridional wind (mean meridional wind), (c) the magnitude of the vertical shear of the domain-averaged horizontal wind (mean vertial shear), and (d) the domain-averaged temperature anomaly from the model climatology (mean temperature anomaly), together with time variations of (e) the domain-averaged 1-day precipitation and its 15-day running average (smoothed precipitation). An oscillation of the mean zonal wind is notable from the beginning. On the other hand, a clear oscillation of the mean meridional wind starts much later, at around day 100. This difference results from the initial conditions as described in the previous section.

After the initial transience, a rather periodic oscillation appears with a period of about 300 days, which is more than twice as long compared to the same high-top experiments in YBN14 (about 135 days). A downward propagation of the oscillations of both mean winds is observed and appears synchronized. The downward propagation rate is about 0.1 km per day from 25 km down to 10 km, and about 0.3 km per day from 10 km to the surface.

Similar to YNB14, a deep penetration of the mean zonal wind oscillation into the troposphere is observed, which is shown by the contours of ± 2.5 m s^{-1} in Fig. 1. Another interesting feature designated by the contour line is the disruption of the QBO-like oscillation in the mean zonal wind at around z = 15 km and t = 560 day, and the following downward propagation of the signal, even though the dynamical process of the recently observed QBO disruption during the Northern Hemisphere winter of 2015/16 (Newman et al. 2016; Osprey et al. 2016) is not included in this minimal model framework; that is, the equator-ward propagation of Rossby waves in a thin layer in the lower stratosphere (Coy et al. 2017).

Figure 1c shows the typical descent of a layer with high mean

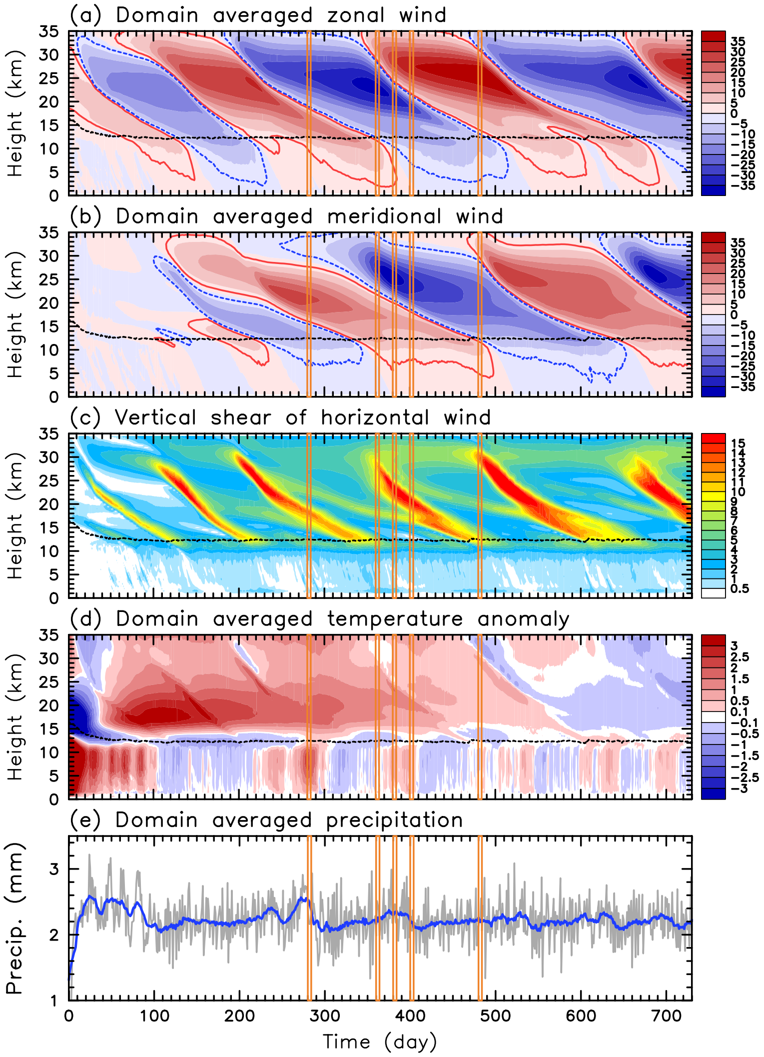

Fig. 1. Time-height sections of the domain-averaged (a) zonal wind, $U(z, t)$, (b) meridional wind, $V(z, t)$, (c) the magnitude of vertical shear of mean horizontal wind (in m s^{-1} km^{-1}), and (d) temperature anomaly from the model climatology, $T'(z, t)$, together with time variations of (e) the domain-averaged 1-day precipitation, $P(t)$, and its smoothed value. The red solid contours and the blue dashed contours in (a) and (b) indicate the values of 2.5 m s^{-1} and −2.5 m s^{-1}, respectively. The thick blue line in (d) is smoothed precipitation with 15-day running average. The orange boxes indicate five 4-day sub-periods mentioned in Fig. 3 and discussed in the text. The black dashed lines in (a), (b), (c), and (d) indicate the tropopause, which are defined by the 2 K km^{-1} contours of the lapse rate of the domain-averaged temperature.

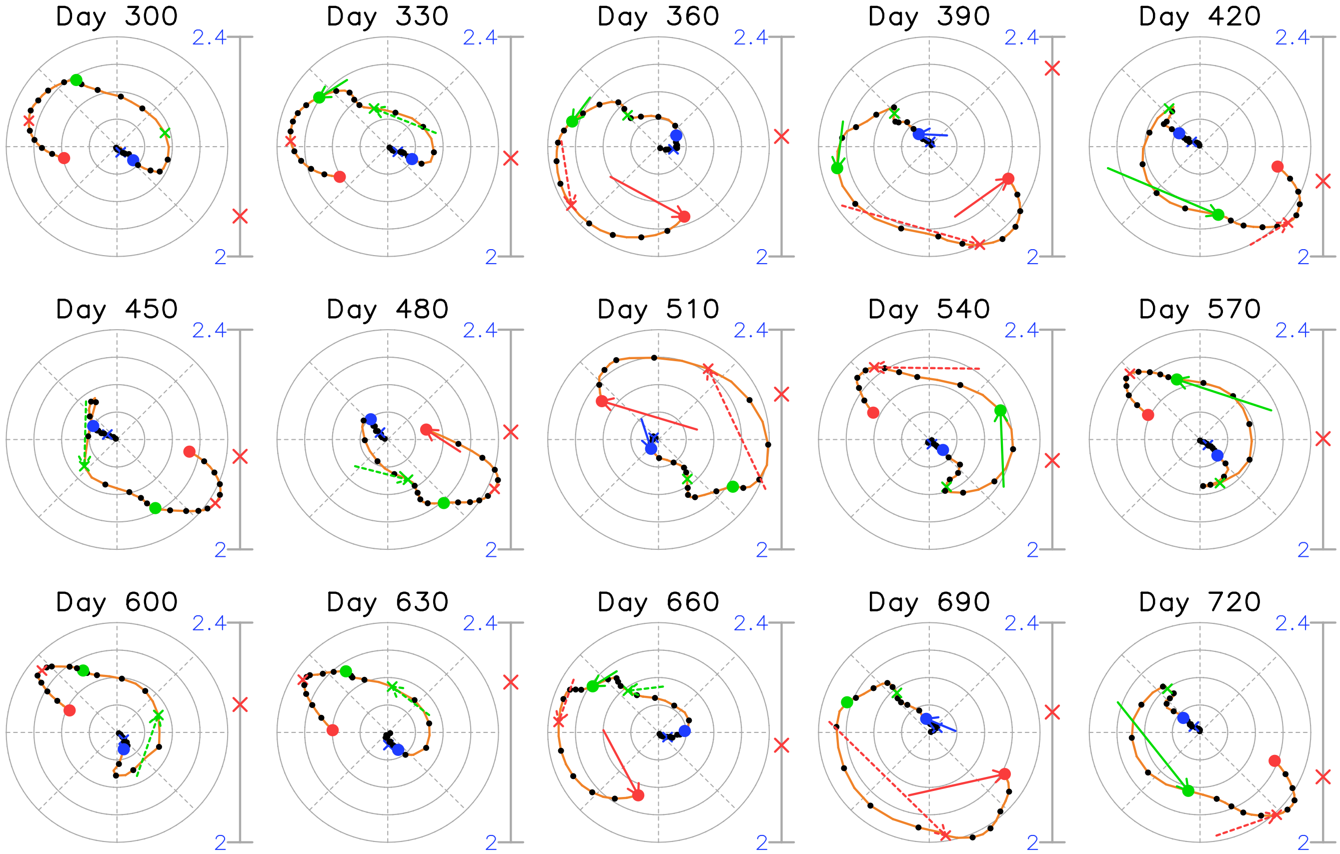

Fig. 2. Hodographs of the domain-averaged horizontal wind, ($U(z, t)$, $V(z, t)$), for every 30 days from day 300 − day 720. The domain-averaged smoothed precipitation $P(t)$ (15-day running mean value) is indicated by the orange X on the right-hand side bar graph. Each circle indicates wind speed with an increment of 10 m s^{-1}. The small black dots indicate 1 km increments in height, and the big crosses and dots indicate 5 km increments and are colored in blue (5 km and 10 km), green (15 km and 20 km), and red (25 km and 30 km). The dashed and solid arrows on each hodograph show the difference of the total mean wind at these 5 km intervals between the current time slice and 30 days previously. For the purpose of clarification, the arrows are visible only when the magnitude of the difference is greater than 10 m s^{-1}.

vertical shear (greater than 15 m s^{-1} km^{-1}) in the stratosphere, which indicates the synchronization of the mean zonal and meridional winds. There is a slower descent of high mean vertical shear with weaker magnitude (less than 10 m s^{-1} km^{-1}) that is in-between the typical descent regions. The mean vertical shear is weakened significantly in the troposphere, although there is a weak signal of fast downward propagation from the altitude of 10 km to near the surface where the shear increases again (greater than 1 m s^{-1} km^{-1} at 1 km).

The signal of the mean temperature anomaly (a warm anomaly below and a cold anomaly above) propagates downward associated with the descent of the high mean vertical shear in the stratosphere in a similar way as in the two-dimensional model (Nishimoto et al. 2016). After the initial warming of 40 days in the stratosphere, there is still a weak cooling that is continuing until the end of the simulation. A modulation is observed in the mean temperature anomaly in the troposphere as well as the smoothed precipitation; the positive temperature anomaly appears with an irregular period of about 100 days and is associated with the periods of larger smoothed precipitation.

The synchronization of the mean zonal wind, $U(z, t)$, and the mean meridional wind, $V(z, t)$, shown in Figs. 1a and b, respectively, is better illustrated using hodographs as an oscillation of the total mean winds ($U(z, t)$, $V(z, t)$) in Fig. 2. At each time step, the mean horizontal wind vectors show a spiral feature with height, that is, a skewed anti-clockwise rotation of the total mean wind vectors, generally increasing in speed with height. This spiral feature also rotates anti-clockwise with time, by changing its shape periodically. The periodicity of approximately 300 days can be seen clearly in this figure, as a repeated appearance of the typical shapes of the hodographs; the hodographs in the first row are similar to those in the third row, whereas those in the second row are roughly 180° out of phase. Time-evolution of hodograph is also shown as an animation of Fig. S1 in the supporting information for the period from day 300 to day 730 with a time interval of 1 day.

The arrows in Fig. 2 indicate the change in the total mean wind over 30 days at every 5 km if the change is greater than 10 m s^{-1}. We note the large acceleration of the total wind corresponds to the levels with large vertical shear of horizontal winds and moves downward with time. Another feature easily recognized in the hodographs is the disruption of the QBO-like oscillation observed in Fig. 1a; it is recognized as a "v"-shaped kink in the hodograph between $z = 15$ km and 20 km for days 510 and 540, and between $z = 10$ km and 15 km for day 570. This feature tends to oppose the anti-clockwise rotation of the skewed spiral.

3.2 Time-variations of moist convective systems

Figure 3 shows the Hovmöller diagrams (time-zonal sections) of (a) meridionally and (b) zonally averaged 1-day precipitation for the whole integration period, and (c, d) those of 5-minute precipitation for five 4-day sub-periods, which are to demonstrate the variety of precipitation patterns as indicated by orange boxes in Figs. 1 and 3a.

Three types of precipitation patterns can be identified in the 5-minute sampling diagrams of meridionally averaged precipitation as shown in Fig. 3c: *quasi-stationary* type of precipitation in which precipitation clusters are almost isolated from the rest of

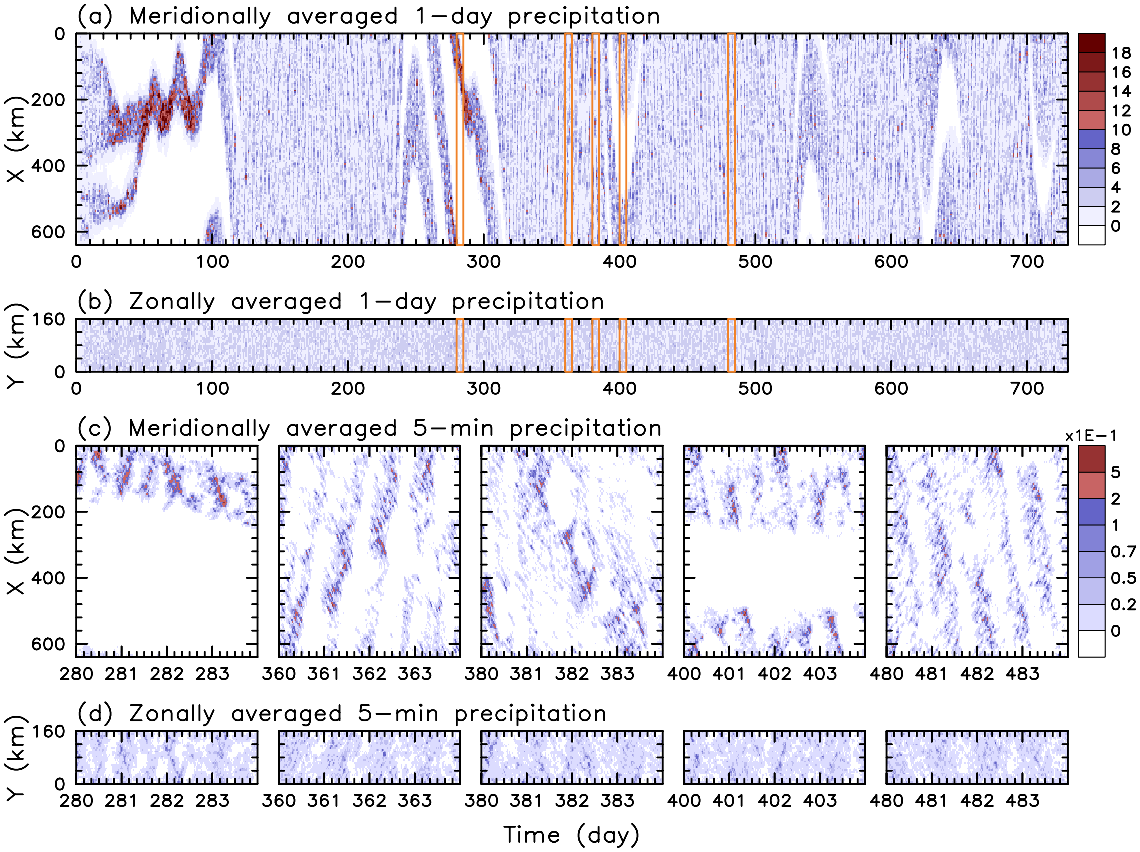

Fig. 3. Hovmöller diagram of (a) meridionally averaged 1-day precipitation, (b) zonally averaged 1-day precipitation, (c) meridionally averaged 5-minute precipitation for five sub-periods of 4 days, as shown as the orange boxes in (a), and (d) zonally averaged 5-minute precipitation for these sub-periods.

the domain (the first and fourth sub-periods), *back-building* type in which a new precipitation system emerges at the rear side of a pre-existing system (the second and fifth sub-periods), and *squall-line* type in which a new system emerges at the front side of a pre-existing one (the third sub-period). The back-building and squall-line types are fast moving, and the precipitation clusters propagate over the entire domain (640 km) in about one day (back-building type) or 2 days (squall-line type). Alternate appearances of these two types, depending on the vertical shear of the mean zonal wind near the surface, were found in the two-dimensional minimal model by Nishimoto et al. (2016). On the other hand, the quasi-stationary type, corresponding to the periods with heavier smoothed precipitation shown in Fig. 1, is a newly found feature in this study. Intermittent self-reorganization of convective systems into quasi-stationary type and transition to fast-moving back-building type or squall-line type precipitation patterns, as seen in Fig. 3a, are fundamental characteristics of self-aggregation in a radiative-moist convective quasi-equilibrium state in this three-dimensional model. These identified patterns are not found in the zonally average diagrams (Figs. 3b and 3d), possibly due to the smaller domain size in the meridional direction.

Figure 4 shows zonal-height cross sections of the meridionally averaged streamlines, clouds and precipitation (top panel), relative humidity (middle), as well as a horizontal cross section of streamlines at $z = 1$ km and 5-minute precipitation (bottom) for five time slices that have the maximum 5-minute precipitation during each sub-period. The plots represent roughly two-dimensional features of cloud, precipitation, and the circulation patterns. For the quasi-stationary sub-periods (a and d), there is no shallow cloud in clear areas and relative humidity is also low there. For the fast-moving back-building type (b and e) or squall-line type sub-periods (c), on the other hand, shallow clouds exist even over non-precipitating areas, and relative humidity is also high in the lower troposphere over the entire domain.

In order to observe the modulation of the precipitation system and its environmental fields, the time variation of domain-averaged precipitation rate, four-day mean domain-averaged zonal and meridional winds, and temperature anomaly as a function of height are shown in Fig. S2 in the supporting information for the five sub-periods given in Fig. 3. The domain-averaged precipitation rate shows large time variations for roughly a period of a day or less for all sub-periods. Vertical shear of the domain-averaged horizontal winds might be related to the modulation of smoothed precipitation, similar to the results of the two-dimensional model (Nishimoto et al. 2016; Bui et al. 2017). Figure 5 shows the time variation of the domain-averaged smooth precipitation and 15-day running mean of the magnitude of vertical shear of the mean horizontal wind at 1 km. There is notable correspondence between the two quantities, with a correlation coefficient of 0.5, which indicates that heavier precipitation periods are associated with stronger mean vertical shear near the surface.

4. Discussion

A QBO-like oscillation is obtained in the present three-dimensional minimal model of the stratosphere-troposphere coupled system. It justifies the two-dimensional model results obtained by YBN14, with some differences in the vertical coupling. The disruption of the QBO-like oscillation in the mean zonal component around day 560 in Fig. 1a and the following downward propagation of the signal are unique features, only obtained in the three-dimensional model. The animation of hodograph in Fig. S1 shows the corresponding signature of clock-wise acceleration in a thin layer around $z = 15$ km from day 520 to day 600, whereas any similar feature is not observed a half period before or after

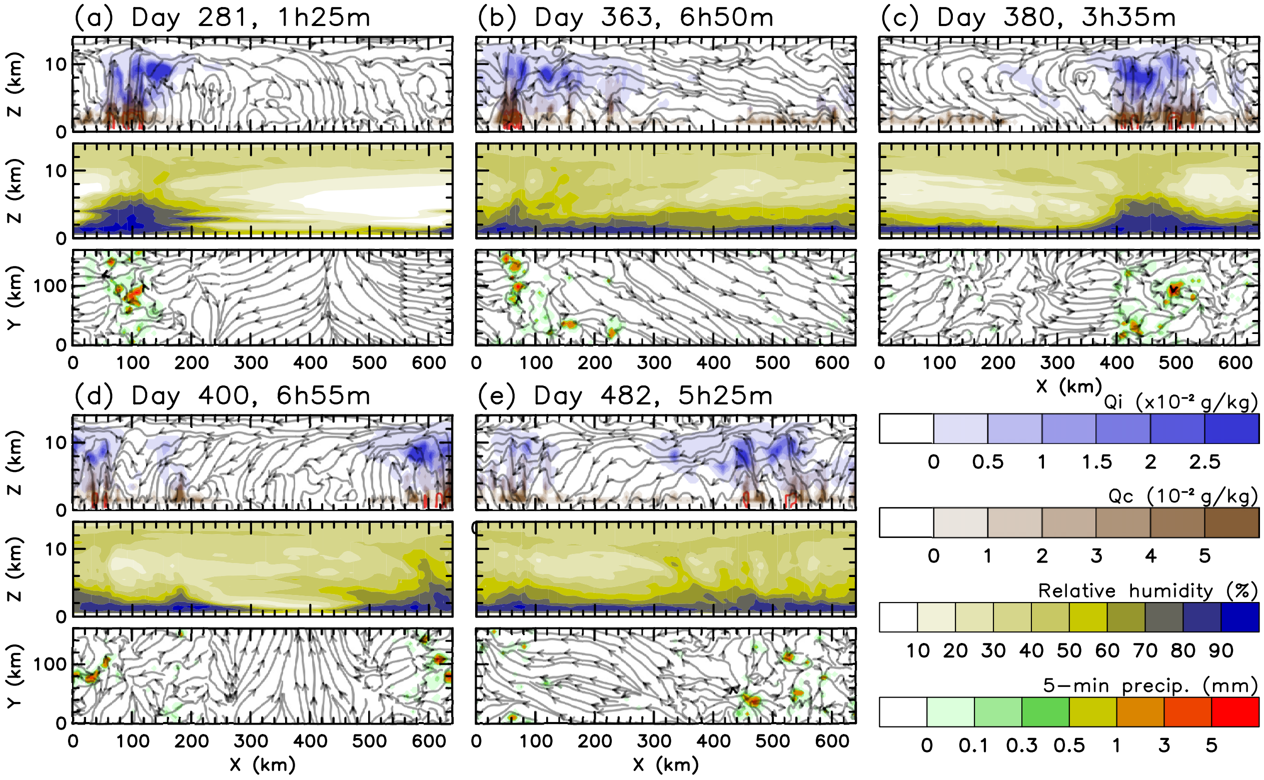

Fig. 4. Zonal-height cross sections of the meridionally averaged stream lines, clouds, and precipitating rain (top panel), relative humidity (middle panel), as well as a horizontal cross section of stream lines at $z = 1$ km and 5-minute precipitation (bottom panel) for five specific time slices in the sub-periods shown in Fig. 3b. The time slices are chosen such that they have the maximum value of 5-minute domain-averaged precipitation in each sub-period.

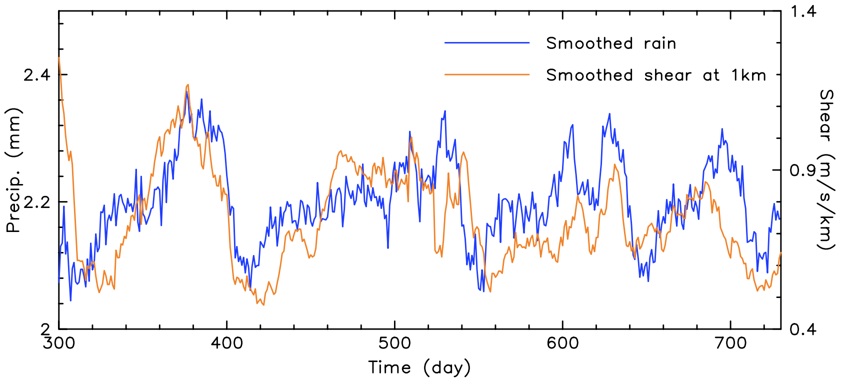

Fig. 5. Time variations of 15-day running mean of domain-averaged precipitation (blue line) and 15-day running mean of the magnitude of vertical shear of the mean horizontal wind near the surface at $z = 1$ km (orange line). The correlation between the two time series is 0.5.

this event as shown in Fig. 2. These facts are indicative of more independent (or irregular) variations in the generation process of gravity waves associated with moist convection systems in the three-dimensional model. These are also consistent with the appearance of positive temperature anomaly in the troposphere and associated larger smoothed precipitation, with an irregular period of about 100 days as shown in Figs. 1c and 1d.

Our three-dimensional minimal model framework is similar to three-dimensional limited-domain simulations used to study self-aggregation of convective systems in the troposphere. Bretherton et al. (2005) investigated the spatial organization of deep moist convection in radiative-convective equilibrium over a constant SST by performing a 100-day simulation with a three-dimensional cloud-resolving limited-domain model with horizontal grid spacing of 3 km, with no ambient rotation and no mean wind. Advancement of computer power enables more computations with wider domain, finer resolution, longer time-integrations, or more runs. Muller and Held (2012) found that self-aggregation is sensitive not only to the domain size, but also to the horizontal resolution. Recently Wing et al. (2018) proposed a radiative-convective equilibrium model intercomparison project (RCEMIP) to investigate clouds and climate sensitivity in the radiative-convective equilibrium setting, and to quantify the dependence of the degree of convective aggregation and tropical circulation regimes on temperature. The QBO-like oscillations obtained in this study with a similar dynamical framework will be a good motivation to study the stratospheric and tropospheric influence on tropical convective systems (Geller et al. 2017) in association with RCEMIP and other related research activities.

5. Conclusions

We carried out a 2-year time integration of a three-dimensional minimal model of the stratosphere-troposphere coupled system under a radiative-moist convective quasi-equilibrium state that can produce a QBO-like oscillation, with a rectangular domain of 640 km × 160 km with doubly periodic boundary conditions. A QBO-like oscillation in both of the mean zonal and meridional winds is obtained with a period of about 300 days (Fig. 1). This period is much longer than the two-dimensional simulation of Yoden et al. (2014) with similar settings.

We noted a synchronization of the zonal and meridional winds, which feature a skewed spiral with anti-clockwise rotation of horizontal wind vectors with height, shown as hodographs in Fig. 2. This spiral feature also rotates anti-clockwise with time by changing its shape periodically as shown by the animation in Fig. S1. This feature may result from a complicated interaction of three-dimensional gravity waves with the vertical shear of the mean horizontal winds. The generation of gravity waves could be analogous to that given by Matsuno (1982) in the study of the mesospheric general circulation interacting with internal gravity waves, though Coriolis effect is zero in our framework. The selective transmission of these gravity waves due to the background mean wind effect and deposition of the wave momentum fluxes due to the eddy viscosity decelerate the mean horizontal winds to produce the anti-clockwise rotation of a skewed spiral as shown in our Figs. 2 and S1. In other words, propagating waves could drive the QBO not only in zonal but also in meridional directions. With the symmetry principle, another solution with clockwise rotation of the flipped spiral is also possible in the present system.

The QBO-like wind oscillations penetrate into the troposphere (Figs. 1a and 1b), whereas rather independent modulations of the mean tropospheric temperature anomaly and smoothed precipitation are observed with irregular periods of about 100 days (Figs. 1c and 1d). The larger value of the smoothed precipitation is associated with the positive temperature anomaly.

Fine temporal output of the simulation reveals three types of precipitation patterns: nearly isolated quasi-stationary type, fast-moving back-building type, and squall-line type (Fig. 3). Alternate appearance of the latter two types was found in the two-dimensional minimal model by Nishimoto et al. (2016), whereas the quasi-stationary type is a newly found feature in our three-dimensional model.

For the quasi-stationary sub-periods, the zonal-height cross sections of the meridionally averaged clouds and relative humidity show there is no shallow cloud with low relative humidity in clear areas, whereas shallow clouds exist even over non-precipitating areas with high relative humidity over the entire domain for the fast-moving back-building type or squall-line type sub-periods (Fig. 4). Intermittent self-reorganization of convective systems into the quasi-stationary type and transition back to the fast-moving back-building type or squall-line type, as seen in Fig. 3a, are fundamental characteristics of self-aggregation in a radiative-moist convective quasi-equilibrium state in the three-dimensional model.

The high correlation between the vertical shear of the mean horizontal wind at 1 km and the smoothed precipitation (Fig. 5) agrees with the results of the counterpart two-dimensional framework investigated by Nishimoto et al. (2016) and Bui et al. (2017). In summary, our three-dimensional minimal model on a non-rotating limited-domain with a doubly periodic lateral boundary condition produces a self-sustained QBO-like oscillation and justifies some essential features of the idealized two-dimensional model results, even though the three-dimensional model has its own unique features such as the anti-clockwise rotation of skewed spiral of the horizontal wind vectors with time, and intermittent self-reorganization of convective systems into the quasi-stationary type.

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