Mechanism for the Spatial Pattern of the Amplitude Changes in Tropical Intraseasonal and Interannual Variability under Global Warming

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ABSTRACT: This study investigates what forms the spatial pattern of the amplitude changes in tropical intraseasonal and interannual variability—represented by the two most important variables, precipitation ($\Delta P'$) and circulation ($\Delta \omega'$)—under global warming, based on 24 models from the phase 5 of the Coupled Model Intercomparison Project (CMIP5). Diagnostic analyses reveal that the moisture budget and thermodynamic energy equations related to the $\Delta P'$ and $\Delta \omega'$ proposed separately in previous studies are simultaneously tenable. As a result, we investigate the mechanism for the spatial pattern of $\Delta \omega'$ from the perspective of the moist static energy (MSE) balance mainly considering the positive contribution from vertical advection. Therefore, based on the simplified MSE balance, the spatial pattern of $\Delta \omega'$ can be approximately projected based on three factors: background circulation variability ω' , the vertical gradient of mean-state MSE $\bar{M}$, and its future change $\Delta \bar{M}$. Under global warming, the middle-level vertical gradient of MSE increases slightly over the Indian Ocean and the Maritime Continent and decreases over the equatorial Pacific where the increase in sea surface temperature (SST) exceeds the tropical mean. The vertical gradient of mean-state MSE is modified by the increase in vertical gradients of moisture and dry static energy (DSE) simultaneously. In short, the change in the vertical gradient of mean-state MSE under global warming can influence the moisture budget and thermodynamic energy balances, resulting in the spatial pattern of $\Delta P'$ and $\Delta \omega'$ at intraseasonal and interannual time scales consequently, mainly determined by the lower boundary moisture condition in the response of the SST change pattern.

KEYWORDS: Climate change; Climate models; Interannual variability; Intraseasonal variability

1. Introduction

The tropical intraseasonal oscillation (ISO), dominated by the Madden–Julian oscillation (MJO) (Madden and Julian 1994), can affect tropical weather systems and global climate systems (Ling et al. 2017; Zhang 2013), such as typhoons or hurricanes (Hsu et al. 2017; Wang and Moon 2017), the Asian and Australian monsoons (Wheeler et al. 2009), El Niño–Southern Oscillation (ENSO) (Hendon et al. 2007; Marshall et al. 2009), and so on. Since the Industrial Revolution, the global atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) have been on the rise, and this increasing trend will continue in the near future (Alexander et al. 2013). In view of the extensive impacts that ISO/MJO has on global climate systems, it is urgent to understand how ISO/MJO may change under GHG-induced warming.

An increase in sea surface temperature (SST) as the lower boundary of the tropical troposphere can destabilize the atmosphere and trigger convections by heating and moistening (Wu and Kirtman 2005; Wu et al. 2006). Thus, as the most typical organized convection in the tropics (Wang et al. 2019), the MJO is sensitive to the possible SST change under GHG-induced global warming. For example, the MJO precipitation (hereafter referred to as MJO P) variance was projected to increase over the entire tropics under global warming with modification by the spatial pattern of SST increase (Bui and Maloney 2020; Maloney and Xie 2013; Takahashi et al. 2011). Under the so-called El Niño-like SST warming pattern (i.e., larger warming in the central-eastern Pacific than the tropical mean), the center of the main MJO activity extends farther eastward, as concluded from the outputs of different single models (Adames et al. 2017b; Arnold et al. 2015; Liu et al. 2013; Subramanian et al. 2014) and the multimodel ensemble (MME) mean of CMIP5 (phase 5 of the Coupled Model Intercomparison Project) (Bui and Maloney 2018; Cui and Li 2019; Maloney et al. 2019; Rushley et al. 2019).

Moreover, it has been projected that the amplitude of MJO P will increase over the Indo-Pacific warm pool, which can be largely attributed to the increase of a nondimensional quantity called $\bar{\alpha}$ that is mainly dominated by the increased vertical

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gradient of moisture in the lower troposphere in response to SST warming (Bui and Maloney 2019b; Maloney et al. 2019; Wolding et al. 2017). The term $\bar{\alpha}$, originally introduced by Chikira (2014), is thought of as the efficiency of vertical moisture advection to apparent heating, which is proportional to the vertical gradient of moisture and inversely proportional to the vertical dry static stability. The increased vertical gradient of moisture can enhance the vertical moisture advection and lower the normalized gross moist stability to support a stronger MJO (Arnold et al. 2013).

However, the change in the amplitude of MJO circulation (hereafter referred to as MJO ω) is different from the change in MJO P in the CMIP5 MME projection (Bui and Maloney 2018; Maloney et al. 2019). The projected MJO ω is characterized by a decrease over the Indo-Pacific warm pool region (Arnold et al. 2015; Liu et al. 2013; Subramanian et al. 2014), which is attributable to the increase in static stability making the atmosphere more stable (Wolding et al. 2017) and an increase over the central and eastern Pacific (Bui and Maloney 2018, 2019b) associated with a farther eastward extension of MJO activity under El Niño-like SST warming. The discrepancy between the amplitude changes in MJO P and ω has been shown to be a consequence of the increased tropical mean static stability denoted by the vertical dry static energy (DSE) gradient (Bui and Maloney 2018; Maloney and Xie 2013). In addition, it has been verified that the amplitude changes in MJO P and ω follow the thermodynamic energy balance (Bui and Maloney 2018).

On the other hand, moisture budget decomposition has been proposed as an approach to understanding the changes in the tropical P variability at the interannual time scale (Power et al. 2013; Seager et al. 2012). Furthermore, a two-layer simplified moisture budget decomposition was suggested as an appropriate method to uncover the relationship between the change in ENSO-induced P and ω variability (Huang 2016; Huang and Xie 2015). Recently, this simplified moisture budget decomposition also successfully explained the relationship between the changes in the Indian Ocean dipole-induced P and ω variability under global warming (Huang et al. 2019), as well as the relationship between the changes in the P and ω responses to local SST anomalies (Ying et al. 2019). These studies show that the changes in the tropical P and ω variability at the interannual time scale strictly follow the moisture budget equation with contributions from mean-state moisture changes and the background ω variability (Huang 2016; Huang and Xie 2015; Ying et al. 2019).

Previous studies on the changes in P and ω variability at intraseasonal and interannual time scales have respectively focused on the aspects of the thermodynamic energy balance and the moisture budget balance. These studies inspire us to consider whether the thermodynamic energy balance and the moisture budget balance are both tenable at the intraseasonal and interannual time scales. Also, if this hypothesis holds, it implies the two restrictions can interpret the amplitude changes of P and ω at intraseasonal and interannual time scales given the mean-state changes and background variability.

However, most of the recent studies investigated the amplitude change in P and ω from the perspective of intensity over some specific domains, no matter the intraseasonal or

interannual variability (Bui and Maloney 2019a,b; Fu et al. 2020; Hsiao et al. 2020; Sun et al. 2020). For example, at the intraseasonal time scale, most researchers focused on the mechanism for the amplitude change in P and ω averaged over the Indo-Pacific warm pool region (Bui and Maloney 2019b; Fu et al. 2020; Hsiao et al. 2020), while some attention was paid to that over the equatorial central-eastern Pacific at interannual time scale (Sun et al. 2020). Here, the present study focuses on the mechanism for the spatial pattern of the amplitude change in P and ω over the entire tropic, which correlates with the pattern of SST future change.

In this study, we diagnose the moisture budget balance and thermodynamic energy balance related to the changes in tropical P and ω variability at intraseasonal and interannual time scales. The two equations are both tenable, which inspires us to investigate the mechanism for the spatial pattern of the change in ω variability from the perspective of MSE budget mainly considering the positive contribution from vertical advection term. As a result, the spatial pattern of the changes in P and ω variability under global warming can be approximately explained by the mean-state changes in MSE and background variability.

The rest of the article is organized into the following sections. Section 2 introduces the data of the CMIP5 models and the methods. Section 3 describes the relationships between the amplitude changes in P and ω , and the mechanism for the spatial pattern of the amplitude change in ω at the intraseasonal time scale. Section 4 reveals the situations at the interannual time scale that are almost the same as at the intraseasonal time scale. Section 5 summarizes our findings.

2. Data and methods

a. Data

This study used 24 models, listed in Table 1, from CMIP5 (Taylor et al. 2012). The daily and monthly outputs were analyzed for the intraseasonal and interannual time scales, respectively. The period of 1980–2000 in historical runs and the period of 2080–2100 in the representative concentration pathway 8.5 (RCP8.5) runs were used to represent the current and future climate, respectively, and their difference denotes the change in a warming climate. All model datasets were interpolated onto a $2.5^\circ \times 2.5^\circ$ grid using bilinear interpolation and the MME mean was defined by the 24-model average. Despite unrealistic simulations of the intraseasonal and interannual variability in some models, we did not select the models used in this study. This is because our conclusions are not dependent on model performance, but almost tenable for all 24 of the models (see the online supplemental material).

b. Methods

At the intraseasonal time scale, the amplitudes of P and ω are represented by the standard deviations of 20–100-day bandpass filtered daily data after removing the 20-yr mean annual cycle. The amplitude of interannual variability was obtained by the standard deviations of monthly anomalies by removing the 20-yr mean annual cycle and the 10-yr running

TABLE 1. A list of the 24 CMIP5 models used in this study.

Model name	Institute
ACCESS1.0	Commonwealth Scientific and Industrial
ACCESS1.3	Research Organization (CSIRO) and Bureau of Meteorology, Australia
BCC-CSM1.1	Beijing Climate Center, China
BCC-CSM1.1-m	Meteorological Administration, China
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University, China
CanESM2	Canadian Centre for Climate Modeling and Analysis, Canada
CMCC-CESM	Centro Euro-Mediterraneo sui
CMCC-CM	Cambiamenti Climatici, Italy
CMCC-CMS	
CNRM-CM5	Centre National de Recherches Météorologiques, France
CSIRO-Mk3.6.0	CSIRO in collaboration with the Queensland Climate Change Centre of Excellence, Australia
FGOALS-g2	State Key Laboratory of Numerical Modeling for Atmospheric Science and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Science, China
GFDL CM3	NOAA/Geophysical Fluid Dynamics
GFDL-ESM2G	Laboratory (GFDL), United States
GFDL-ESM2M	
IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace, France
IPSL-CM5A-MR	
IPSL-CM5B-LR	
MIROC5	The University of Tokyo, National
MIROC-ESM-CHEM	Institute for Environment Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MPI-ESM-LR	Max Planck Institute for Meteorology,
MPI-ESM-MR	Germany
MRI-CGCM3	Meteorological Research Institute, Japan
NorESM1-M	Norwegian Climate Centre, Norway

mean in each period. In addition, we can write the standard deviation operator [the prime ($\cdot$)'] as

$$(aX)' = |a|X',$$

where a represents the climatological mean state such as the vertical change in moisture or DSE ($\partial\bar{q}/\partial p$ or $\partial\bar{s}/\partial p$), X represents the intraseasonal or interannual variability, and $|\cdot|$ denotes the absolute value.

In interannual variation, given the dominance of the anomalous vertical advection of mean-state moisture in P variability (Seager et al. 2012) and the positive values of $\partial\bar{q}/\partial p$ at almost all altitudes, the moisture budget decomposition under global warming can be written as

$$\Delta P' \approx \alpha \Delta \left\langle \omega' \frac{\partial \bar{q}}{\partial p} \right\rangle \quad (1)$$

after removing the absolute value of $\partial\bar{q}/\partial p$, where P is precipitation, ω is pressure velocity, q is specific humidity, α is the

specific volume ($\alpha = 1/\rho$, in which ρ is water density), the angle brackets $[\langle \cdot \rangle] = (1/g) \int_{p(\text{bot})}^{p(\text{top})} (\cdot) dp$, in which g is gravitational acceleration] denote the pressure-weighted vertical integral from 1000 to 200 hPa, the primes for P and ω denote the standard deviation of the interannual variability, the overbar for q denotes the 20-yr long-term mean of the period in historical or RCP8.5 runs, and Δ denotes the change between the future and history. Equation (1) can be further partitioned into two components as follows:

$$\Delta P' \approx \alpha \left\langle \Delta \frac{\partial \bar{q}}{\partial p} \omega' \right\rangle + \alpha \left\langle \frac{\partial \bar{q}}{\partial p} \Delta \omega' \right\rangle. \quad (2)$$

Although Eqs. (1) and (2) are put forward from the perspective of interannual variability, they are also tenable for the intraseasonal variability, which will be verified in the results.

On the other hand, ISO time scale anomalies regulated by weak temperature gradient theory satisfy the thermodynamic energy equation (Maloney and Xie 2013):

$$Q' \approx \omega' \left| \frac{\partial \bar{s}}{\partial p} \right|, \quad (3)$$

where Q is the apparent heat source and s is DSE ($s = C_p T + gz$, in which T is temperature, g is gravitational acceleration, z is geopotential height, and C_p is the specific heat of dry air at constant pressure); the primes for Q and ω denote the standard deviation of ISO. At the intraseasonal time scale, the P variability is approximately proportional to the vertical integral of the apparent heat source (Maloney and Xie 2013). As a result, we have the thermodynamic energy balance under global warming between the ISO P and ω :

$$\Delta P' \approx -\frac{\alpha}{L_v} \Delta \left\langle \omega' \frac{\partial \bar{s}}{\partial p} \right\rangle, \quad (4)$$

where L_v is the latent heat of condensation. The term $\partial\bar{s}/\partial p$ is negative at almost all altitudes, and thus the negative sign appears in Eq. (4) converted from the absolute value $|\partial\bar{s}/\partial p|$. Equation (4) can be further partitioned into two components as follows:

$$\Delta P' \approx -\frac{\alpha}{L_v} \left\langle \Delta \frac{\partial \bar{s}}{\partial p} \omega' \right\rangle - \frac{\alpha}{L_v} \left\langle \frac{\partial \bar{s}}{\partial p} \Delta \omega' \right\rangle. \quad (5)$$

Like Eqs. (1) and (2), Eqs. (4) and (5) are tenable for both the intraseasonal and the interannual variability, although they are put forward from the perspective of intraseasonal variability.

In Eqs. (2) and (5), the terms associated with changes in the vertical gradients of mean-state moisture and temperature represented by DSE [$\langle \Delta(\partial\bar{q}/\partial p) \omega' \rangle$ and $\langle \Delta(\partial\bar{s}/\partial p) \omega' \rangle$] are defined as the thermodynamic components, whereas the other terms associated with changes in vertical motion variability [$\langle (\partial\bar{q}/\partial p) \Delta \omega' \rangle$ and $\langle (\partial\bar{s}/\partial p) \Delta \omega' \rangle$] are defined as the dynamic components.

3. Spatial patterns of the amplitude changes in the ISO P and ω

Figure 1 shows the spatial patterns of P and ω amplitudes at the intraseasonal time scale (hereafter referred to as P_{ISO} and

FIG. 1. Spatial distributions of the (a),(b) P_{ISO} and (c),(d) 500-hPa ω_{ISO} in the (left) historical experiment and (right) future change (RCP8.5) experiment of the CMIP5 MME.

ω_{ISO}) in the historical and future (RCP8.5) simulations of the MME. The historical P_{ISO} (Fig. 1a) resembles the pattern of climatological mean P , with a large amplitude located over the Indo-Pacific warm pool and the intertropical convergence zone (ITCZ) (Adames et al. 2017b; Wolding et al. 2017). Under global warming, P_{ISO} generally increases over the entire tropical ocean, with the largest increase over the equatorial Pacific (Fig. 1b). On the other hand, the historical ω_{ISO} (Fig. 1c) parallels that of P_{ISO} , but the change in ω_{ISO} ($\Delta\omega_{\text{ISO}}$) exhibits apparent differences compared with the change in P_{ISO} (ΔP_{ISO}). The term ω_{ISO} is projected to decrease over most tropical regions but to increase considerably over the equatorial Pacific and the northern Indian Ocean (Fig. 1d). The increased ω_{ISO} is approximately located over the area where the SST increase exceeds the tropical mean (Fig. 2), but the spatial correlation coefficient between them is only 0.22, and nonsignificant using the Student's t test, over the equatorial region (20°S–20°N). This result implies that certain other processes might be responsible for modifying the impact of the SST pattern of future change on the spatial pattern of $\Delta\omega_{\text{ISO}}$, such as the change in mean states demonstrated specifically in the following section.

a. Relationships between ΔP_{ISO} and $\Delta\omega_{\text{ISO}}$

Following the moisture budget and thermodynamic energy equations [Eqs. (2) and (5)], ΔP_{ISO} can be decomposed into two components: the thermodynamic components, $\langle \Delta(\partial\bar{q}/\partial p)\omega_{\text{ISO}} \rangle$ and $\langle \Delta(\partial\bar{s}/\partial p)\omega_{\text{ISO}} \rangle$ (Figs. 3a,b), and the dynamic components, $\langle (\partial\bar{q}/\partial p)\Delta\omega_{\text{ISO}} \rangle$ and $\langle (\partial\bar{s}/\partial p)\Delta\omega_{\text{ISO}} \rangle$ (Figs. 3c,d). In general, the spatial pattern of the thermodynamic components is dominated by the pattern of historical 500-hPa ω_{ISO} (Fig. 1c), due to the greater spatial gradient in ω_{ISO} than in $\Delta(\partial\bar{q}/\partial p)$ or $\Delta(\partial\bar{s}/\partial p)$, while the dynamic components are dominated by that of $\Delta\omega_{\text{ISO}}$ (Fig. 1d) because of the greater spatial gradient in $\Delta\omega_{\text{ISO}}$ than in $\partial\bar{q}/\partial p$ or $\partial\bar{s}/\partial p$. The sums of the thermodynamic and dynamic components accurately reproduce the spatial patterns of ΔP_{ISO} , with spatial correlation coefficient of 0.96 in both cases, which is also tenable in the individual models (Figs. S1 and S2 in the online supplemental material). This indicates that it is feasible to apply the moisture budget and thermodynamic energy equations to the explanation of the spatial pattern of ΔP_{ISO} . Generally, the thermodynamic component makes positive contributions to

ΔP_{ISO} , especially over the Indo-Pacific warm pool, while the dynamic component makes positive contributions only over equatorial Pacific and negative contributions over the residual regions (Fig. 3).

b. Mechanism for the spatial pattern of $\Delta\omega_{\text{ISO}}$

That ΔP_{ISO} is regulated by the moisture budget and thermodynamic energy equations simultaneously inspires us to investigate the mechanism for the spatial pattern of $\Delta\omega_{\text{ISO}}$ from the perspective of MSE budget including moisture and DSE together. According to the previous MSE budget analysis (Arnold et al. 2013, 2015), the enhancement of MJO amplitude is associated with the positive contribution from vertical MSE advection, and thus we mainly consider the contribution of the change in vertical advection to $\Delta\omega_{\text{ISO}}$. Therefore, we directly subtracted Eq. (2) from Eq. (5) and obtained the following MSE equation under global warming:

$$\left\langle \Delta\omega' \frac{\partial \bar{m}}{\partial p} \right\rangle \approx - \left\langle \omega' \Delta \frac{\partial \bar{m}}{\partial p} \right\rangle + \text{res}, \quad (6)$$

where m is MSE ($m = L_v q + s$) and res denotes the residual terms. The prime for ω denotes the standard deviation of ISO and the overbar for m denotes the 20-yr long-term mean of the period in historical or RCP8.5 runs. Note that, despite the application of subtraction between two approximated equations [Eqs. (2) and (5)], the contributions from ignored terms in Eqs. (2) and (5), such as horizontal advection, radiative forcing terms, and so on, are retained and merged into the residual term in Eq. (6).

The spatial pattern of $\langle \Delta\omega' (\partial \bar{m} / \partial p) \rangle$ is shown in Fig. 4a, with negative values over the equatorial Pacific and northern Indian

FIG. 2. Spatial distribution of the change in background SST with the tropical-mean warming removed.

FIG. 3. The (a),(b) thermodynamic and (c),(d) dynamic components of the (left) moisture budget and (right) thermodynamic energy equations [Eqs. (2) and (5)] and (e),(f) their sums in RCP8.5 at the intraseasonal time scale. Contours in (e) and (f) denote the amplitude change in intraseasonal P (the contour interval is 0.2 mm day^{-1} , and negative contours are dashed). The numbers in the top-right corner of (e) and (f) are the uncentered pattern correlations between the amplitude change in P and the sum of the two components.

Ocean and positive values over the Indo-Pacific warm pool regions, which parallels the spatial pattern of $\Delta\omega_{\text{ISO}}$ except for the sign with the spatial correlation coefficient of -0.74 (Fig. 1d). This indicates that factors determining the spatial pattern of $\langle\Delta\omega'(\partial\bar{m}/\partial p)\rangle$ are also suitable for that of $\Delta\omega_{\text{ISO}}$. As expressed in Eq. (6), the term $\langle\Delta\omega'(\partial\bar{m}/\partial p)\rangle$ is approximately balanced by the vertical advection of the change in climatological MSE by the historical amplitude of pressure velocity [$\langle\omega'\Delta(\partial\bar{m}/\partial p)\rangle$] and residual terms. The spatial patterns of $\langle\Delta\omega'(\partial\bar{m}/\partial p)\rangle$ and $-\langle\omega'\Delta(\partial\bar{m}/\partial p)\rangle$ whose centered pattern correlation coefficient is 0.76 over 15°S – 15°N are both nonuniform over equatorial regions, with minima over the northern Indian Ocean and equatorial Pacific where ω_{ISO} is projected to increase (Fig. 4b).

To further confirm the linear relationship in Eq. (6), Fig. 5 displays the scatterplot between every grid point of $\langle\Delta\omega'(\partial\bar{m}/\partial p)\rangle$ and $-\langle\omega'\Delta(\partial\bar{m}/\partial p)\rangle$ over the equatorial regions (15°S – 15°N). A significant linear relationship exists according to Eq. (6), with a correlation coefficient of 0.83. The slope of the regression equation is 0.66 (close to 1) and the intercept of the y axis is 2.82, representing the comprehensive contributions of residual terms, which indicates that the residual (res) term contributes a more critical role in the intensity than the spatial pattern of $\Delta\omega'$.

In previous studies (Bui and Maloney 2018, 2019a,b), adopting 500-hPa vertical velocity to represent vertical motion is a common practice. It means that Eq. (6) can be further simplified as

$$\Delta\Omega'\bar{M} \approx -\Omega'\Delta\bar{M} + \text{res}, \quad (7)$$

where M is the vertical MSE gradient averaged from 400 to 600 hPa [$M = [(\partial L_v q / \partial p) + (\partial s / \partial p)]_{\text{avg}}$], and Ω is 500-hPa pressure velocity distinguished from the all-level pressure velocity ω . Therefore, we can approximately project the spatial

pattern of $\Delta\omega_{\text{ISO}}$ based on three factors: the background circulation variability ω' , the middle-level vertical gradient of mean-state MSE $\bar{M}$, and its future change under global warming.

Figure 6 shows the spatial distributions of atmospheric middle-level $\bar{M}$ and $\Delta\bar{M}$. Although $\bar{M}$ is negative over the entire equatorial regions, the vertical MSE gradient over climatological P areas are relatively smaller than that over the equatorial eastern Pacific due to the frequent convection activities (Fig. 6a). Under global warming, the spatial pattern of the change in vertical gradient of MSE is nonuniform. Specifically, the vertical gradient of MSE is projected to increase over the

FIG. 4. Spatial distributions of the terms (a) $\Delta\omega'(\partial\bar{m}/\partial p)$ and (b) $-\omega'\Delta(\partial\bar{m}/\partial p)$ (W m^{-2}) at the intraseasonal time scale.

FIG. 5. Scatterplot of the left-hand side and the first term on the right-hand side in Eq. (6), for all grid points within the equatorial region (15°S – 15°N). The regression equation and correlation between the left-hand side and the first term on the right-hand side are shown in the top-right corner. The string in the top-left corner denotes this result is at the intraseasonal time scale. Units: W m^{-2} .

Indian Ocean and the Maritime Continent, but not significantly, while it is projected to decrease over equatorial Pacific, with maxima over the equatorial eastern Pacific and secondary maxima over the central Pacific, where the SST increase exceeds the tropical mean (Fig. 6b). As with the two subcomponents of $\Delta \bar{M}$, $\Delta(\partial L_v q / \partial p)_{\text{avg}}$ and $\Delta(\partial s / \partial p)_{\text{avg}}$, the spatial pattern of $\Delta(\partial L_v q / \partial p)_{\text{avg}}$ over the equatorial regions is

quite similar to that of $\Delta \bar{M}$, with maxima over the eastern Pacific and secondary maxima over the central Pacific west of the ΔSST peak due to the restraint of the Clausius–Clapeyron equation $\Delta q \sim \bar{q} \Delta \text{SST}$ (Xie et al. 2010) (Fig. 6c). The steepening vertical gradient of moisture is beneficial to the enhancement of MJO precipitation amplitude (Adames et al. 2017a,b; Arnold et al. 2015; Wolding et al. 2017). However, the vertical gradient of DSE representing static stability is projected to increase over the entire tropics, with maxima over the eastern Pacific (Fig. 6d). It means that the tropical atmosphere will be more stable and thus will not facilitate the enhancement of atmospheric circulation (Bui and Maloney 2018; Maloney and Xie 2013). Another distinction between the change in vertical gradients of moisture and DSE is that $\Delta(\partial L_v q / \partial p)_{\text{avg}}$ is positive over the equatorial tropics while $\Delta(\partial s / \partial p)_{\text{avg}}$ is negative, due to the larger vertical temperature gradient caused by the faster warming rate of the upper troposphere than that of the lower troposphere under global warming especially over the eastern Pacific (Arnold et al. 2013; Bui and Maloney 2019b). This indicates that $\Delta(\partial L_v q / \partial p)_{\text{avg}}$ and $\Delta(\partial s / \partial p)_{\text{avg}}$ go in opposite directions in terms of their contributions to $\Delta \bar{M}$, but the thermodynamic effect of $\Delta(\partial L_v q / \partial p)_{\text{avg}}$ overwhelms the dynamic effect of $\Delta(\partial s / \partial p)_{\text{avg}}$ to form the spatial pattern of $\Delta \omega_{\text{ISO}}$.

4. Spatial pattern of the amplitude changes in the P and ω of interannual variability

The successful decomposition and explanation for the spatial patterns of P_{ISO} and ω_{ISO} inspire us to examine whether the mechanism for the intraseasonal variability can be extended to explain the formation of the spatial patterns of the changes in P and ω at the interannual time scale. Figure 7 shows the spatial patterns of P and 500-hPa ω amplitudes at the interannual time scale (hereafter referred to as P_{IAV} and ω_{IAV}) in the historical and future (RCP8.5) simulations. In general, the patterns of

FIG. 6. The vertical gradient of mean-state MSE averaged from 400 to 600 hPa in the (a) historical experiment and (b) future change (RCP8.5) experiment. (c), (d) Changes in averaged latent heat energy and vertical DSE gradients, respectively. The black curve in (b) is the 3.25°C contour of SST change in RCP8.5.

FIG. 7. As in Fig. 1, but for the interannual time scale.

P_{IAV} (ω_{IAV}) and its future changes, ΔP_{IAV} ($\Delta\omega_{IAV}$), are very similar to those at the intraseasonal time scale, with only slight differences in numerical values.

The relationship between ΔP_{IAV} and $\Delta\omega_{IAV}$ can also be described using the simplified moisture budget and thermodynamic energy equations, simultaneously. The spatial patterns of the thermodynamic (Figs. 8a,b) and dynamic components (Figs. 8c,d) resemble those of the intraseasonal time scale, and their sums can also accurately reproduce the spatial pattern of ΔP_{IAV} , with spatial correlation coefficients of 0.94 and 0.97 respectively (Figs. 8e,f), which is also tenable in the individual models (Figs. S3 and S4). The contributions from thermodynamic and dynamic components to the spatial pattern of ΔP_{IAV} also resemble that of intraseasonal time scale (Fig. 8).

Factors determining the spatial pattern of $\langle\Delta\omega'(\partial\bar{m}/\partial p)\rangle$ at interannual time scale are also suitable for that of $\Delta\omega_{IAV}$ due to their similar spatial distribution (Figs. 9a and 7d). The term $\langle\Delta\omega'(\partial\bar{m}/\partial p)\rangle$ is also approximately balanced by $-\langle\omega'\Delta(\partial\bar{m}/\partial p)\rangle$ and residual terms according to Eq. (6). The spatial patterns of $\langle\Delta\omega'(\partial\bar{m}/\partial p)\rangle$ and $-\langle\omega'\Delta(\partial\bar{m}/\partial p)\rangle$ resemble that of the intraseasonal time scale (Figs. 9a,b) with a centered pattern correlation coefficient of 0.79, while their magnitudes are much closer compared with the intraseasonal time scale.

The linear relationship between every grid point of $\langle\Delta\omega'(\partial\bar{m}/\partial p)\rangle$ and $-\langle\omega'\Delta(\partial\bar{m}/\partial p)\rangle$ is intuitively displayed in Fig. 10, with a correlation coefficient of 0.79. The slope of the regression equation is 0.79 (close to 1), and the intercept of the y axis is 2.81 nearly the same as the intercept at intraseasonal time scale 2.82 (Fig. 5). Thus, it means that the spatial pattern of $\Delta\omega_{IAV}$ can also be approximately projected by the mean-state changes in vertical gradient of mean-state MSE (Figs. 6a,b) and background variability (Fig. 7d). In short, the mechanism for the spatial pattern of ΔP_{ISO} and $\Delta\omega_{ISO}$ is also applicable for that of ΔP_{IAV} and $\Delta\omega_{IAV}$.

5. Conclusions and discussion

In this study, we examined the mechanism for the spatial pattern of the amplitude changes in tropical P and ω at intraseasonal and interannual time scales by comparing the RCP8.5 and historical experiments based on the 24 CMIP5 models. The spatial distributions of the amplitude changes in P (ω) at intraseasonal and interannual time scales show great similarities. Under global warming, P_{ISO} (P_{IAV}) increases over the entire tropical region, while ω_{ISO} (ω_{IAV}) increases over the northern Indian and equatorial Pacific Oceans and decreases over the

FIG. 8. As in Fig. 3, but for the interannual time scale.

FIG. 9. As in Fig. 4, but for the interannual time scale.

Indo-Pacific warm pool (Bui and Maloney 2018; He and Li 2019; Maloney and Xie 2013).

The relationships between $\Delta P'$ and $\Delta \omega'$ at the two time scales can be described using the moisture budget and thermodynamic energy equations simultaneously. Accordingly, $\Delta P'$ can be decomposed into a thermodynamic component, due to the increase in background low-level moisture or vertical gradient of temperature, and a dynamic component, due to the amplitude change in ω variability. The thermodynamic component makes positive contributions to $\Delta P'$ over the entire tropic, while the dynamic component makes positive contributions

only over the equatorial Pacific and negative contributions over the Indo-Pacific warm pool regions.

Since the relationships between $\Delta P'$ and $\Delta \omega'$ satisfy moisture and DSE balances simultaneously, we can explore the mechanism for the spatial pattern of $\Delta \omega'$ from the perspective of MSE balance. However, we only consider the positive contribution from vertical advection terms directly associated with ω' . Therefore, based on the analysis of simplified MSE budget [Eq. (6)], the spatial pattern of $\langle \Delta \omega' (\partial \bar{m} / \partial p) \rangle$ with similar spatial patterns of $\Delta \omega'$ is mainly dominated by that of $-\langle \omega' \Delta (\partial \bar{m} / \partial p) \rangle$. Thus, the spatial pattern of $\Delta \omega'$ can be approximately projected based on three factors: the background circulation variability ω' , the middle-level vertical gradient of mean-state MSE $\bar{M}$, and its future change under global warming $\Delta \bar{M}$. When the background circulation variability ω' and the mean-state vertical gradient of MSE $\bar{M}$ are close to the distribution of the ITCZ, the spatial pattern of $\Delta \bar{M}$ is dominated by the sum of increased moisture and vertical DSE gradients. To be more specific, the increases in vertical gradients of moisture and DSE are largely over the equatorial Pacific, where the local warming is greater than the tropical mean (Xie et al. 2010). In short, the spatial pattern of $\Delta \omega'$ is dominated by that of the change in the vertical gradient of mean-state MSE, and then the spatial pattern of $\Delta P'$ can be diagnosed from $\Delta \omega'$ with the moisture budget or thermodynamic energy balances. Moreover, the spatial pattern of the change in the vertical gradient of mean-state MSE is controlled by the Δ SST pattern under global warming and upper atmosphere warming.

The effects of the change in the mean-state vertical moisture and temperature gradients on the amplitude of ISO were also considered by a nondimensional parameter $\bar{\alpha}$ in some previous studies (Bui and Maloney 2019b; Maloney et al. 2019; Wolding et al. 2017), and both the $\bar{\alpha}$ parameter and Eq. (6) consider the balance between the changes in the vertical gradients of mean-state moisture and temperature. However, the parameter $\bar{\alpha}$ was defined by the vertical gradient of moisture divided by that of DSE, whereas we consider the sum of vertical moisture and DSE gradients as the vertical MSE gradient in Eq. (6) with different expressions. In essence, the $\bar{\alpha}$ parameter was constructed to represent the efficiency of moistening, which indirectly reflects the intraseasonal ω variability change under global warming, whereas Eq. (6) is derived from the MSE budget to investigate the mechanism for the spatial pattern of $\Delta \omega'$. As a result, the linear relationships based on Eq. (6) for intraseasonal and interannual time scales are both significant and with high correlation coefficients (Figs. 5 and 10). Moreover, Eqs. (2) and (5) can directly and clearly explain the relationship between $\Delta P'$ and $\Delta \omega'$ in two ways not relying on whether the model simulates the ISO well.

The mechanism for the pattern and magnitude of $\Delta P'$ and $\Delta \omega'$ at interannual time scale over the entire tropic was also investigated by He and Li (2019). They also adopted the simplified moisture and thermodynamic equations to explain the formation of $\Delta P'$ and $\Delta \omega'$, but they retained the diabatic heating in the thermodynamic equation that is dominated by latent heating corresponding to precipitation variability. In this study, we further converted the diabatic heating to

FIG. 10. As in Fig. 5, but for the interannual time scale.

precipitation variability and investigated from the MSE perspective, showing a clearer mechanism for the formation of $\Delta P'$ and $\Delta \omega'$.

The present study is based on the MME of 24 CMIP5 models without model selection, because the moisture and thermodynamic balances [Eqs. (2) and (6)] are both tenable for each model. Despite the failure of some models to simulate ISO phase speed, frequency, etc., the model performance does not influence the amplitude change in the P and ω variability at two time scales.

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