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ENSO Modulation of the QBO Periods in GISS E2.2 Models

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Abstract. Observational studies have shown that the El Niño–Southern Oscillation (ENSO) exerts an influence on the Quasi-Biennial Oscillation (QBO). The downward propagation of the QBO tends to speed up and slow down during El Niño and La Niña, respectively. Recent results from general circulation models have indicated that the ENSO modulation of the QBO requires a relatively high horizontal resolution, and that it does not show up in the climate models with parameterized but temporally constant gravity wave sources. Here, we demonstrate that the NASA GISS E2.2 models can capture the observed ENSO modulation of the QBO period with a horizontal resolution of 2° latitude by 2.5° longitude and its gravity wave sources parameterized interactively. This is because El Niño events lead to more vigorous gravity wave sources generating more absolute momentum fluxes over the equatorial belt, as well as less filtering of these waves into the tropical lower stratosphere through a weakening of the Walker circulation. Various components of the ENSO system such as the SSTs, the convective activities, and the Walker circulation are intimately involved in the generation and propagation of parameterized gravity waves, through which ENSO modulates the QBO period in GISS E2.2 models.

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1. Introduction

The QBO dominates the interannual variability in the tropical stratosphere (Baldwin et al., 2001) while ENSO is the primary mode of interseasonal–interannual variability over the tropical Pacific Ocean (Wang et al., 2016). It is well-known that both the QBO and the ENSO have far-reaching implications for global weather and climate systems (Hamilton et al., 2015; Philander, 1990; Domeisen et al., 2019).

The QBO and the ENSO defy linear relationships (Angell, 1986; Xu, 1992; Garfinkel and Hartmann, 2007). However, Maruyama and Tsuneoka (1988) spotted an intriguing connection between the anomalously short easterly phase of the QBO at 50 hPa in 1987 and the El Niño event that persisted through that year. Based on the results from a mechanistic model, Geller et. al (1997) suggested that the equatorial sea surface temperatures (SST) modulate the wave momentum fluxes into the stratosphere and thus the QBO. Remarkably, an observational study conducted by Taguchi (2010) demonstrated that the downward propagation of the QBO tends to speed up during El Niño and slow down during La Niña while the amplitude of the QBO tends to be smaller during El Niño and larger during La Niña, respectively. Using radiosonde data from 10 near-equatorial stations distributed along the Equator, Yuan et al. (2014) found that the ENSO modulation of the QBO period is more robust than that of the QBO amplitude.

The QBO influences the distribution and transport of various chemical constituents (Zawodny and McCormick, 1991; Trepte and Hitchman, 1992; Hasebe, 1994; Kawatani et al., 2014), the extratropical circulation in the winter stratosphere (Holton and Tan, 1980; Labitzke, 1982), tropical moist convection (Collimore et al., 2003; Liess and Geller, 2012), the activities of tropical cyclones (Gray et al., 1984; Ho et al., 2009), the ENSO (Gray et al., 1992; Huang et al., 2012; Hansen et al. 2016), the Hadley circulation (Hitchman and Huesmann, 2009), the tropospheric subtropical jet (Garfinkel and Hartmann, 2011a,

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2011b), the boreal summer monsoon (Giorgetta et al., 1999), and the Madden-Julian Oscillation (Yoo and Son, 2016). Thus, it is imperative that weather and climate models have the capacity to simulate the ENSO modulation of the QBO.

Schirber (2015) conducted two sets of experiments to explore this issue using the general circulation model European Centre/Hamburg 6 (ECHAM6) wherein a convection-based gravity wave scheme was newly implemented. The first set of experiments was called QBOW where the initial QBO configurations consisted of a westerly jet above the 10 hPa level and an easterly jet below that level. Likewise, in the second set of experiments named as QBOE, the initial QBO conditions included an easterly and westerly jet above and below the 10 hPa level, respectively. Schirber showed that for QBOW, the ensemble mean period of the QBO from the El Niño runs is shorter than that from the La Niña runs while for QBOE, the ensemble mean periods are comparable between the El Niño and the La Niña runs. He also noted that there is no systematic change in amplitude of the QBO jets between El Niño and La Niña runs. Using version 3 of the EC-Earth Consortium's climate model with its horizontal resolution of T255 spectral truncation, Christiansen et al. (2016) reported that all ensemble members had a faster QBO descent rate during El Niño than during La Niña, and that their ensemble mean QBO phase speeds were comparable to those derived from the reanalyses.

Employing two atmospheric general circulation models (AGCM) developed under the Model for Interdisciplinary Research on Climate (MIROC) framework, Kawatani et al. (2019) investigated the possible mechanism of the ENSO modulation of the QBO. They first compared a 100-year perpetual El Niño run with a 100-year perpetual La Niña run from the MIROC-AGCM with T106 horizontal resolution and 500-m vertical spacing in the stratosphere without any nonorographic gravity wave parameterizations. Then they repeated the two AMIP-style perpetual El Niño and La Niña experiments but using the atmospheric part of the Model for Interdisciplinary Research on Climate, Earth System

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Model (MIROC-ESM) with T42 horizontal resolution and 700-m vertical spacing in the stratosphere where the effects of nonorographic gravity waves are parameterized and the gravity wave sources are held constant in time. They found that the MIROC-AGCM simulates shorter QBO periods during El Niño than during La Niña because of the larger equatorial vertical wave fluxes of zonal momentum in the uppermost troposphere and consequently the much larger resolved gravity wave forcing in the stratosphere during warm ENSO phase. However, they found almost no difference in the average QBO periods simulated by the MIROC-ESM between El Niño and La Niña because the QBO was generated by the parameterized nonorographic gravity wave forcing in the model where the gravity wave sources were held constant in time, thus did not respond to the SST changes associated with the ENSO cycle.

Serva et al. (2020) found that a relatively high horizontal resolution was necessary to simulate the observed modulation of the QBO descent rate under strong ENSO events, while the amplitude response is generally weak at any horizontal resolution. They also pointed out that over-dependence on parameterizing the effects of gravity waves with temporally invariant sources is detrimental to the realistic simulation of the coupling between the ocean and the tropical stratosphere in current climate models.

As far as the ENSO modulation of the QBO period is concerned, both Kawatani et al. (2019) and Serva et al. (2020) emphasized the importance of a relatively high horizontal resolution and the inadequacy of non-interactive gravity wave sources. However, the exploratory work of Schirber (2015) shows that the ENSO modulation of the QBO period can, to some extent, be simulated in the GCM ECHAM6 with T63 and an associated Gaussian grid of ~1.9° horizontal resolution because rather than being held constant in time, the properties of non-interactive gravity wave sources in the tropics are determined by the simulated convection which is modulated by ENSO phases.

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Rind et al. (1988) pioneered the use of meteorologically interactive gravity wave sources in the Goddard Institute for Space Studies (GISS) climate models. By increasing the vertical resolution and revising the formulations, various versions of the GISS models subsequently simulate a spontaneous QBO (Rind et al., 2014, 2020; DallaSanta et al., 2021). The GISS E2.2 models are comprehensive climate models optimized for the middle atmosphere (Rind et al., 2020; Orbe et al., 2020). Their outputs have been submitted to the archive of the Coupled Model Intercomparison Project Phase 6 (CMIP6). Bushell et al. (2020) pointed out that most of current climate models are highly dependent on parameterized nonorographic gravity wave forcing to simulate a QBO. Unsurprisingly, DallaSanta et al. (2021) found that the parameterized convective gravity waves play a dominant role in generating the spontaneous QBO in the GISS E2.2 models.

In this paper, we will compare the QBO simulated by the GISS E2.2 models with observations and investigate how the ENSO modulates the QBO period in those models. Section 2 revisits the ENSO modulation of the QBO from the observational point of view. Section 3 evaluates the ENSO modulation of QBO period in the historical runs simulated by five versions of the GISS E2.2 models. Section 4 explores the physical mechanisms underlying the simulated modulation. Conclusions and discussion are presented in section 5.

2. Revisiting the ENSO modulation of the QBO from observations

2.1 Observations

Before evaluating the GISS E2.2 models, we first follow Taguchi (2010) to revisit the ENSO modulation of the QBO from the observational point of view.

The monthly mean zonal winds are provided by Free University of Berlin (FUB). The FUB data were produced by combining the radiosonde observations at the following three equatorial stations: Canton

Island near 172°W, 3°S (closed in 1967), Gan/Maledive Islands near 73°E, 1°S (closed in 1975), and Singapore near 104°E, 1°N (Naujokat, 1986). We use 63 years (i.e., 756 months) of the FUB data ranging from 1953 to 2015 at the following seven pressure levels: 70, 50, 40, 30, 20, 15, and 10 hPa. As in Taguchi (2010), we first fill the missing zonal winds at the 10 hPa level for the first 3 years by linear extrapolation in log-pressure height, and then remove the climatological seasonal cycle from the data for each calendar month. We further smooth the deseasonalized zonal winds using a 5-month moving average (for more details, refer to Taguchi, 2010).

The National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST) V5 datasets (Huang et al., 2017) are provided by National Centers for Environmental Information (NCEI). ERSST produced on a 2° × 2° grid is derived from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). The latest version of ERSST, version 5, uses new datasets from ICOADS Release 3.0 SST, combining information from Argo floats above 5 m and Hadley Centre Ice-SST version 2 ice concentrations. In addition, the monthly Outgoing Longwave Radiation (OLR) on a2.5° × 2.5° grid is provided by NCEI for the 1979–2015 period. We use the OLR values as a proxy for tropical convection since cloud top temperatures are negatively correlated with cloud height in the tropics.

We use the ERSSTv5 data to construct the Oceanic Niño Index (ONI) ranging from 1953 to 2015. We use the same method to calculate the ONI as the Climate Prediction Center (CPC) of NOAA. Namely, the ONI is defined as a 3-month running mean of ERSSTv5 SST anomalies in the Niño 3.4 region (5°S – 5°N, 120°– 170°W) based on centered 30-year base periods updated every 5 years (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). This method ensures a proper identification of El Niño and La Niña by taking the secular changes in SSTs into account. The SST anomalies are defined as the deviations of the SST from its climatological annual cycle over a

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selected base period. Specifically, the SST anomalies during 1951–1955 are based on the 1936–1965 base period; the SST anomalies during 1956–1960 are based on the 1941-1970 base period; and so on. Thus, as the CPC of NOAA we used the ERSSTv5 SST from January 1936 to January 2016 period to obtain the ONI from January 1953 to December 2015.

Following the CDC of NOAA, we refer to El Niño or La Niña episodes as the periods when the ONIs are greater than +0.5°C or less than –0.5°C for at least five consecutive months, respectively. We will use this same criterion to identify El Niño and La Niña events simulated by the GISS E2.2 models in section 3. Since the temperature measurement is only accurate to the tenths place, all our calculated ONIs are rounded to the nearest tenth. Based on the rounded ONIs, our identified El Niño and La Niña episodes are almost identical to those listed at the abovementioned website of NOAA CPC. Accordingly, we identified 21 El Niño and 15 La Niña events between 1953 and 2015.

2.2 ENSO modulation of the QBO derived from observations

Following Wallace et al. (1993), we decompose the deseasonalized and smoothed FUB zonal winds from 10 to 70 hPa into two leading pairs of empirical orthogonal functions (EOFs) and principal components (PCs) because they typically account for more than 90% of the vertical structure variance (Wallace et al., 1993; DallaSanta et al., 2021). For the sake of robustness, we exclude the FUB data after 2015 as the first two EOFs explain no more than 60% of total variance during the 2016 and 2019/20 QBO disruptions (Anstey et al., 2021).

Fig. 1 depicts the two leading EOFs derived from the deseasonalized and smoothed FUB zonal winds between 1953 and 2015. The vertical structures of those two EOFs are very similar to those depicted in Fig. 2a of Taguchi (2010) who used the FUB zonal winds from 1953 to 2008. Our calculated two leading EOFs account for 95.9% of the vertical structure variance (59.6% by EOF1 and 36.3% by EOF2) which is very close to the value of 96.1% obtained by Taguchi (2010). Thus, the QBO variability can be, to a

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very good approximation, compactly depicted by the trajectory of $\left(PC_1(t), PC_2(t)\right)$ in a linear space spanned by the first two orthonormal EOFs.

Following previous studies (Wallace et al., 1993; Taguchi, 2010, Christiansen et al. 2016; Serva et al. 2020; DallaSanta et al., 2021), the instantaneous amplitude (A) and phase (ψ) of the QBO are defined as

$$A = \sqrt{PC_1^2 + PC_2^2} \tag{1}$$

$$\psi = atan2(PC_2, PC_1) \tag{2}$$

Differentiating (2) with respect to time yields the instantaneous phase speed of the QBO:

$$\psi' = (PC_1 \cdot PC_2' - PC_1' \cdot PC_2)/(PC_1^2 + PC_2^2) \tag{3}$$

Now we have two sample spaces: one consists of 21 independent El Niño events and the other contains 15 independent La Niña events. For each ENSO event, we define the amplitude and phase speed (Ψ') of the QBO as the values of A in Eq. (1) and ψ' in Eq. (3) that are averaged over the number of months of that event. Thus, two random variables A and Ψ', i.e., the amplitude and phase speed of the QBO, are defined both on the El Niño sample space and on the La Niña sample space. We employ Welch's *t*-test (Moser and Stevens, 1992) to examine whether there is a significant difference in A or Ψ' between the El Niño and La Niña population means.

To examine whether the sample mean QBO amplitude is significantly different between El Niño and La Niña, we first construct the statistic:

$$t = \frac{\bar{A}_1 - \bar{A}_2}{s_{\bar{A}_1 - \bar{A}_2}} \tag{4}$$

where $\bar{A}_1$ and $\bar{A}_2$ are the sample mean A for El Niño and La Niña episodes, respectively.

$$s_{\bar{A}_1 - \bar{A}_2} = \sqrt{\frac{s_{A_1}^2}{N_1} + \frac{s_{A_2}^2}{N_2}} \tag{5}$$

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where s_{A_1} and s_{A_2} are the corrected sample standard deviation of A for El Niño and La Niña, respectively while N_1 and N_2 are the sample sizes of El Niño and La Niña events. According to Moser and Stevens (1992), the degrees of freedom for the *t*-distribution is

$$\nu = \frac{\left(s_{A_1}^2/N_1+s_{A_2}^2/N_2\right)^2}{\left(\frac{s_{A_1}^2}{N_1}\right)^2/(N_1-1)+\left(\frac{s_{A_2}^2}{N_2}\right)^2/(N_2-1)} \quad (6)$$

As mentioned before, there are 21 El Niño and 15 La Niña episodes between 1953 and 2015, i.e., $N_1 = 21$ and $N_2 = 15$. Our calculations yield $\bar{A}_1 = 37.2\, ms^{-1}$, $\bar{A}_2 = 40.6\, ms^{-1}$, $\nu = 33$, and $t = -2.01$. Apparently, $\bar{A}_1 < \bar{A}_2$, which suggests that the QBO amplitude is smaller during El Niño than during La Niña. Performing a two-tailed test with $\nu = 33$ and $t = -2.01$, however, we find that the QBO amplitudes during El Niño episodes are not statistically different from those during La Niña episodes at the 5% significance level. This is consistent with the finding of the observational study by Yuan et al. (2014), namely, the ENSO modulation of the QBO amplitude is less robust than that of the QBO period. This is also consistent with the findings of the modeling studies conducted by Schirber (2015) and Serva (2020).

Note that when we use the FUB zonal winds and the ERSSTv5 data over the 1953–2008 period as Taguchi (2010), our calculations yield $N_1 = 19$, $N_2 = 13$, $\bar{A}_1 = 36.7\, ms^{-1}$, $\bar{A}_2 = 41.5\, ms^{-1}$, $\nu = 30$, and $t = -3.23$. A two-tailed test shows that the difference of the QBO amplitude between El Niño and La Niña is statistically significant at the 1% significance level. Note that most data used by Yuan et al. (2014) ended in 2011. The sample sizes of the El Niño and La Niña events are relatively small since 1953 when the equatorial zonal winds began to be available. Since the results of various studies are sensitive to how the available data are selected, we will not further explore in this study whether the ENSO modulates the QBO amplitude for the sake of robustness.

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To examine whether the sample mean QBO phase speed is significantly different between El Niño and La Niña, we similarly use Eqs. (4) – (6) except that A_1 and A_2 are replaced by Ψ_1' and Ψ_2', respectively. Based on the data from 1953 to 2015, our calculations yield $N_1 = 21$ and $N_2 = 15$, $\overline{\Psi_1'} = 0.244$ radians/month, $\overline{\Psi_2'} = 0.186$ radians/month, $\nu = 28$, and $t = 2.47$. Evidently, $\overline{\Psi_1'} > \overline{\Psi_2'}$, indicating that the phase speed of the QBO is greater during El Niño than during La Niña. Performing a two-tailed test with $\nu = 28$ and $t = 2.47$, we ascertain that the phase speed of QBO during El Niño episodes are statistically different from those during La Niña episodes at the 5% significance level. Put in another way, the mean QBO period of 25.8 months (i.e., $2\pi/0.244$) during El Niño is statistically shorter than that of 33.8 months (i.e., $2\pi/0.186$) during La Niña. Furthermore, when we use the FUB zonal winds and the ERSSTv5 data over the 1953–2008 period as Taguchi (2010), our calculations yield $N_1 = 19$ and $N_2 = 13$, $\overline{\Psi_1'} = 0.250$ radians/month, $\overline{\Psi_2'} = 0.182$ radians/month, $\nu = 25$, and $t = 2.83$. Apparently, we reach a similar conclusion that the mean QBO period of 25.1 months (i.e., $2\pi/0.250$) during El Niño is statistically shorter than that of 34.5 months (i.e., $2\pi/0.182$) during La Niña. Since our conclusion is consistent with that of Taguchi (2010), we regard it robust that the QBO descent is faster during El Niño than during La Niña. Henceforth, we will focus only on the ENSO modulation of the QBO period in this study.

To facilitate comparison with other studies (e.g., Taguchi, 2010; Christiansen et al., 2016; Serva et al. 2020), we also calculate the mean phase speed of the QBO by averaging ψ' in Eq. (3) over all the 210 months of the El Niño episodes and over all the 201 months of the La Niña episodes between 1953 and 2015. Subsequently, we obtain the mean QBO period of 25.9 months during El Niño and of 32.0 months during La Niña for the 1953–2015 period. Similarly, we obtain the mean phase speed of the QBO by averaging ψ' in Eq. (3) over all the 186 months of the El Niño episodes and over all the 174 months of the La Niña episodes for the 1953–2008 period. The resultant values are 25.3 and 32.0 months, respectively, which are very close to 25 and 32 months inferred by Taguchi (2010). No matter whether the selected FUB data span from 1953 to 2008 or range from 1953 to 2015, we robustly conclude that the QBO descent rate is faster during El Niño than during La Niña.

Note that it is difficult to rigorously determine the degrees of freedom for a *t*-test when we choose the monthly data as sample points which share some common characteristics, i.e., are not independent of each other during an ENSO event (for more details, refer to Taguchi, 2010). In the remaining of this paper, when we need to conduct a Welch's *t*-test we choose the QBO period averaged over each ENSO episode as a sample point. Otherwise, the mean values during El Niño or La Niña are referred to the quantities averaged over all the months of El Niño or La Niña category in alignment with previous works conducted by Taguchi (2010), Christiansen et al. (2016), and Serva et al. (2020).

The QBO is mainly driven by tropical waves (Lindzen and Holton, 1968; Holton and Lindzen, 1972; Plumb 1977) of which tropical convection is an important source (Holton, 1972; Salby and Garcia, 1987; Bergman and Salby, 1994; Tsuda et al., 2009; Alexander et al., 2017). To investigate how tropical convection is influenced by the ENSO, we first produce the monthly OLR anomalies ranging from 1979 to 2015 by deseasonalizing the monthly OLR data downloaded from the website of NOAA NCEI. Then we obtain the mean OLR anomalies for La Niña and El Niño conditions by averaging the monthly OLR anomalies over all the months that fall into La Niña and El Niño categories, respectively. Fig. 2a show that mean OLR anomalies exhibit a broad and positive pattern that spans the central and eastern equatorial Pacific and a negative pattern in the maritime continent for the La Niña conditions. In contrast, Fig. 2b show that they exhibit a broad and negative pattern that spans the central and eastern equatorial Pacific and a positive pattern in the maritime continent for the El Niño conditions. The large differences in the mean OLR anomalies in Fig. 2c between El Niño and La Niña conditions are closely related with the contrast in the SST anomalies patterns shown in Fig. 3. Namely, the distinctive patterns of positive

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and negative SST anomalies extend over the central and eastern Pacific during the El Niño and La Niña episodes, respectively, which not only gives rise to the corresponding positive and negative rainfall anomalies (Philander, 1990) and the concomitant OLR anomalies shown in Fig. 2, but also leads to various teleconnections outside the tropics (Domeisen et al., 2019).

In the next section, we will evaluate how the ENSO modulates of the QBO periods in the E2.2 models and whether those models can realistically capture the contrast in the OLR patterns that generally underlies the difference in wave driving of the QBO between warm and cold ENSO conditions.

3. ENSO modulation of the QBO period in GISS E2.2 models

3.1 Description of the models and simulations

GISS E2.2 is a climate model specially optimized for the middle atmosphere (Rind et al., 2020; Orbe et al., 2020) and its output was submitted to the Coupled Model Intercomparison Project Phase 6 (CMIP6) archive. The horizontal resolution of all GISS E2.2 models is 2° (latitude) × 2.5° (longitude) for the atmosphere and the model extends from the surface to 0.002 hPa (~89 km) with 102 vertical layers (for more details, see Table 1 in Rind et al., 2020). Note that an adequate vertical resolution is necessary for climate models to internally generate a spontaneous QBO (Scaife et al., 2000; Richter et al. 2014; Rind et al, 2014, 2020; Geller et al. 2016a; Butchart et al. 2018).

According to composition interactivity, the atmospheric component of the GISS E2.2 models was configured in two ways for CMIP6. The first configuration is denoted as NonINTeractive ("NINT") where the fields of radiatively active components such as ozone and multiple aerosol species are specified from previously calculated offline fields (Kelley et al. 2020; Miller et al., 2021). The second configuration includes interactive gas-phase chemistry and a mass-based (One-Moment Aerosol, OMA) aerosol module, where aerosols and ozone are driven by emissions and calculated prognostically (Bauer

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et al., 2020; Nazarenko et al., 2022). The abovementioned NINT and OMA configurations correspond to physics-version=1 ("p1") and physics-version=3 ("p3"), respectively, in the CMIP6 archive.

The basic dynamics and tropospheric physics structure of the GISS E2.2 models were based on the GISS E2.1 model (Kelley et al., 2020). One version of the cloud parameterization schemes used in E2.2, termed as "standard physics" (SP), has not been fully upgraded to the state-of-the-art module customized for E2.1 which has only 40 vertical layers up to 0.1 hPa (Rind et al., 2020). Accordingly, E2.2–SP has a younger sibling, E2.2–AP, whose cloud parameterization schemes, termed as "Altered Physics" (AP), are more aligned with those in E2.1 and whose outputs were thus favored for the submission to the CMIP6 archive. "Altered Physics" in E2.2–AP brings about a somewhat different response to SST as compared with the "standard physics" in E2.2–SP. Since the QBO in the GISS models are mainly driven by gravity waves (DallaSanta et al., 2021) and the phase velocities and momentum fluxes of gravity wave sources are coupled to convective cloud-top-pressure altitudes, convective mass fluxes, background wind fields, etc. (Rind et al., 1988, 2014, 2020), both E2.2–SP and E2.2–AP are included in this study to gain insight into the mechanisms through which ENSO modulates the QBO period despite the fact that the outputs of E2.2–SP were not submitted to the CMIP6 archive. Note that outputs from E2.2–SP models, following the CMIP6 protocol and naming, are available from NASA NCCS portal (under the title E2.2.1).

Here we look into two atmosphere-only (AMIP) ensemble simulations where the evolution of SST and sea ice fraction (SIF) is specified and three coupled ensembles where the respective model atmosphere interacts with the ocean component termed as the GISS Ocean v1 (GO1) which extends from the surface to the ocean floor with 40 vertical layers and has a horizontal resolution of 1° latitude by 1.25° longitude (Schmidt, et al., 2014; Kelley et al., 2020). Table 1 lists the five model configurations and their respective ensemble simulations investigated in this study.

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The first two ensembles in Table 1 were generated by AMIP–OMA–SP and AMIP–OMA–AP models where the SST and SIF from the HadISST1 dataset (Rayner et al., 2003) were prescribed for the simulations between 1870 and 2014 while their climatological annual cycles over the 1876–1885 period were imposed for the earlier simulations between 1850 and 1869. Both AMIP–OMA–SP and AMIP–OMA–AP prognostically calculate the concentrations of ozone, methane, chlorofluorocarbons, aerosols, etc. AMIP–OMA–SP and AMIP–OMA–AP differ only in the package of cloud parameterization schemes, which leads to their different responses to SST and thus may have important implications for simulating the ENSO modulation of the QBO period. We discarded the simulations ranging from 1850 to 1869 in this study because they are irrelevant to the ENSO modulation of the QBO in the absence of interannual variations in the prescribed SST over that period. Note that the two extended historical AMIP simulations from 1870 to 2014 listed in Table 1 were not submitted to the CMIP6 archive. However, AMIP–OMA–AP did generate a 5-member ensemble over the 1979–2014 period that was submitted to the CMIP6 archive and tagged as E2-2-G.amip.r[1-5]i1p3f1. It is worth noting that the climatological characteristics over the 1979–2014 period derived from the AMIP–OMA–AP ensemble listed in Table 1 should be comparable to those derived from E2-2-G.amip.r[1-5]i1p3f1 albeit the climate trajectories of the individual ensemble members over the 1979–2014 period are expected to differ between those two ensembles starting from January 1850 and January 1979, respectively, due to the chaotic nature of climate systems.

The other three ensembles in Table 1 were generated by the Coupled–NINT–SP, Coupled–NINT–AP, and Coupled–OMA–AP models where the respective atmospheric components are coupled with GO1. Both the Coupled–NINT–SP and Coupled–NINT–AP simulations were performed with the prescribed atmospheric composition generated from the AMIP-style OMA simulations using the historical forcings over the 1850–2014 period. As mentioned earlier with regard to the AMIP–OMA–SP

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and AMIP–OMA–AP runs, the difference in cloud physics between the Coupled–NINT–SP and Coupled–NINT–AP models is exploited to gain a deeper insight into the mechanisms through which the ENSO modulates the QBO periods. Coupled–OMA–AP, the last of the abovementioned three ensembles, is computationally expensive because not only the atmosphere and ocean interact with each other but also the radiative, dynamical, and chemical processes are coupled to each other. All three coupled runs started from January 1850 and ended in December 2014.

3.2 ENSO modulation of the QBO period derived from the ensemble simulations

Now we investigate the ENSO modulation of the QBO period in the ensemble simulations listed in Table 1. As mentioned in the preceding subsection, there are no interannual variations in the prescribed SST over the 1850–1869 period for both the AMIP–OMA–SP and AMIP–OMA–AP runs. Thus, our analyses focus on the 1870–2014 period for those two ensembles. For the sake of conciseness and consistency, we also discarded the outputs from three coupled runs over the 1850–1869 period. In short, we only analyze the data over the 1870–2014 period from the ensemble simulations listed in Table 1.

Following section 2, we define the ONI as a 3-month running mean of either prescribed SST anomalies from the AMIP–OMA–SP or AMIP–OMA–AP runs or simulated SST anomalies from the Coupled–NINT–SP, Coupled–NINT–AP, and Coupled–OMA–AP runs in the Niño 3.4 region (5°S– 5°N, 120°– 170°W) based on centered 30-year base periods updated every 5 years. This method can properly identify El Niño and La Niña by removing the secular changes in SSTs. As in section 2, the SST anomalies are defined as the deviations of the SST from its climatological annual cycle over a selected base period. Specifically, the SST anomalies during 1886–1890 are based on the 1871–1900 base period; the SST anomalies during 1891–1895 are based on the 1876-1905 base period; the SST anomalies during 1991–1995 are based on the 1976-2005 base period; the SST anomalies during 1996–2000 are based on the 1981–2010 base period. In addition, the SST anomalies during the earliest 1870–1885 and latest

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2011–2014 spans are ad hoc based on the 1870–1899 and 1985–2014 base periods, respectively. Thus, we used the specified or simulated SSTs over the 1870–2014 period to obtain the ONI from February 1870 to November 2014. For convenience and conciseness, we will only explore the ENSO influence on the QBO period over the 1871–2013 time span in this study.

To obtain the QBO winds from the ensemble simulations listed in Table 1, we first calculate the zonal mean monthly mean zonal winds averaged from 5° S to 5° N over the 1871 to 2013 period at the following seven pressure levels: 70, 50, 40, 30, 20, 15, and 10 hPa. Then we remove the climatological seasonal cycle from the equatorial zonal mean monthly mean zonal winds at each of those seven levels for each calendar month. We further smooth the deseasonalized data using a 5-month moving average following Taguchi (2010) and section 2.

As in section 2, we decompose the QBO winds from 10 to 70 hPa over the 1871–2013 period into two leading pairs of empirical orthogonal functions (EOFs) and principal components (PCs). For each of the 24 ensemble simulations listed in Table 1, the first two leading EOFs account for at least 92.9% of the vertical structure variance which is slightly smaller than the value of 95.9% derived from the observations discussed in section 2. Fig. 4 depicts the first two leading EOFs from each of all five Coupled–NINT–AP runs. For each of those five runs, the first two leading EOFs account for at least 93.8% of the vertical structure variance. The vertical structures of those two EOFs from each Coupled–NINT–AP run are broadly similar to those derived from observations in Fig. 1. The respective vertical structures of the first two leading EOFs are almost identical among all five Coupled–NINT–AP ensemble runs, which is expected because all runs share the same model and differ from each other only in their initial conditions. It is worth noting that the vertical structures of the first two leading EOFs shown in Fig. 4 somewhat differ from those shown in Fig. 1 below the 20 hPa level because none of CMIP models could simulate a QBO in the lower stratosphere that is as strong as the observed (Richter et al., 2020).

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In addition, we find that the vertical structures of the first two leading EOFs from other four ensemble simulations listed in Table 1 (figures not shown) are comparable to those from the Coupled–NINT–AP runs. Thus, the simulated QBO variabilities in each ensemble can be, to a very good approximation, compactly depicted by the trajectory of $\left(PC_1(t), PC_2(t)\right)$ in a linear space spanned by the first two orthonormal EOFs.

For the ensemble simulations listed in Table 1, we define an El Niño or La Niña event in the same way as we did in section 2. Similarly, Eq. (3) is used to calculate the instantaneous (i.e., monthly) phase speed of the simulated QBO. For each El Niño or La Niña event, the mean phase speed of the simulated QBO from any individual run listed in Table 1 is obtained by averaging the instantaneous phase speeds of the simulated QBO over the number of months of that event. Accordingly, we have one sample space consisting of independent El Niño events and the other consisting of independent La Niña events. As in section 2, we employ a two-tailed Welch's *t*-test to examine whether there is a significant difference in the phase speed of the simulated QBO between the El Niño and La Niña population means.

Table 2 describes how the ENSO influence the QBO period in each member of all ensembles, where E[1-5] represent AMIP–OMA–SP, AMIP–OMA–AP, Coupled–NINT–SP, Coupled–NINT–AP, and Coupled–OMA–AP ensembles, respectively while r1, r2,… indicate its respective member of each ensemble. For the member r1 of E1, i.e., the first run of the AMIP–OMA–SP ensemble, we identified 34 El Niño and 30 La Niña events between 1871 and 2013, i.e., $N_1 = 34$ and $N_2 = 30$ in Eqs. (5) and (6). Then we obtained the phase speed of the QBO for each episode of those 34 El Niño and 30 La Niña events, from which we derived the mean phase speed of the QBO averaged over the 34 El Niño and 30 La Niña events, respectively. Accordingly, our mean phase speeds of the QBO simulated by r1 of E1 averaged over the El Niño and La Niña events are obtained as 0.202 radians/month and 0.185 radians/month, respectively, and the standard deviations about those mean phase speeds as 0.0345

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radians/month and 0.0275 radians/month, respectively. Substituting those numbers into Eqs. (4) – (6) yields $\nu = 61$, and $t = 2.25$. Therefore, the phase speed of the QBO simulated by r1 of E1 is statistically significantly greater during El Niño than during La Niña at the 5% significance level. Accordingly, we register the mean QBO period of 31.1 months (i.e., $2\pi/0.202$) during the El Niño episodes and 34.0 months (i.e., $2\pi/0.185$) during the La Niña episodes as the entries for r1 of E1 in Table 2. Since the phase speeds of the QBO simulated by r1 of E1 are statistically significantly different between the El Niño and La Niña categories at the 5% significance level, we can regard the QBO periods as being statistically significantly different between El Niño and La Niña episodes and register their difference, -2.9 months, in Table 2 with red and bold indicating this significance. Similarly, we calculated the QBO periods during ENSO extremes and their difference simulated by every member of all ensembles and registered them in Table 2 where the red and bold numbers indicate that the phase speed of the simulated QBO is statistically significantly greater during El Niño than during La Niña at the 5% significance level.

Table 2 shows that 23 of 24 runs from the five GISS E2.2 models listed in Table 1 can simulate the ENSO modulation of the QBO period discussed in section 2. For each member of the Coupled–NINT–AP and Coupled–OMA–AP ensemble runs, the phase speed of the simulated QBO is statistically significantly greater during El Niño than during La Niña at the 5% significance level. For the AMIP–OMA–SP and AMIP–OMA–AP ensembles, most members also generate a spontaneous QBO whose phase speed is statistically significantly greater during El Niño than during La Niña at the 5% significance level. Intriguingly, in none of the Coupled–NINT–SP ensemble runs, the phase speed of the simulated QBO is statistically significantly different between El Niño and La Niña episodes at the 5% significance level albeit the contrast in the QBO periods between the two categories simulated by r1 of E3 (i.e., Coupled–NINT–SP) is equal to -6.2 months and greater than that simulated by most members of Coupled–NINT–AP and Coupled–OMA–AP. We will further look into this issue in section 5.

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4. Mechanisms of the ENSO modulation of the QBO period in GISS E2.2 models

4.1 ENSO modulation of the QBO forcings

The QBO owes its existence to wave-mean flow interaction (Lindzen and Holton, 1968; Holton and Lindzen,1972; Plumb, 1977). The evolution of zonal mean zonal winds is governed by the transformed-Eulerian-mean (TEM) momentum equation formulated in pressure coordinates on a sphere (Andrews et al., 1983):

$$\frac{\partial \bar{u}}{\partial t} = \bar{G} + \frac{1}{\rho_0 a \cos\varphi}\vec{\nabla}\cdot\vec{F} - \left\{\frac{\bar{v}^*}{a\cos\varphi}\left[\frac{\partial}{\partial\varphi}(\bar{u}\cos\varphi) - f\right] + \bar{\omega}^*\frac{\partial\bar{u}}{\partial p}\right\} + \bar{X}, \tag{7}$$

where the Eliassen-Palm flux $\vec{F}$ is defined as

$$\vec{F} = \{F^{(\varphi)}, F^{(p)}\} = a\cos\varphi\,\{-\overline{u'v'} + \psi\bar{u}_p, -\overline{u'\omega'} - \psi[(a\cos\varphi)^{-1}(\bar{u}\cos\varphi)_\varphi - f]\}, \tag{8}$$

and its divergence as

$$\vec{\nabla}\cdot\vec{F} = \frac{1}{a\cos\varphi}\frac{\partial}{\partial\varphi}\left(F^{(\varphi)}\cos\varphi\right) + \frac{\partial F^{(p)}}{\partial p}. \tag{9}$$

In Eq. (7), t denotes time, p pressure, φ latitude, (u, v, ω) "velocity" in (longitude, latitude, pressure) coordinates, a the mean radius of Earth, ρ_0 pressure-dependent basic density, and f the Coriolis parameter. In Eq. (8), ψ is defined as

$$\psi = \overline{v'\theta'}/\bar{\theta}_p = -\overline{v'T'}/(\frac{\kappa\bar{T}}{p} - \frac{\partial\bar{T}}{\partial p}), \tag{10}$$

where θ denotes potential temperature, T temperature, and κ the ratio of the gas constant to the specific heat at constant pressure. Note that in Eqs. (7) – (10) primes denote departures from the zonal means which are represented by overbars, and residual meridional and vertical velocities, i.e., $\bar{v}^*$ and $\bar{\omega}^*$, are defined as $(\bar{v} - \frac{\partial\psi}{\partial p})$ and $(\bar{\omega} + \frac{1}{a\cos\varphi}\frac{\partial(\psi\cos\varphi)}{\partial\varphi})$, respectively.

On the right hand side (RHS) of Eq. (7), the first term, $\overline{G}$, is the forcing from the gravity waves parameterized in E2.2 models; the second term, $\frac{1}{\rho_0 a \cos\varphi}\vec{\nabla}\cdot\vec{F}$, is the forcing driven by the waves resolved by GISS E2.2 models; the third term, $-\left\{\frac{\overline{v}^*}{a\cos\varphi}\left[\frac{\partial}{\partial\varphi}(\overline{u}\cos\varphi)-f\right]+\overline{\omega}^*\frac{\partial\overline{u}}{\partial p}\right\}$, is associated with the TEM advection; and last term, $\overline{X}$, is the zonal component of friction or other nonconservative mechanical forcing (Andrew et al., 1987) that is small as far as the QBO is concerned and thus ignored in this study.

Section 3 shows that each historical simulation of the AMIP–OMA–SP, AMIP–OMA–AP, Coupled–NINT–AP and Coupled–OMA–AP models brings about a faster downward propagation of the simulated QBO during El Niño than during La Niña. The difference in the phase speed of the simulated QBO between ENSO extremes is statistically significant at the 5% significance level for most of those model runs. For Coupled–NINT–SP, one of its historical runs exhibits an opposite response, namely, the simulated QBO propagates downward slower during El Niño than during La Niña while other four runs of that model do bring about a faster phase speed of the QBO during warm ENSO events. However, no matter whether the difference in the QBO period simulated by Coupled–NINT–SP is positive or negative between ENSO extremes, it is not statistically significant at the 5% significance level. In this section, we start with investigating how the first three terms in Eq. (7), i.e., the parameterized gravity wave forcing, the resolved wave forcing, and the TEM advection, respond to ENSO extremes and how their evolutions are related with those of the QBO winds simulated by the GISS E2.2 models.

As shown in sections 2 and 3, both the observed and simulated QBO can be very well represented by the trajectory of $\left(PC_1(t), PC_2(t)\right)$ in a linear space spanned by the first two orthonormal EOFs. In other words, at any time t, the QBO wind profile, $U'_{profile}$ is very close to the following linear combination: $PC_1(t)\cdot EOF_1 + PC_2(t)\cdot EOF_2$. Here, the QBO wind, U', refers to the deseasonalized and smoothed zonal mean monthly mean zonal winds averaged from 5° S to 5° N. We construct the composite fields

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of the QBO winds, the gravity wave forcing, the resolved wave forcing, and the TEM advection according to the phase angle of the QBO wind profiles. For each month that falls into the El Niño or La Niña category, we use Eq. (2) to calculate the phase angle of the QBO wind profile, each cycle of which over the 1871–2013 period is divided into 24 bins with the bin size of 15°. Note that if two QBO wind profiles belong in the same bin, they look similar because any one of them can be expressed by the other multiplied by a scalar factor. Therefore, for each of the El Niño and La Niña categories, it is very natural for us to generate the composite QBO winds for that category by averaging all wind profiles in each bin and produce the concomitant composite fields of the gravity wave forcing, the resolved wave forcing, and the TEM advection in the corresponding bin.

Fig. 5 depicts the composite fields of the QBO winds (black contours) and parameterized (left panels) and resolved (right panels) wave forcing averaged over all realizations of the Coupled–NINT–AP ensemble. All composite fields in this section are the mean values over the 5°S–5°N latitudes. The ensemble average is achieved on the basis that the respective vertical structures of the first two leading EOFs are almost identical among all five Coupled–NINT–AP ensemble runs as demonstrated in Fig. 4. Both Figs. 5a and 5b show a characteristic feature of the QBO. Namely, the maximum eastward and westward wave forcing from parameterized gravity waves are located below and propagate downward with the westerly and easterly QBO jets. Fig. 5c reveals the stronger gravity wave forcing in both eastward and westward shear zones of the QBO winds during El Niño than during La Niña, which gives rise to the faster phase speed of the QBO during warm ENSO episodes than during its cold counterparts. Figs. 5d and 5e also show that the relationship between resolved wave forcing and the QBO winds are somewhat more complex. When zonal wind anomalies are close to zero, the coherent and modest resolved westward wave forcing help the easterly shear zone of the QBO winds to propagate downwards from the 10 hPa level to the 70 hPa level during both the cold and warm ENSO episodes while the

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coherent and modest resolved eastward wave forcing help the westerly shear zone of the QBO winds to propagate downwards only from the 20 hPa level to the 70 hPa level during both the cold and warm ENSO episodes. At altitudes above the 20 hPa level, easterly jet cores are modestly weakened by the resolved eastward wave forcing during the two extreme ENSO phases. In particular, Fig. 5f indicates that at altitudes above the 30 hPa level the response of the resolved wave forcing to the ENSO acts to slow down the downward propagation of the QBO during El Niño than during La Niña. However, the parameterized gravity wave forcing shown in Fig. 5 clearly dominates over the resolved wave forcing, which is consistent with the finding of DallaSanta et al. (2021) that the parameterized convective gravity waves play a dominant role in generating the spontaneous QBO in the GISS E2.2 models.

Figs. 6a–6c depict the composite fields of the QBO winds (black contours) and TEM advection averaged over all realizations of the Coupled–NINT–AP ensemble. Comparing Figs. 6a–6c with Fig. 5 reveals that the TEM advection composite is also larger than composite resolved wave forcing in the Coupled–NINT–AP model. Thus, the QBO simulated by this model is mainly controlled by the gravity wave forcing and the TEM advection. Figs. 6a–6b also show that the maximum positive and negative advective tendencies are located above rather than below and propagate downward with the westerly and easterly QBO jets, thus acting to slow down the downward propagation of the QBO, which is mainly caused by the persistent tropical upwelling and a general feature of the QBO (Giorgetta et al. 2006; Rind et al., 2014). Figs. 6c indicates that there exist stronger positive and negative advective tendencies above the westerly and easterly QBO jets during El Niño than during La Niña. In other words, the TEM advection alone leads to a slower phase speed of the QBO during El Niño than during La Niña. This is not surprising because El Niño gives rise to a stronger tropical upwelling in the lower stratosphere (Calvo et al., 2010; Simpson et al., 2011).

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Figs. 6d–6f show the composite the QBO winds (black contours) and the composite sum of gravity wave forcing, resolved wave forcing, and TEM advection averaged over all realizations of the Coupled–NINT–AP ensemble. In other words, the upper, middle, and lower panels depict the sum of the fields shown in all the corresponding panels of Figure 5 and Figs. 6a–6c. The pattern of the composite sum is generally determined by the pattern of gravity wave forcing even though the latter is more coherent than the former. Thus, we conclude that the shorter QBO period during El Niño simulated by Coupled–NINT–AP is mainly caused by stronger gravity wave forcing during warm ENSO episodes. We also find that stronger gravity wave forcing during warm ENSO events are simulated by AMIP–OMA–SP, AMIP–OMA–AP, and Coupled–OMA–AP models (figures not shown), which help us understand why most members from each of those four ensembles generate a spontaneous QBO whose phase speed is statistically significantly greater during El Niño than during La Niña at the 5% significance level.

Now we explore how ENSO influences gravity wave forcing, resolved wave forcing, and TEM advection simulated by the Coupled–NINT–SP model, i.e., the remaining model listed in Tables 1and 2. Contrasting between Fig. 7a and Fig. 5c reveals that the ensemble mean composite response to the ENSO of gravity wave forcing simulated by Coupled–NINT–SP is substantially weaker than that simulated by Coupled–NINT–AP. Although the Coupled–NINT–SP simulations still bring about enhanced westward gravity wave forcing in the easterly shear zones of the simulated QBO winds during El Niño in contrast to La Niña, the magnitude of the reinforcement is only about two thirds of that simulated by Coupled–NINT–AP. In particular, in Fig. 7a there is no coherent pattern of enhanced eastward gravity wave forcing in the westerly shear zones of the QBO winds simulated by Coupled–NINT–SP, which is in glaring contrast to the coherent pattern of positive enhancement shown in Fig. 5c generated from the Coupled–NINT–AP ensemble. Figs. 7b and 7c show that both resolved wave forcing and TEM advection respond to the ENSO weakly and uniformly in the Coupled–NINT–SP ensemble simulations. Combining all three composite fields together, Fig. 7d demonstrates that the ensemble mean of the Coupled–NINT–SP simulations still simulates a coherent but much weaker response to the ENSO of resultant forcing at altitudes above the 40 hPa level, which helps us to explain why only some of the Coupled–NINT–SP ensemble runs can simulate a faster QBO descent rate during El Niño than during La Niña and the ENSO does not make a difference in the phase speed of the QBO that is statistically significant at the 5% significance level in any of those Coupled–NINT–SP runs.

4.2 ENSO modulation of the generation and propagation of parameterized gravity waves

A natural question that arises is how the simulated gravity wave forcing relates to the SST anomalies of ENSO extremes specified in or simulated by the GISS E2.2 models listed in Table 1. Figs. 8a and 8b show the ensemble averages of the composite SST anomalies averaged over all La Niña and El Niño months respectively over the 1871–2013 period simulated by Coupled–NINT–AP. Comparing Figs. 8a and 8b with Figs. 3a and 3b reveals that the amplitude of the ENSO simulated by Coupled–NINT–AP is larger than the observed. Figs. 8a and 8b also indicate that the model has a capability to simulate the ENSO amplitude asymmetry (Cane and Zebiak, 1987; Yu and Mechoso, 2001), namely, the amplitudes of the ENSO are relatively larger during warm episodes than during cold episodes. As in Fig. 3 of Zhao and Sun (2022), Figs. 8c depicts the sum of the composite SST anomalies shown in Figs. 8a and 8b that they used to characterize the ENSO amplitude asymmetry. Their Fig. 3 reveals that most CMIP6 models cannot simulate the pattern of a positive residual in the sum of the composites of ENSO extremes in the tropical eastern Pacific. Further comparison between Fig. 3 in Zhao and Sun (2022) and Fig. 8c indicates that the ENSO amplitude asymmetry simulated by Coupled–NINT–AP is only about 50% of that simulated by the GISS-E2-1-H model discussed in their study whose ENSO amplitude asymmetry is comparable to the observed. Since this study is chiefly concerned with the ENSO modulation of the

QBO period, we focus on the ensemble mean difference between the composite SST anomalies of ENSO extremes, which can be interpreted as the peak-to-peak amplitude of the ENSO cycle.

Comparing Fig. 9a with Fig. 3c indicates that the peak-to-peak ENSO amplitude derived from the HadISST1 dataset over the 1871–2013 period is somewhat smaller than that derived from the ERSSTv5 dataset over the 1953–2015 period, which is consistent with the finding by Grothe et al. (2019) that the increase in the ENSO variability is statistically significant (>95% confidence) from the preindustrial to recent era, no matter whether the latter is defined by the previous 30, 50, 75, or 100 years before 2016. Fig. 8c and Fig. 9 also reveal that the ENSO amplitude simulated by Coupled–OMA–AP is somewhat stronger than that simulated by Coupled–NINT–AP which in turn is substantially greater than that simulated by Coupled–NINT–SP. Even though the ENSO amplitude from Coupled–NINT–SP is weakest among three coupled models, it is noticeably greater than that specified in the AMIP–OMA–SP and AMIP–OMA–AP models.

We also ascertain that the Hadley circulation simulated by each of the five models listed in Table 1 strengthens and weakens during warm and cold ENSO episodes respectively, which is consistent with the finding by Oort and Yienger (1996); that the responses of the Hadley circulation to ENSO extremes are comparable between the Coupled–OMA–AP and Coupled–NINT–AP ensembles; that both of them are substantially stronger than that simulated by Coupled–NINT–SP, which is stronger than the simulated responses from two AMIP models whose responses to ENSO extremes are comparable (figures not shown).

Schirber (2015) discovered that the parameterized gravity wave mean momentum source is about 15% larger in the El Niño ensemble than in the La Niña ensemble because the El Niño leads to enhanced precipitation and convective heating. Similarly, we calculate the absolute value of convective momentum fluxes (ACMF) at the source altitude and composite the ACMF anomalies averaged over the

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latitudinal belt between 5°S and 5°N from El Niño and La Niña categories respectively over the 1871–2013 period. Fig. 10 shows the composite difference in the equatorial mean ACMF anomalies between El Niño and La Niña over the 1871–2013 period, indicating that the absolute momentum fluxes at the source levels over the equatorial best is larger during El Niño episodes than during La Niña episodes for each of 24 runs listed in Table 1. This finding is consistent with that of Geller et al. (2016b), Alexander et al. (2017), and Kang et al. (2018). The ensemble mean difference in the absolute momentum fluxes at the source levels averaged over that equatorial belt between El Niño and La Niña is obtained as 0.07, 0.15, 0.10, 0.12, 0.12 mPa for AMIP–OMA–SP, AMIP–OMA–AP, Coupled–NINT–SP, Coupled–NINT–AP, and Coupled–OMA–AP, respectively. Note that these composite differences in ACMF between El Nino and La Nina translate into ACMF being about 10-20% larger in the El Niño ensembles than in the La Niña ensembles, thus agree with the Schirber (2015). Since the QBO period is inversely dependent upon the momentum flux (Plumb, 1977), the differences in equatorial absolute momentum fluxes at the source altitude contribute to shortening and lengthening of the simulated QBO period during warm and cold ENSO phases, respectively.

Fig. 3 shows that the locations of warmest SSTs shift from the maritime continent during La Niña episodes to the central and eastern equatorial Pacific during El Niño episodes. Since strong convective activities over tropical oceans are generally located above the regions where the SSTs exceed 26°– 28° C (Graham and Barnett, 1987; Zhang, 1993), strong convective activities also shift eastward from cold to warm ENSO phases, as illustrated in Fig.2. Using satellite data, the climatological study by Sullivan et al. (2019) demonstrated that the occurrence of organized deep convection during El Niño events increases threefold in the central and eastern Pacific and decreases twofold outside of these regions in contrast to that during La Niña events. It is well-established that the Walker circulation strengthens during La Niña and weakens during El Niño (Bjerknes, 1969).

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To illustrate how the ENSO influences the Walker circulation, we first obtain the ERA5 (Hersbach et al., 2020) monthly mean zonal winds over the 1979–2015 period from the European Centre for Medium-Range Weather Forecasts (ECMWF), Copernicus Climate Change Service (C3S). Next, we construct the equatorial zonal winds as the zonal winds averaged from 5°S to 5°N. Then we define the equatorial winds during La Niña and El Niño as the equatorial winds averaged over all months that fall into the La Niña and El Niño categories, respectively. Fig. 11 illuminates that the Walker circulation during El Niño is substantially weaker than that during La Niña over the equatorial Pacific and the eastern equatorial Indian ocean. In particular, the westerlies above the central and eastern Pacific and the easterlies above the maritime continent and the eastern Indian ocean are substantially weaker in the upper equatorial troposphere during in El Niño than during La Niña. Kawatani et al. (2019) argue that the weaker upper tropospheric winds during El Niño episodes enable a greater amount of gravity wave momentum fluxes to be transferred from the troposphere into stratosphere because less gravity waves are filtered out. This argument assumes critical-level absorption of otherwise weakly damped, vertically propagating gravity waves, which was adopted by Lindzen and Holton (1968). The weaker Walker circulation leads to a shorter QBO period during El Niño while the stronger Walker circulation results in a longer QBO period during La Niña.

To illuminate how the E2.2 models simulate the response of upper tropospheric winds to the ENSO extremes, we first construct the anomalous monthly zonal winds based on centered 30-year base periods updated every 5 years as per section 2 or section 3, which ensures a proper extraction of the ENSO signal by removing the secular and multi-decadal variations in zonal winds. Next, we average the anomalies of zonal winds from 5°S to 5°N to obtain the monthly equatorial zonal winds anomalies between 1871 and 2013. Then we composite the equatorial zonal wind anomalies during La Niña and El Niño by averaging them over all months that fall into the La Niña and El Niño categories, respectively. Fig. 12 depicts the

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ensemble mean composite difference in the equatorial zonal wind anomalies between warm and cold ENSO extremes simulated by the E2.2 models listed in Table 1. The patterns of the simulated wind anomalies shown in Fig. 12 are very similar to that derived from the ERA5 reanalysis shown in Fig. 11c. Namely, the weakened Walker circulation simulated by the E2.2 models during El Niño episodes results in weaker upper tropospheric westerlies over the central and eastern equatorial Pacific and weaker upper tropospheric easterlies over the maritime continent and eastern equatorial Indian ocean while the intensified Walker circulation simulated by the E2.2 models during La Niña episodes leads to stronger upper tropospheric westerlies over the central and eastern equatorial Pacific and stronger upper tropospheric easterlies over the maritime continent and eastern equatorial Indian ocean. The difference in the wind filtering of upward propagating gravity waves causes a greater transfer of gravity wave momentum fluxes into the tropical stratosphere during El Niño episodes than during La Niña episodes, leading to a shorter QBO period during El Niño events than during La Niña events. Further comparison between Figs. 11 and 12 reveal that the contrast in the Walker circulation between warm and cold ENSO extremes simulated by two AMIP models, i.e., AMIP–OMA–SP and AMIP–OMA–AP, is comparable to that derived from the ERA5 reanalysis. However, the difference in the Walker circulation over the central and eastern equatorial Pacific between warm and cold ENSO extremes simulated by three coupled ocean-atmosphere models, i.e., Coupled–NINT–SP, Coupled–NINT–AP, and Coupled–OMA–AP, is substantially smaller than that derived from the ERA5 reanalysis.

While the comparison of the observed and simulated changes in the Walker circulation between warm and cold ENSO extremes shown in Figs. 11 and 12 can account for a shorter QBO period simulated by all GISS E2.2 models and can also explain why the two AMIP models can better capture the ENSO modulation of the QBO period than the Coupled–NINT–SP model as indicated in Table 2, it nether can explain why both the Coupled–NINT–AP and Coupled–OMA–AP models can comparably capture the

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ENSO modulation of the QBO period as two AMIP models nor can illuminate why these two coupled models with the altered physics perform better than the coupled model with the standard physics (i.e., Coupled–NINT–SP). However, further comparing the simulated SST changes between warm and cold ENSO extremes shown in Figs. 8 and 9 hints that the unduly amplified ENSO in the coupled AP runs holds the key to those unsettled issues that is detailed as follows.

Using a large ensemble of multiple climate models, Serva et al. (2020) discovered that the AMIP historical runs generally better capture the ENSO modulation of the QBO period than the coupled ocean-atmosphere historical simulations. In particular, among a few coupled ocean-atmosphere models that do, to various extents, capture the ENSO modulation of the QBO period, the common feature is that each of them can largely simulate the observed OLR anomaly pattern shown in Fig. 2c albeit the magnitudes of those simulated OLR anomalies from their historical runs are roughly 50% stronger than the observed (for more details, refer to their Fig. 8 in Serva et al., 2020). For the sake of comparison, we construct the ensemble mean composite difference in the OLR anomalies between warm and cold ENSO extremes in the same way we constructed the ensemble mean composite difference in the zonal wind anomalies depicted in Fig. 12.

Figs. 13a and 13b show that the patterns of the OLR anomalies simulated by AMIP–OMA–SP and AMIP–OMA–AP largely resemble the observed one shown in Fig. 2c. Although the pattern simulated by AMIP–OMA–AP matches better with the observed, the convective activities during El Niño episodes simulated by AMIP–OMA–SP and AMIP–OMA–AP are apparently inadequate over the region where the upper tropospheric westerlies weaken most conspicuous during warm ENSO extremes shown in Figs. 12a and 12b, respectively. Thus, although the contrast in the wind filtering of gravity waves between El Niño and La Niña episodes simulated by the two AMIP E2.2 models are comparable to the observed, the difference in the gravity wave momentum flux transferred into the equatorial stratosphere between warm and cold ENSO extremes should be smaller than the observed. This partly explains why the observed contrast between the mean QBO period during El Niño episodes (i.e., 25.1 months) and the mean QBO period during La Niña episodes (i.e., 34.5 months) is higher than that simulated by the two AMIP models shown in Table 2 (i.e., E1 and E2 in Table 2). As exhibited by the coupled models capable of simulating the ENSO modulation of the QBO period, Figs. 13d and 13e show that the contrast in the OLR anomalies between warm and cold ENSO extremes simulated by Coupled–NINT–AP and Coupled–OMA–AP are apparently sharper than the observed one shown in Fig. 2c. In particular, the tropical convection in the central and eastern Pacific during El Niño episodes simulated by Coupled–NINT–AP and Coupled–OMA–AP is both more extensive and more intensive than that simulated by the two AMIP models shown in Figs. 13a and 13b, which is consistent with the fact that the composite differences in the SST anomalies simulated by Coupled–NINT–AP shown in Fig. 8d and by Coupled–OMA–AP shown in Fig. 9c are substantially sharper than that prescribed in the two AMIP models shown in Fig. 9a. Thus, even though the wind filtering of gravity waves during El Niño episodes simulated by Coupled–NINT–AP and Coupled–OMA–AP shown in Figs 12d and 12e are significantly smaller than that simulated by AMIP–OMA–SP and AMIP–OMA–AP shown in Figs 12a and 12b, respectively, the combined effect of the lower contrast in the wind filtering and the higher contrast in the amount of gravity wave momentum fluxes generated by convective activities between warm and cold ENSO extremes over the central and eastern tropical Pacific results in a comparable ENSO modulation of the QBO period simulated by AMIP–OMA–SP and AMIP–OMA–AP to that simulated by the two AMIP models as illustrated in Table 2. Finally, comparing Fig. 13c with Fig. 2c and other four panels in Fig. 13 reveals that convective activities during the warm ENSO phase simulated by the Coupled–NINT–SP model are substantially weaker than both the observed and those simulated by other four models list in Table 1. Combining the small composite OLR difference shown in Fig. 13c and the small difference in

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the wind filtering shown in Fig. 9c between warm and cold ENSO extremes over the central and eastern equatorial Pacific results in a low contrast in gravity wave forcing between warm and cold ENSO phases shown in Fig. 7a, which, short of the compensating effect of the excessively amplified ENSO in Coupled–NINT–AP and Coupled–OMA–AP simulations, leads to a relatively weaker ENSO modulation of the QBO period simulated by the Coupled–NINT–SP model as illustrated in Table 2.

5. Discussion and Conclusions

Both Kawatani et al. (2019) and Serva et al. (2020) pointed out that a relatively high horizontal resolution is necessary to simulate the ENSO modulation of the QBO period. Employing an earth system model with T42 (~2.79°) horizontal resolution, Kawatani et al. (2019) further demonstrated that the ENSO modulation of the QBO could not be simulated with their fixed gravity wave sources. Serva et al. (2020) also pointed out that the reliance on stationary parameterizations of gravity waves is partly responsible for failing to simulate the observed modulation of the QBO by the ENSO in current climate models.

Rind et al. (1988) implemented various interactive gravity wave sources in the GISS climate models. With the momentum flux of the parameterized convective waves dependent on the convective mass flux, buoyancy frequency at the top of the convective region, wind velocity averaged over the convective layers, etc. and with a horizontal resolution of 2° latitude by 2.5° longitude, all the five versions of GISS E2.2 models in this study can simulate the ENSO modulation of the QBO period to various degrees. For each of 24 runs conducted in this study, the absolute momentum fluxes at the source levels over the equatorial belt is larger during El Niño episodes than during La Niña episodes, leading to a shorter and longer QBO period, respectively.

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Realistic simulation of the ENSO modulation of the QBO periods entails the realistic simulation of both the ENSO and the QBO. With the realistic SSTs specified, both the composite difference in the Walker circulation and the composite OLR difference between warm and cold ENSO extremes simulated by the two AMIP E2.2 models are close to the observed. Since the AMIP model with the "altered physics" performs better than that with the "standard physics" as far as the simulated OLR is concerned, the ensemble mean difference in the QBO period between La Niña and El Niño episodes (i.e., ~4.5 months) simulated by AMIP–OMA–AP is larger than that simulated by AMIP–OMA–SP (i.e., ~3.9 months), which indicates that convective parameterization scheme is important not only for simulating the resolved waves as pointed out by Horinouchi et al. (2003) and Lott et al. (2014), but also for parameterizing gravity waves. However, the convective activities simulated by both AMIP E2.2 models are still inadequate over the central and eastern equatorial Pacific as compared to the observed, which may partly account for why the ensemble mean differences in the QBO period between La Niña and El Niño episodes simulated by both AMIP models are smaller than the observed difference (i.e., ~9.4 months).

Although the simulated Walker circulations associated with the ENSO cycle are comparable among the three coupled ocean-atmosphere models in this study, the E2.2 model with the "standard physics" performs well in its simulated SSTs which is very close to the observed while the ENSO amplitudes simulated by other two models with the "altered physics" are substantially greater than observed. The model with the "standard physics" not only fails to properly simulate the shift of the strongest convection from the maritime continent during La Niña to the central and eastern equatorial Pacific during El Niño, but also grossly fail to simulate the sufficient amplitude of the OLR concomitant with the ENSO cycle. The weaker response of the Walker circulation and convective activities to the ENSO cycle together with the dislocated centers of convection concomitant to cold and warm ENSO extremes leads to the

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smallest ensemble mean difference in the QBO period between La Niña and El Niño episodes (i.e., ~2.7 months) simulated by the Coupled–NINT–SP model. The weaker variation of the Walker circulation and the excessive change in convection compensate to give an impression of realistically simulating the ENSO modulation of the QBO period by the other two models with the "altered physics", i.e., Coupled–NINT–AP and Coupled–OMA–AP, with their ensemble mean differences in the QBO period between La Niña and El Niño episodes being ~4.8 and ~5.6 months, respectively. However, it is worth pointing out that we don't regard those two models as the best among the five models listed in Table 1 because the relatively satisfactory results are achieved in a compensatory, thus unrealistic, way. Serva et al. (2020) conducted both the atmosphere-only and coupled historical simulations and found that the peak-to-peak amplitudes of the OLR associated with the ENSO cycle are two times larger than the observed for a few models that relatively well capture the ENSO modulation of the QBO period, which together with our results suggests that the parameterized convection is a linchpin of realistically simulating the ENSO, the QBO, and the ENSO modulation of the QBO.

Intriguingly, the simulated difference in the QBO period between La Niña and El Niño is 6.2 months from the first realization simulated by Coupled–NINT–SP. However, it is not statistically significant at the 5% significance level. Meanwhile, the differences in the QBO period between La Niña and El Niño from most of the realizations simulated by Coupled–NINT–AP and Coupled–OMA–AP are apparently less than 6.2 months but are all statistically significant. To gain a deeper insight, we calculate the frequency power spectra of standardized ONIs derived from the observed and simulated SSTs. Fig. 14a depicts the power spectral densities (PSD) of standardized ONI between 1953 and 2015 derived from the NOAA ERSSTv5 SST while Fig. 14b delineates the PSD of standardized ONI between 1871 and 2013 derived from the HadISST1 dataset. Figs. 14a and 14b show that although the ENSO accounts for the lion's share of SST variabilities, there is a good amount of SST variabilities on the decadal and

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multidecadal time scales. Fig. 14d illustrates the PSD of standardized ONI between 1871 and 2013 simulated by the second realization of Coupled–NINT–AP while Fig. 14e illuminates that simulated by the second realization of Coupled–OMA–AP, which demonstrate that the ENSO overwhelmingly dominates over any other noises in SST variabilities simulated by those E2.2 models with the "altered physics". Furthermore, Fig. 14c shows the PSD of standardized ONI between 1871 and 2013 simulated by the first realization of Coupled–NINT–SP. Apparently, the SST variabilities simulated by the E2.2 model with the "standard physics" are comparable to the observed, thus more realistic. The smaller ratio of the ENSO signal to the noise simulated by the first realization of Coupled–NINT–SP and the much larger ratio simulated by the second realizations of the E2.2 models with "alter physics" explain why the difference of 6.2 months in the QBO period between La Niña and El Niño from the former is not statistically significant while why the differences of 2.6 and 4.8 months from the latter are statistically significant as shown in Table 2.

None of the E2.2 configurations robustly simulate an ENSO modulation of QBO amplitude, consistent with the weaker signal present in observations (Yuan et al., 2014). In order to realistically simulate the ENSO modulation of the QBO, various aspects of climate models such as the SSTs, the Walker circulations, the parameterizations of convection and gravity waves need to be further improved, which is fortunately ongoing under the auspices of the SPARC Quasi-Biennial Oscillation initiative (Butchart et al., 2018).

Data availability

The monthly mean zonal winds from Free University of Berlin are obtained from https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html. The NOAA ERSSTv5 SST is acquired from https://www.ncei.noaa.gov/products/extended-reconstructed-sst. The NCEI OLR is downloaded from https://www.ncei.noaa.gov/products/climate-data-records/outgoing-longwave-radiation-monthly. The ERA5 monthly mean zonal winds are obtained from the ECMWF C3S at Climate Data Store: https://cds.climate.copernicus.eu/. The GISS ModelE E2.2 data are available from the Earth System Grid Federation and also from the NASA Center for Climate Simulation data portal (including non-CMIP6 simulations).

Author contributions

All authors made equal contributions to this work.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1 The model configurations and respective ensemble simulations

Model configuration	Simulation	CMIP6 archive tag	Period	Ensemble size	Ensemble name
AMIP–OMA–SP	Historical AMIP	N/A	1850–2014	5	E1
AMIP–OMA–AP	Historical AMIP	N/A*	1850–2014	4	E2
Coupled–NINT–SP	CMIP6 Historical	N/A#	1850–2014	5	E3
Coupled–NINT–AP	CMIP6 Historical	E2-2-G.historical.r[1-5]i1p1f1	1850–2014	5	E4
Coupled–OMA–AP	CMIP6 Historical	E2-2-G.historical.r[1-5]i1p3f1	1850–2014	5	E5

*E2-2-G.amip.r[1-5]i1p3f1 in the CMIP6 archive are the outputs of the same model, but range from 1979 to 2014.

Coupled–NINT–SP outputs follow the CMIP6 protocol and naming. Four of five runs are available from NCCS portal at https://portal.nccs.nasa.gov/datashare/giss_cmip6/CMIP/NASA-GISS/GISS-E2.2.1-G/

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Table 2 The ENSO influence on the QBO period

Member		r1			r2			r3			r4			r5		
ENSO Phase		EL	LA	EL–LA	EL	LA	EL–LA	EL	LA	EL–LA	EL	LA	EL–LA	EL	LA	EL–LA
Period (month)	E1	31.1	34.0	**–2.9**	34.9	35.9	–1.0	29.4	32.9	–3.5	29.7	36.7	**–7.0**	30.5	35.7	**–5.2**
	E2	33.1	36.5	**–3.4**	31.5	35.6	**–4.1**	32.1	35.4	–3.2	29.4	36.8	**–7.4**	n/a	n/a	n/a
	E3	27.5	33.7	–6.2	28.0	30.5	–2.5	30.5	29.8	0.7	30.0	31.5	–1.5	28.2	32.0	–3.8
	E4	31.2	35.0	**–3.8**	29.8	32.4	**–2.6**	29.7	35.4	**–5.7**	28.0	34.7	**–6.7**	28.0	33.4	**–5.4**
	E5	32.6	38.6	**–6.0**	33.0	37.8	**–4.8**	33.0	38.0	**–5.0**	32.3	39.2	**–6.9**	32.3	37.6	**–5.3**

E[1-5] denote the ensemble simulations AMIP-OMA, AMIP-OMA-AP, Coupled-NINT-SP, Coupled-NINT-AP, and Coupled-OMA-AP, respectively. r[1-5] indicate the ensemble members of those simulations. EL and LA are short for El Niño than during La Niña, respectively. The red and bold numbers can be regarded as being statistically significantly different from zero at the 5% significance level.

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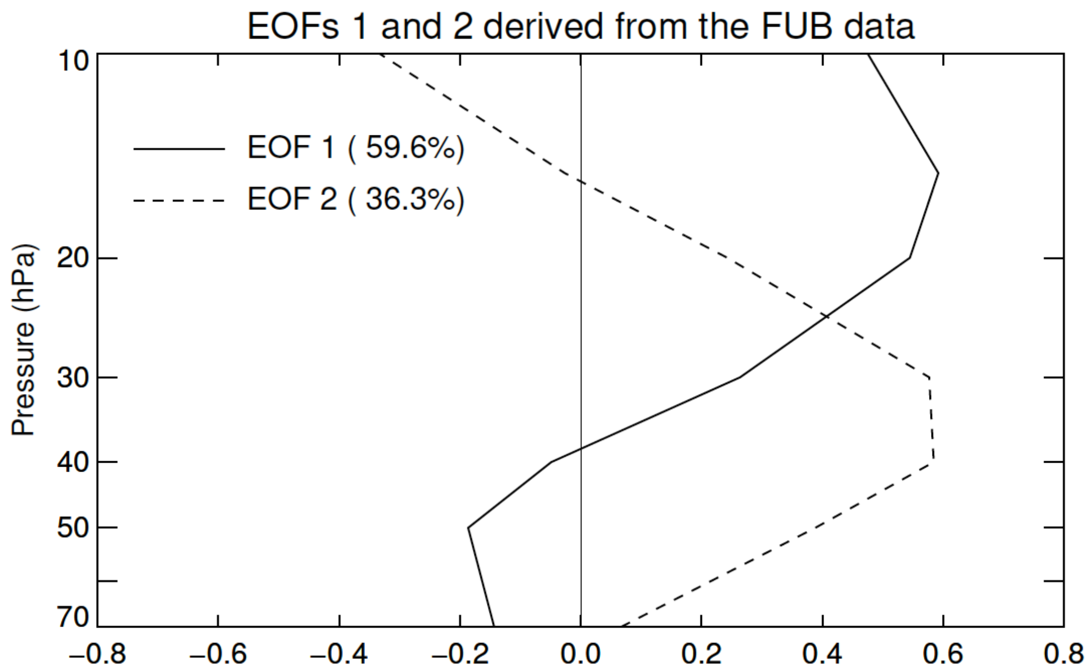

Fig. 1. The first (solid line) and second (dashed line) orthonormal eigenvectors derived from the deseasonalized and smoothed FUB zonal winds between 1953 and 2015.

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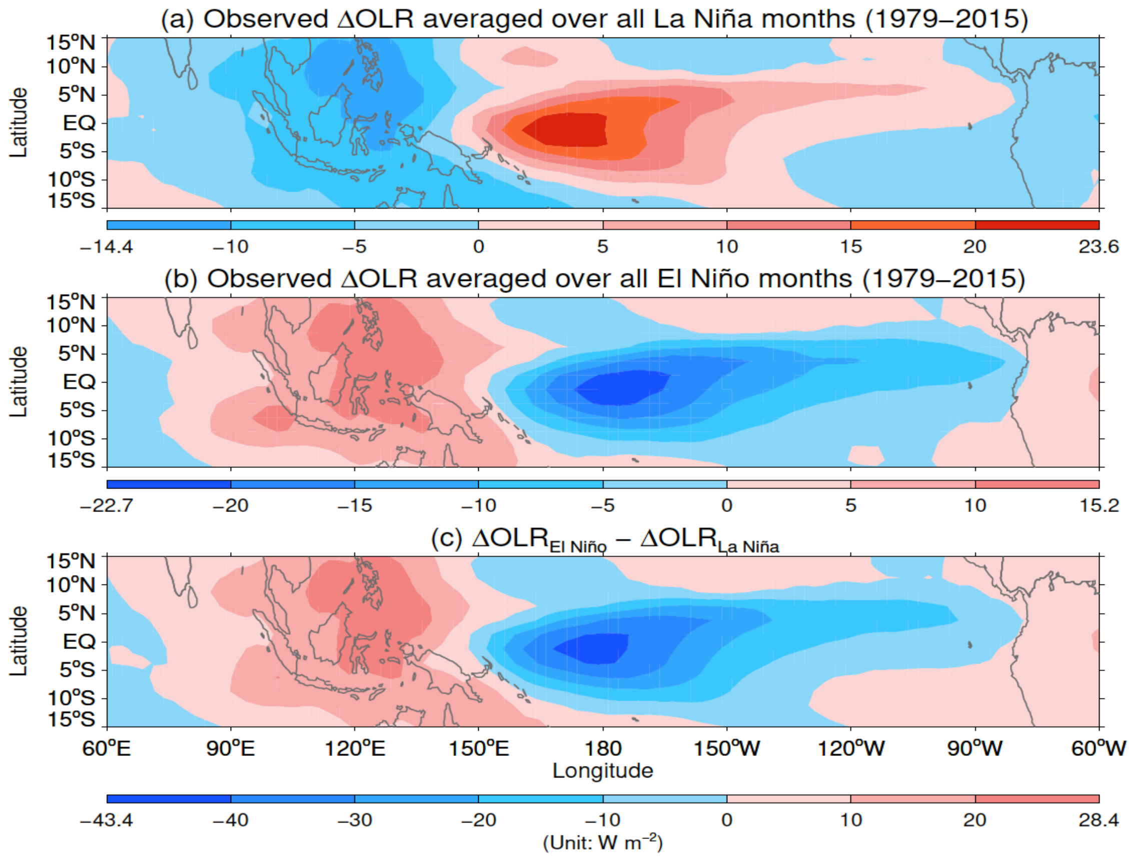

Fig. 2. Mean OLR deviations from climatology for (a) La Niña and (b) El Niño conditions over the tropical Indian and Pacific oceans. (c) Differences of mean OLR anomalies between El Niño and La Niña conditions. The mean composite OLR anomalies and their differences are derived from the datasets provided by NOAA NCEI.

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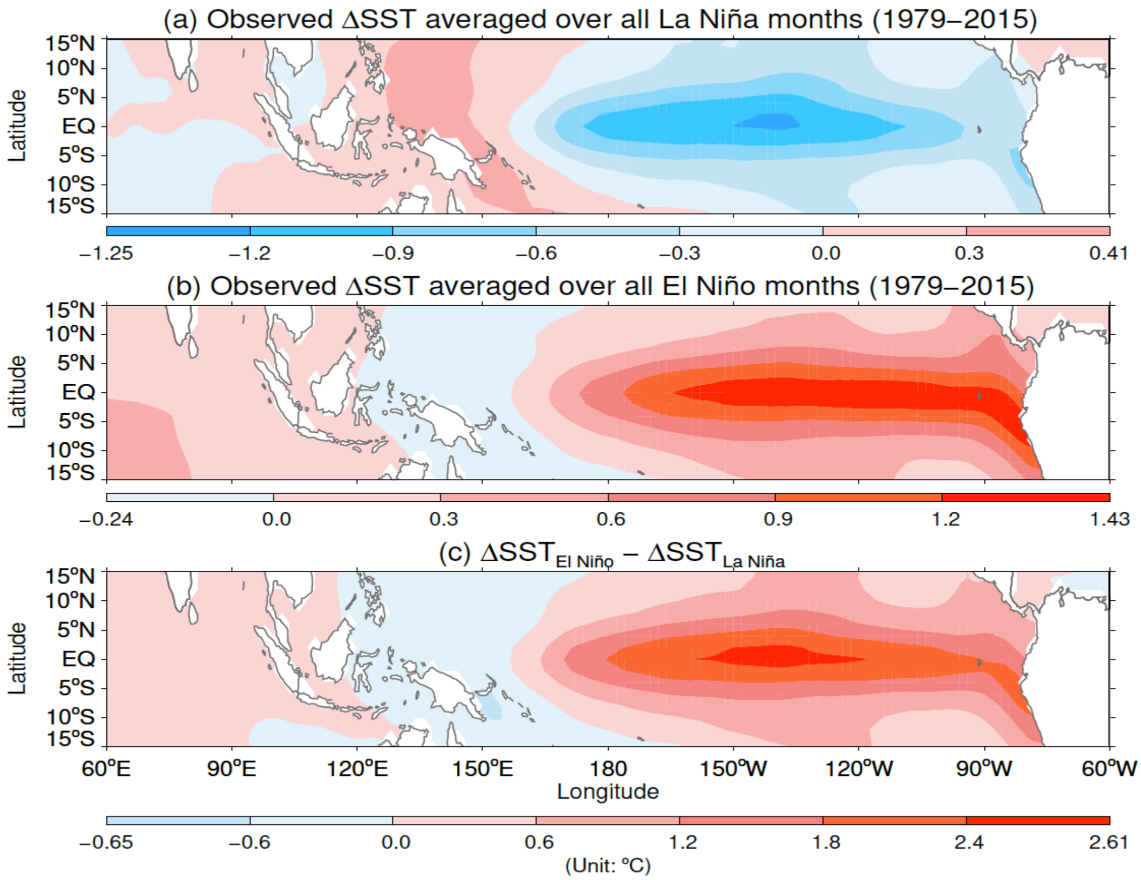

Fig. 3. Mean SST deviations from climatology for (a) La Niña and (b) El Niño conditions over the tropical Indian and Pacific oceans. (c) Differences of mean SST anomalies between El Niño and La Niña conditions. The mean composite SST anomalies and their differences are derived from the NOAA ERSSTv5 SST.

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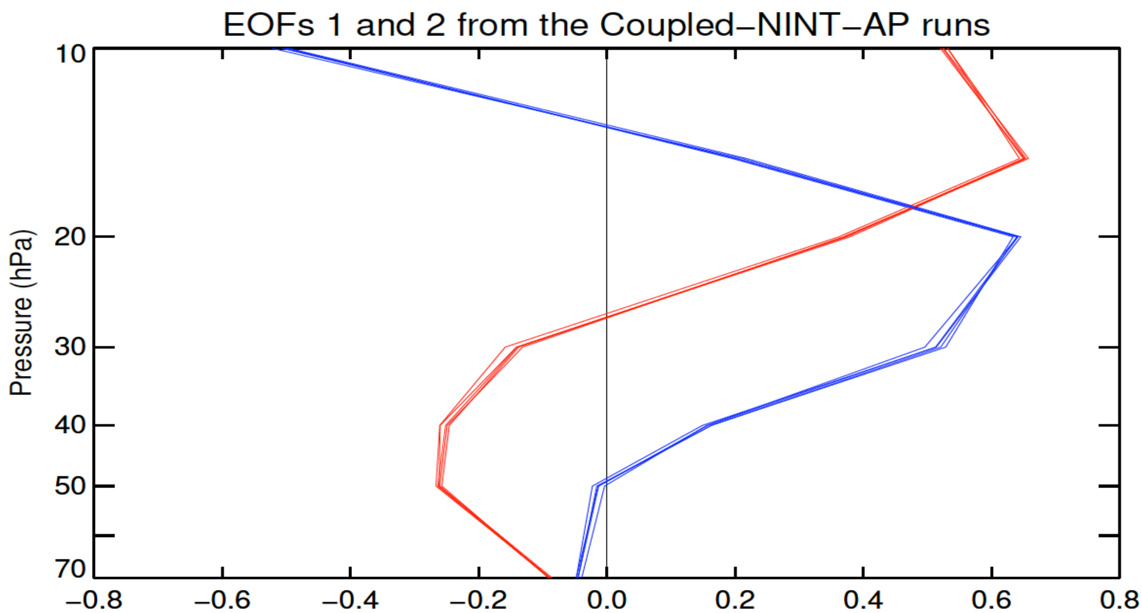

Fig. 4. The first (red lines) and second (blue lines) orthonormal eigenvectors derived from the deseasonalized and smoothed equatorial zonal mean zonal winds between 1873 and 2013 from the five Coupled–NINT–AP runs.

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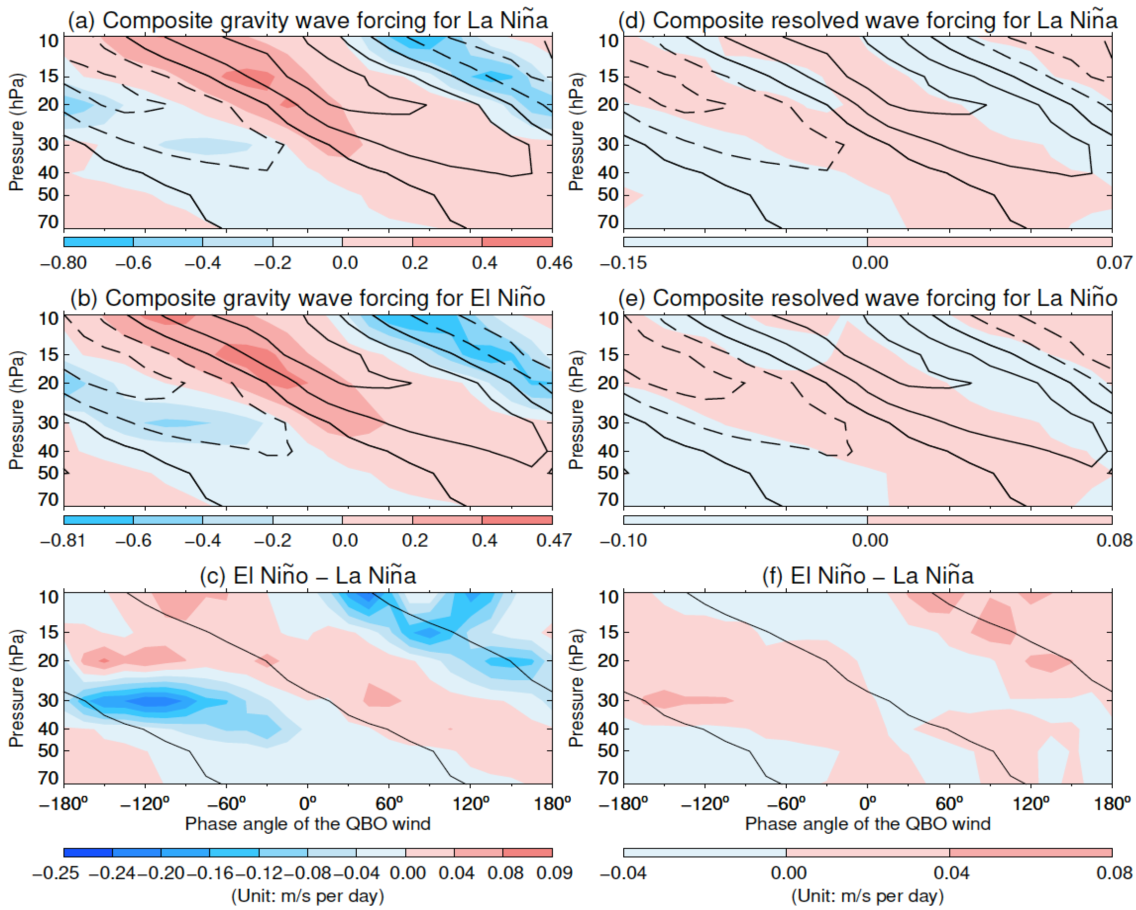

Fig. 5. Ensemble average of the composite QBO winds simulated by the Coupled–NINT–AP model during La Niña (upper panels) and El Niño (middle panels) is depicted by black contour lines where the contour interval is 10 m s^{-1} with dashed lines denoting negatives and solid lines denoting positives and zero. The location of strong shear zones of the QBO winds during ENSO extremes is delineated by the zero wind contour lines in lower panels. For color filled contours, left panels depict the ensemble average of the composite gravity wave forcing simulated by the Coupled–NINT–AP model averaged from 5°S to 5°N during La Niña (a) and El Niño (b) and its composite difference between El Niño and La Niña (c); right panels depict the ensemble average of the composite resolved wave forcing simulated by the Coupled–NINT–AP model during La Niña (d) and El Niño (e) and its composite difference between El Niño and La Niña (f).

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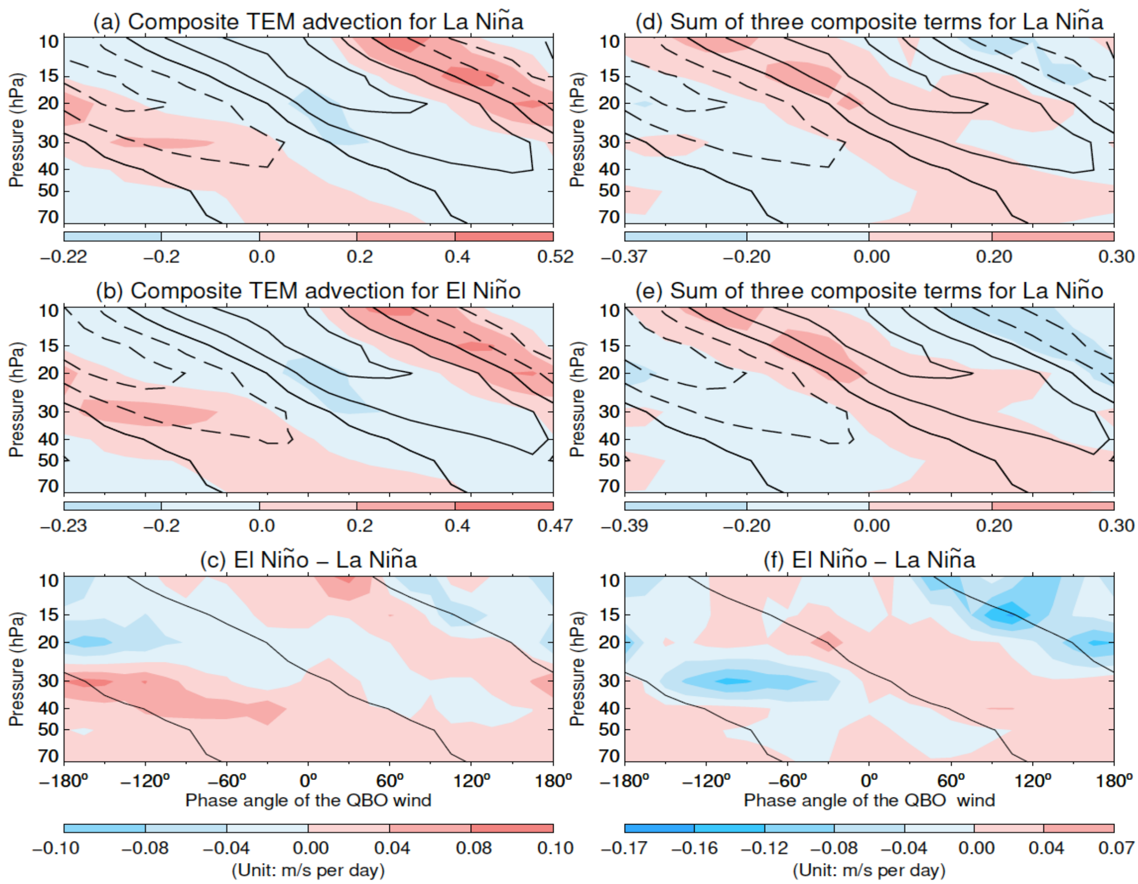

Fig. 6. The black contour lines are the same as those in Fig. 5. For color filled contours, left panels depict the ensemble average of the composite TEM advection simulated by the Coupled–NINT–AP model averaged from 5°S to 5°N during La Niña (a) and El Niño (b) and the composite difference between El Niño and La Niña (c); right panels depict the ensemble mean totaling of the composite fields of gravity wave forcing, resolved wave forcing, and TEM advection simulated by the Coupled–NINT–AP model during La Niña (d) and El Niño (e) and the composite difference between El Niño and La Niña (f).

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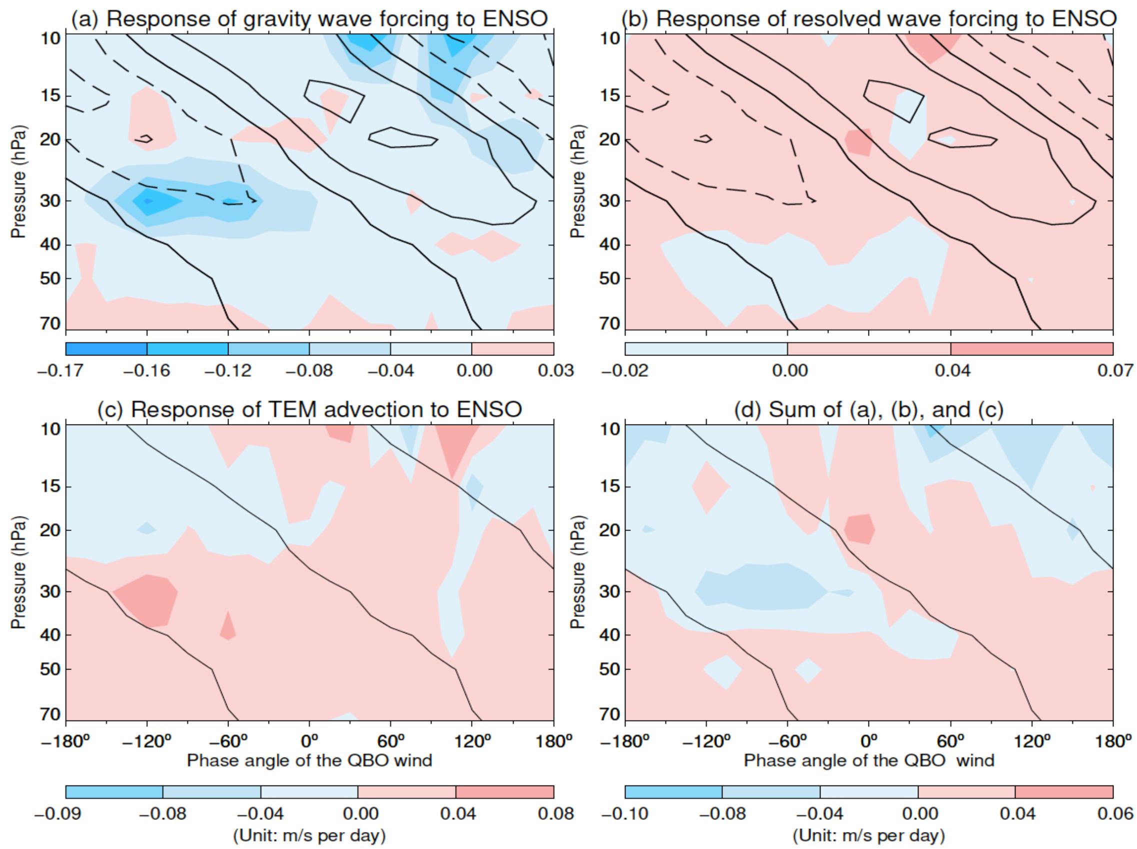

Fig. 7. (a) and (b) are the same as the bottom panels in Fig. 5 except for the Coupled–NINT–SP model. (c) and (d) are the same as the bottom panels in Fig. 6 except for the Coupled–NINT–SP model.

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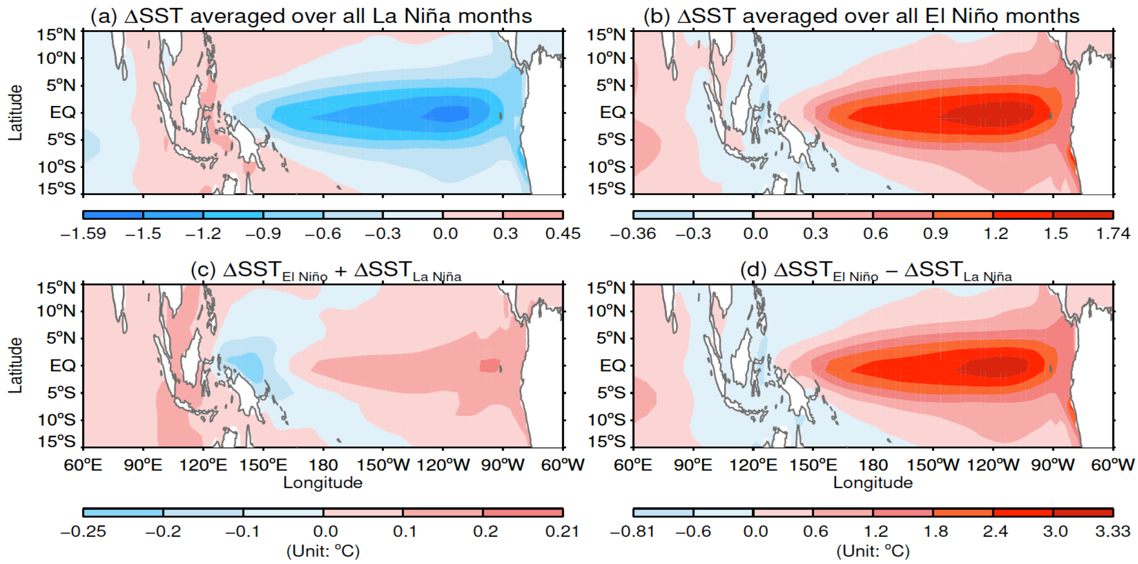

Fig. 8. Ensemble mean of the composite SST anomalies averaged over all La Niña (a) and El Niño (b) months respectively over the 1871–2013 period, their sum (c) and difference (d) simulated by the Coupled–NINT–AP model.

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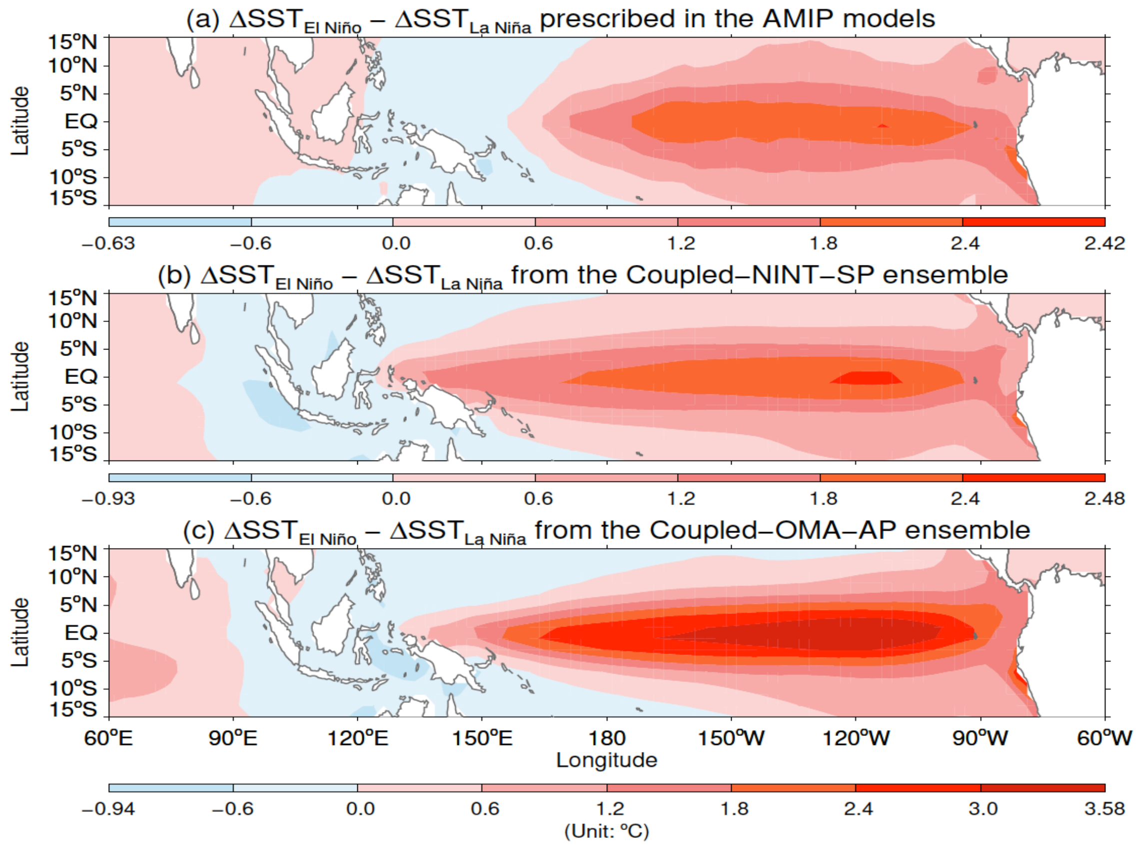

Fig. 9. Difference in the composite SST anomalies between El Niño and La Niña over the 1871–2013 period specified in the AMIP–OMA–SP and AMIP–OMA–AP models (a) and ensemble mean difference in the composite SST anomalies between El Niño and La Niña over the 1871–2013 period simulated by the Coupled–NINT–SP (b) and Coupled–OMA–AP (c) models.

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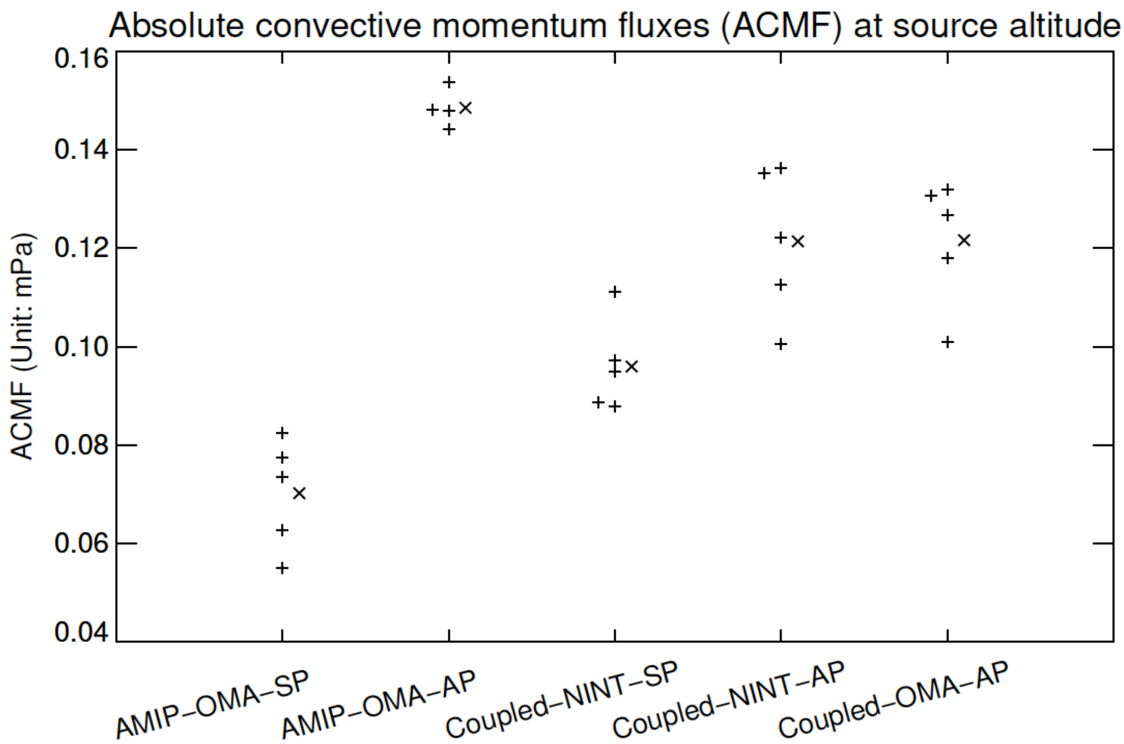

Fig. 10. Difference in the composite ACMF anomalies at the source altitude averaged over the 5°S – 5°N latitudinal belt between El Niño and La Niña over the 1871–2013 period. Plus symbol (+) denotes the difference from individual runs while cross symbol (×) represents each ensemble mean difference. Some symbols are slightly shifted leftward or rightward to avoid overlapping with other symbols.

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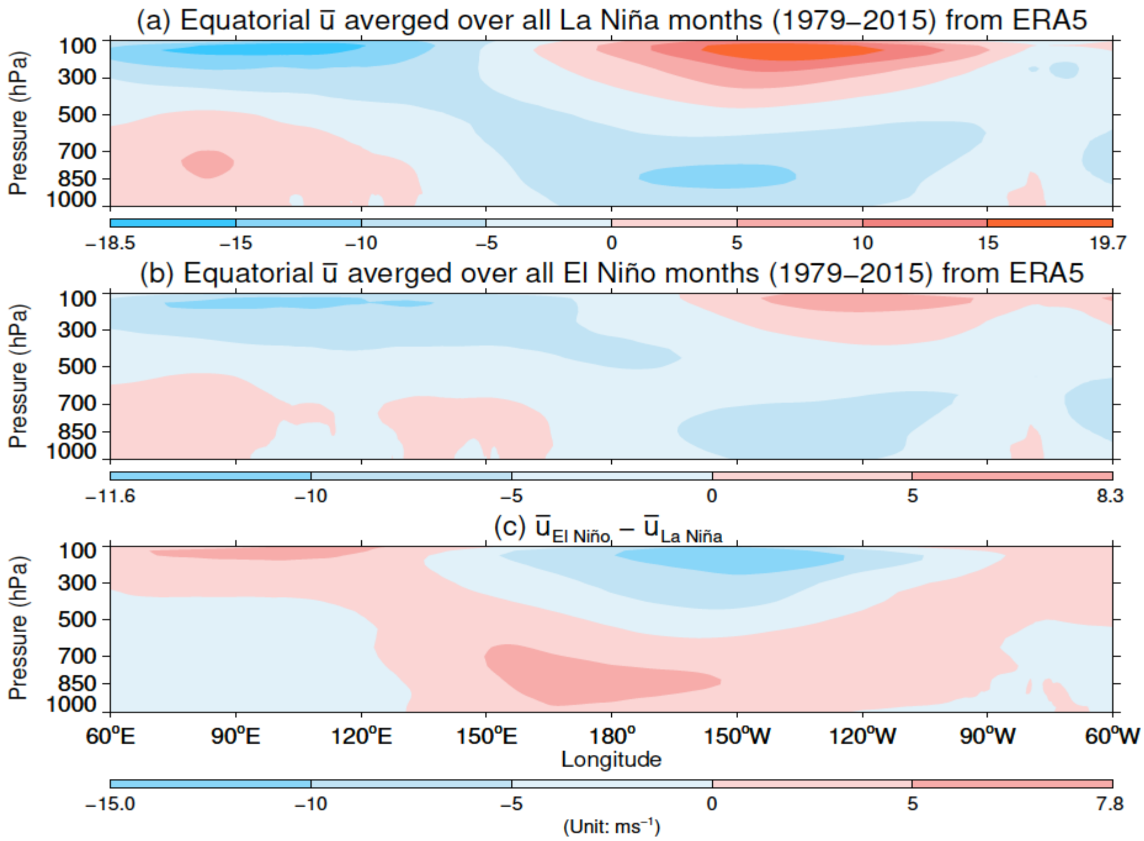

Fig. 11. Zonal winds from ERA5 averaged from 5°S to 5°N that are further averaged over all La Niña (a) and El Niño (b) months between 1979 and 2015 respectively, and their differences (c).

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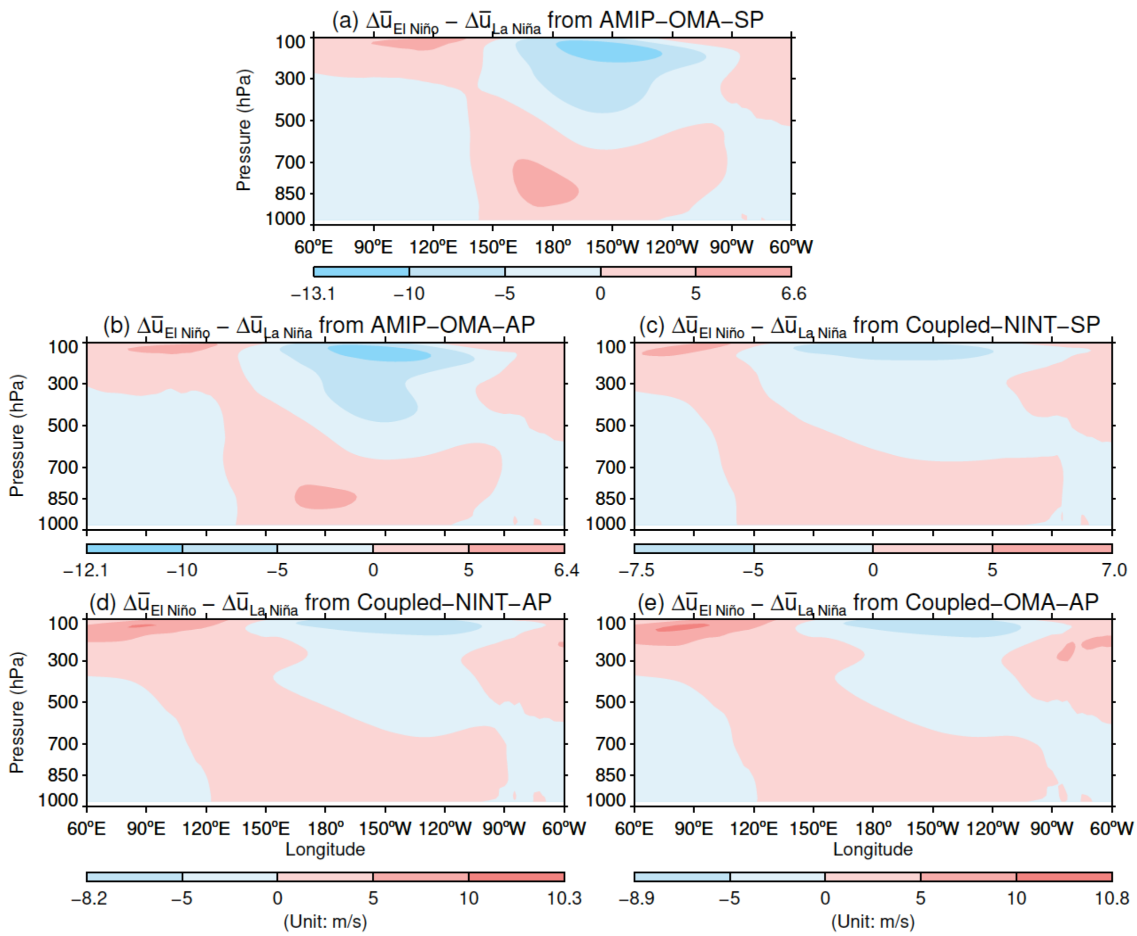

Fig. 12. Same as Fig. 11c but for the ensemble averages of the composite difference in zonal wind anomalies between El Niño and La Niña simulated by AMIP–OMA–SP (a), AMIP–OMA–AP (b), Coupled–NINT–SP (c), Coupled–NINT–AP (d), and Coupled–OMA–AP (e).

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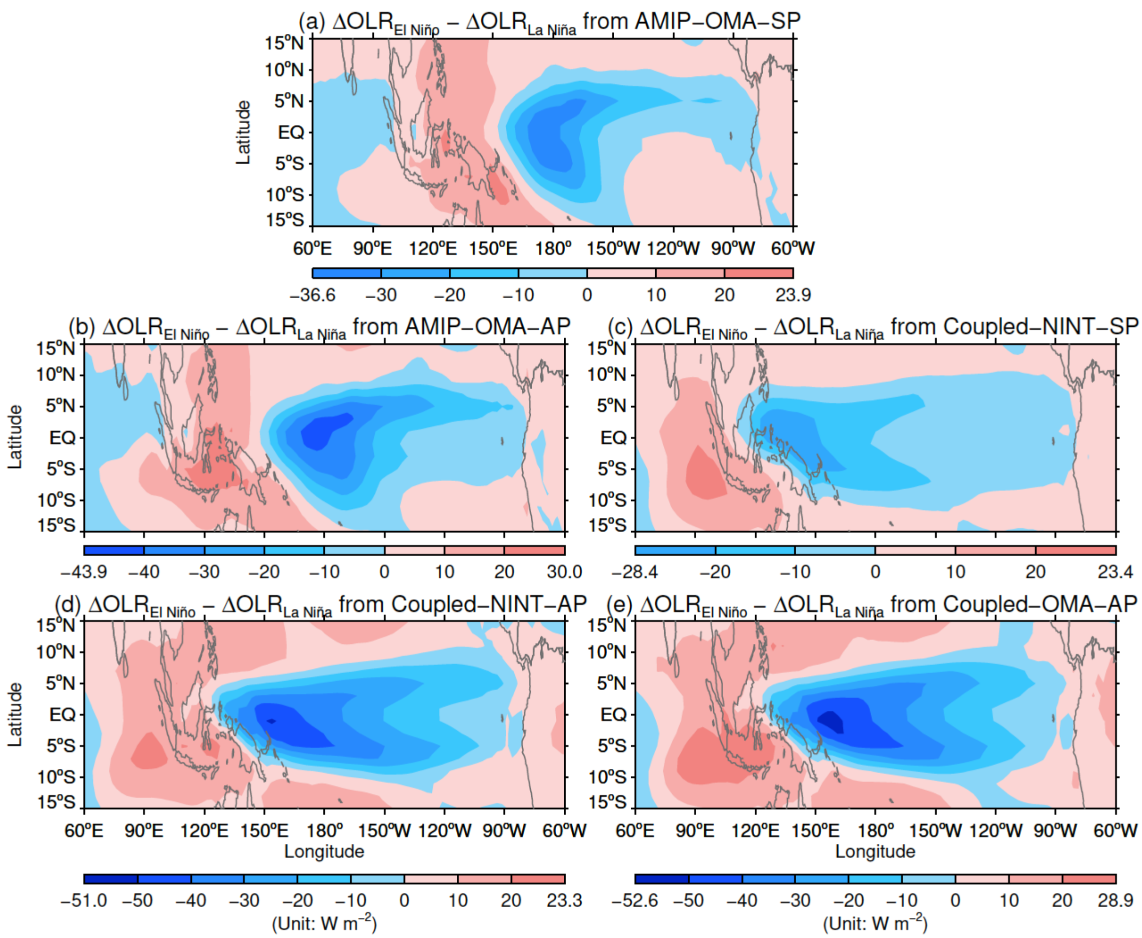

Fig. 13. Same as Fig. 12 but for the ensemble averages of the composite difference in OLR anomalies between El Niño and La Niña simulated by AMIP–OMA–SP (a), AMIP–OMA–AP (b), Coupled–NINT–SP (c), Coupled–NINT–AP (d), and Coupled–OMA–AP (e).

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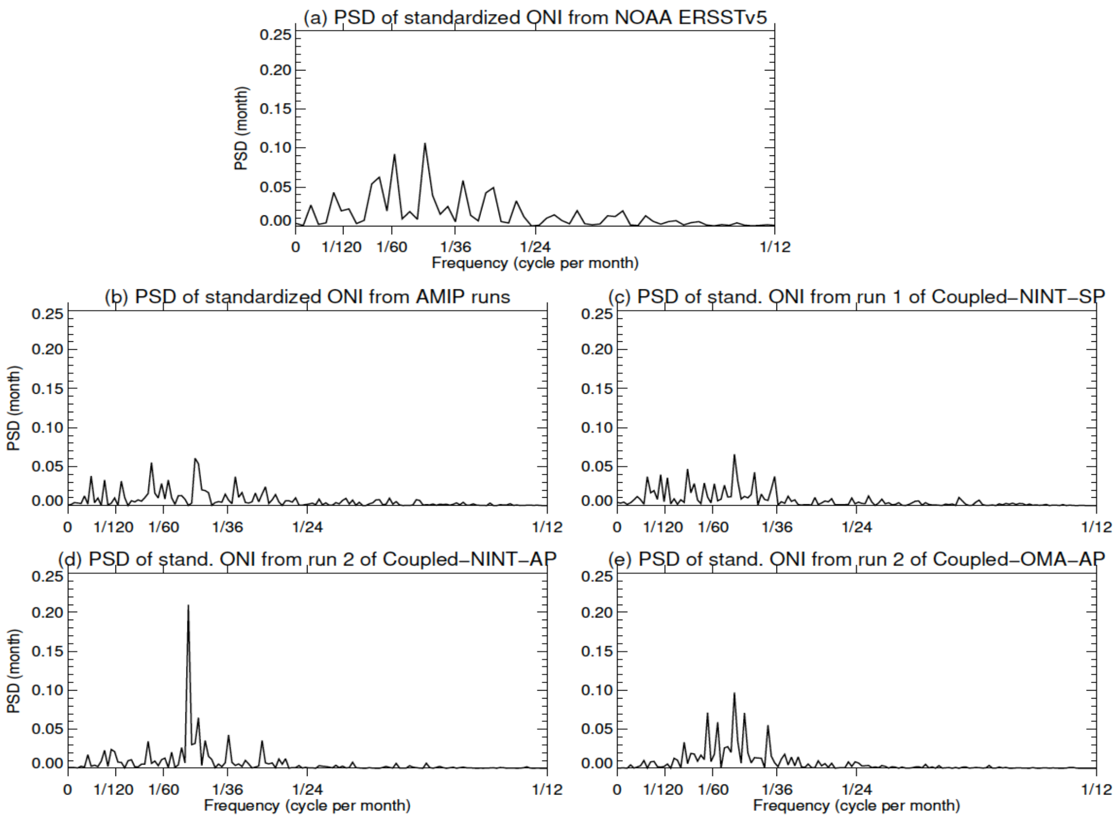

Fig. 14. Power spectral densities (PSD) of the standardized ONI between 1953 and 2015 derived from the NOAA ERSSTv5 SST (a), of standardized ONI between 1871 and 2013 derived from the HadISST1 dataset (b), of standardized ONI between 1871 and 2013 simulated by the first realization of Coupled–NINT–SP (c), and of those from the second realizations of Coupled–NINT–AP (d) and Coupled–OMA–AP (e).