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QBOi El Niño Southern Oscillation experiments: Assessing relationships between ENSO, MJO, and QBO

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Abstract. This study uses an ensemble of climate model experiments coordinated by the Quasi-Biennial Oscillation initiative (QBOi) to analyze the Madden-Julian Oscillation (MJO) in the presence of either perpetual El Niño or La Niña sea surface temperatures during boreal winter. In addition to the prescribed El Niño Southern Oscillation (ENSO) conditions, the nine models internally generate QBOs, meaning each may influence the MJO. The diagnostics used include wavenumber-frequency spectra of tropical convective and dynamical fields, measures of MJO lifetime, an evaluation of MJO diversity and visualization of MJO vertical structure, as well as an assessment of QBO morphology and the QBO's impact on tropical convection. Kelvin wave spectral power increases in the El Niño simulations whereas equatorial Rossby waves power is stronger in the La Niña simulations. Consistent with the reported relationship between these waves and the MJO, all models simulate faster MJO propagation under El Niño conditions. This change in speed is corroborated by the MJO diversity analysis, which reveals that models better reproduce the observed "fast propagating" and "standing" MJO archetypes given perpetual El Niño and La Niña, respectively. Regardless of ENSO, QBO descent into the lower stratosphere is underestimated and we detect little QBO influence on tropical tropopause stability and MJO activity. With little influence from the QBO on the MJO activity in these runs, we can be confident that the aforementioned changes in the MJO indeed arise from the different ENSO boundary conditions.

1 Introduction

The tropical circulation is influenced by various forms of internal variability, each operating at different timescales, yet still influencing each other. The Madden-Julian Oscillation (MJO) is dominant at intraseasonal timescales (Madden and Julian 1994; Lin, 2022). It consists of large-scale eastward propagating fluctuations in tropical precipitation and circulation that traverse the Indian Ocean and Maritime Continent through to the Pacific over roughly 30 to 60 days (Hendon and Salby 1994). MJO variability fluctuates a lot year to year as does other variability in the climate system. At interannual timescales, the El Niño Southern Oscillation (ENSO; Philander, 1990) is one of the most important sources of tropical tropospheric variability. It is characterized by shifting patterns of sea surface temperatures (SSTs) and associated changes in ocean and atmospheric circulations in the tropical Pacific. ENSO varies on timescales between two to seven years, and consists of three phases, the warm El Niño, the cold La Niña and a "neutral" phase where neither polarity dominates. Also operating at interannual timescales is the Quasi Biennial Oscillation (QBO), which is the dominant mode of variability in the lower tropical

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stratosphere, defined by alternating easterly and westerly shear zones descending from 5 to 100 hPa with an average periodicity of 28 months (Baldwin et al. 2001).

The three described oscillations, ENSO, QBO, and MJO, have been shown to influence each other in multiple ways. ENSO's La Niña and El Niño phases are associated with shifts of intraseasonal tropical atmospheric variability like the MJO towards the Indo-Pacific Warm Pool and Date Line, respectively (Kessler 2001; Tam and Lau 2005). In addition, ENSO can influence the amount of time the MJO spends in particular Wheeler and Hendon (2004) MJO phases and the duration of MJO events overall, which are shorter during El Niño and longer during La Niña (Pohl and Matthews 2007; Pang et al. 2016; Wei and Ren 2019; Wang et al. 2019; Dasgupta et al. 2021; Fernandes and Grimm 2023).

Despite these apparent sensitivities of the MJO to ENSO, there is also convincing evidence that the relationship between seasonal mean MJO activity and ENSO is weak (Lin 2022). Slingo et al. (1999) found that the observed intraseasonally filtered zonal mean 200 hPa zonal wind (their metric of "MJO activity") is weakly dependent on ENSO phase. They affirmed this further by using an ensemble of AMIP simulations. Hendon et al. (1999) validated and refined their definition of MJO activity, finding it to capture the salient features of the MJO and again that its variability is mostly independent of ENSO. These results also align with those of Newman et al. (2009) who showed that air-sea coupling has a small effect on intraseasonal atmospheric variability in empirical models that run with and without atmosphere-ocean interaction. With these results in mind, it is less clear how the MJO should respond to the ENSO conditions prescribed in our simulations. In fact, a common idea amongst the studies just mentioned is that the MJO's interannual variability originates predominantly from internal atmospheric processes other than those associated with ENSO.

It is increasingly recognized that the easterly and westerly phases of the QBO exert an influence on the MJO (Yoo and Son, 2016; Son et al. 2017; Sakaeda et al. 2020; Martin et al. 2021; Jin et al. 2023; Huang et al. 2023). The MJO's amplitude is stronger during easterly QBO boreal winters compared to westerly QBO winters over the observed record since 1979 (Yoo and Son 2016; Densmore et al. 2019). However, despite improvement in the representation of simulated QBOs (Richter et al. 2020) and MJOs (Ahn et al. 2020) across model generations, current Earth system models generally do not simulate the QBO-MJO relationship (Kim et al. 2020; Lim and Son 2020; Martin et al. 2023), nor do they simulate a sufficiently strong tropical tropopause response to the QBO (Serva et al. 2022). Attempts to understand this deficiency are further complicated by a curious tendency for easterly QBO boreal winters to overlap with La Niña winters during the short observational record (Randall et al. 2023). For this reason, more process level understanding of how the ENSO and the QBO influence the MJO is needed, which we pursue here using unique coordinated model experiments.

We examine the influence of ENSO and the QBO on the MJO using a multi-model ensemble of experiments with perpetual El Niño and La Niña conditions in nine global models that internally generate QBOs. These simulations were coordinated by

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the Atmospheric Processes And their Role in Climate (APARC, previously "SPARC") Quasi-Biennial Oscillation initiative (QBOi), which seeks to improve the fidelity of tropical stratospheric variability in general circulation and Earth system models through coordinated multi-institutional climate model experiments (Butchart et al. 2018). The perpetual-ENSO experiments used here are a continuation of the QBOi Phase 1 experiments and have companion studies that examine ENSO's effect on the QBO (Kawatani et al., in preparation) and the combined influence of ENSO and the QBO on global teleconnections (Naoe et al., in preparation).

2 Methods

2.1 Experimental setup

Butchart et al. (2018) established a set of simplified modeling experiments for Phase 1 of the QBOi. Their Experiment 2, the "present-day time slice" simulation, forms the basis for these perpetual ENSO simulations. It was designed to allow for an evaluation of the accuracy of modeled QBOs under present-day conditions, that is, how the model QBOs operate in a climate forced with fixed repeating annual cycles of global sea surface temperature (SSTs), sea ice concentration (SIC), and external forcings representative of the time averaged 1988-2007 state.

The perpetual ENSO runs analyzed here are equivalent to Experiment 2, but with global El Niño or La Niña SST anomalies superimposed on top of the climatological SST forcing. An assessment of the MJO is not conducted for Experiment 2 because essential variables such as daily horizontal winds, outgoing longwave radiation (OLR), and precipitation, were not archived. In creating the composite El Niño or La Niña forcings, the characterization of ENSO follows the Japan Meteorological Agency (JMA) convention, where ENSO is defined by the spatially averaged NINO.3 (5°S-5°N,150°W-90°W) monthly SST anomalies from 1950-2016. Anomalies are defined as deviations from the climatological seasonal cycle and computed relative to the most recent sliding 30-year period of JMA COBE-SST version 1 data (JMA, 2006). The anomalies are smoothed using a five-month running mean and the periods during which the anomalies exceed 0.5°C (-0.5°C) for at least six consecutive months are labeled as El Niño (La Niña) periods. However, after averaging the SST anomalies for all El Niño Januarys, Februarys, etc., and doing the same for La Niña, the composite average annual cycles of El Niño and La Niña SSTs show only modest amplitudes (e.g., 1.92 °C for El Niño Januarys). To amplify the atmospheric response to ENSO in the simulations, the annual cycles are multiplied by 1.8 and 1.4, respectively, making their amplitudes comparable to the strongest observed ENSO events. A similar scaling is applied to the corresponding global signatures in NINO.3 SST anomalies (Fig. 1), which are superimposed on 1988–2007 climatological SSTs and prescribed in the models. Note that this procedure does not completely capture the development, mature phase, and decay of all observed El Niño events, due to diversity in the evolutions of events.

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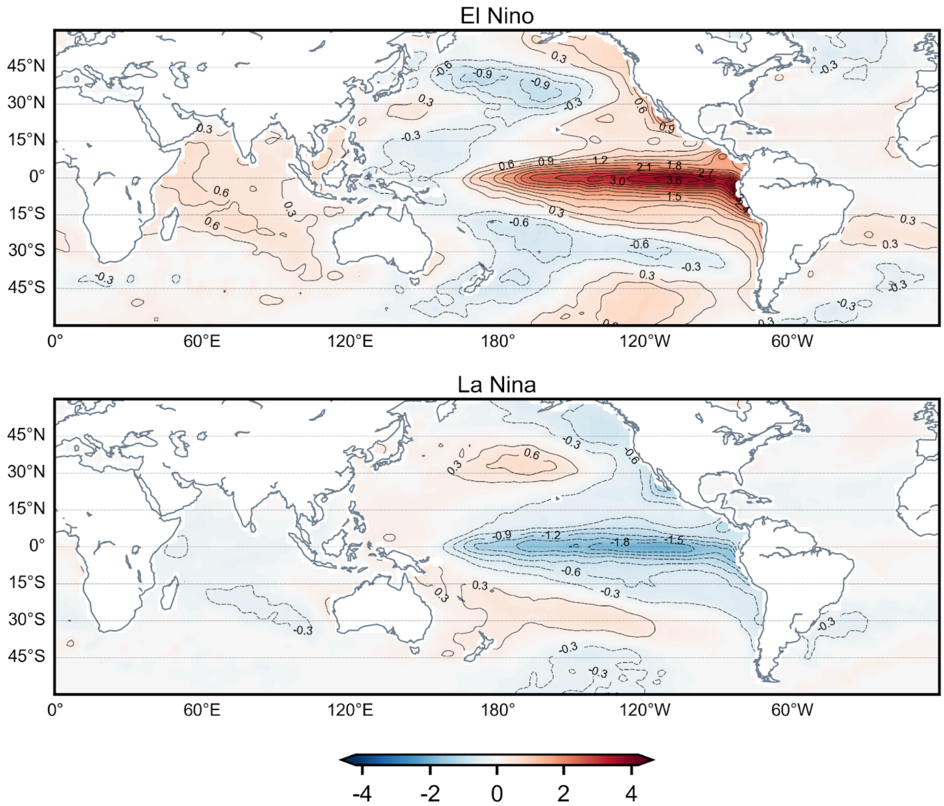

Figure 1: November-April composites of the El Niño and La Niña JMA COBE SST anomalies that are prescribed in the perpetual ENSO simulations.

In addition to the prominent El Niño and La Niña signals, the November-April (NDJFMA) SSTs shown in Figure 1 include the signatures of the basin-scale Interdecadal Pacific Oscillation (IPO) (Henley et al. 2015) and Indian Ocean SSTs that are in phase with ENSO. In some regions like the tropical Pacific and Indian Oceans, the amplitude of the global SSTs associated with the El Niño (Fig. 1b) are roughly double that of La Niña (Fig. 1a).

2.2 Models

Table 1: The models used in this study, the number of years per simulation, and some relevant literature. Only one realization is used from each model.

Model	Number of years	Convective parameterizations
EC-EARTH3.3	101	Bechtold (2014)

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ECHAM5sh	40	Tiedkte (1989), Nordeng (1994)
EMAC	106	Tiedkte (1989)
LMDz6	80	Emanuel (1991), Hourdin et al. (2013)
GISS-E2-2-G	30	Rind et al. (2020); Kelley et al. (2020)
MIROC-AGCM-LL	100	Pan and Randall (1998); Emori et al. (2001)
MIROC-ESM	100	Pan and Randall (1998); Emori et al. (2001)
MRI-ESM2.0	50	Yukimoto et al. (2019)
CESM1(WACCM5-110L)	101	Zhang and McFarlane (1995)

The models considered in this work are listed in Table 1 along with the number of years analyzed for each model and references on each model's convective parameterization. These parameterizations impact the representation of tropical phenomena (Holt et al. 2020; Kawatani et al., in preparation), including the simulation of intraseasonal oscillations (Ham and Hong, 2013). For example, past sensitivity tests with the version of MIROC-ESM that we use here have shown that its cumulus parameterization struggles to simulate an MJO of realistic amplitude with capability to propagate over the Maritime Continent (Miura et al. 2012). The updated scheme (Chikira and Sugiyama 2010) in use in newer versions of the model, MIROC6, has helped ameliorate these issues (Ahn et al. 2017; 2020). The importance of simulated convection-circulation coupling has been identified for other models (Kim et al. 2014; Zhu et al. 2020; Wang et al. 2022).

2.3 Observation-based reference data

To be consistent with previous studies (Wei and Ren 2019), the ENSO-MJO relationship is considered during November to April. The six observed La Niña years, where the year is associated with November, are 1970, 1984, 1988, 2017, 2020, and 2021 and the eight El Niño years are 1968, 1982, 1986, 1991, 1997, 2009, 2015, 2018. Each corresponds to an instance when the smoothed NINO.3 anomalies exceed +/- 0.5C for at least six consecutive months. For comparison with the models, the subsequent analyses include "observed" El Niño and La Niña composites, formed by averaging deseasonalized 1959-2022 ERA5 reanalysis (Hersbach et al. 2020) over the aforementioned years. These El Niño and La Niña composites are not scaled by factors of 1.8 and 1.4, respectively, in contrast to the ENSO SSTs prescribed in the simulations. Hence the ERA5 responses are expected to be more modest in amplitude compared with responses from the models. However, the difficulties that the models have simulating the MJO in some respects can render this untrue in practice.

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Building on the analysis of the ENSO-MJO relationship, it is also important to consider other atmospheric phenomena such as the QBO. The QBO-MJO relationship in the models is analyzed during December through February for consistency with previous studies (e.g., Son et al. 2017).

2.4 MJO analyses

We implement a number of widely-used methods to evaluate the MJO in the perpetual ENSO simulations. In the interest of exploring changes to MJO lifetime by ENSO phase as well as visualizing the MJO's vertical structure, we compute Real-time Multivariate MJO indices (RMMs) for each perpetual ENSO simulation using the same methodology as Wheeler and Hendon (2004, WH04). The RMMs are derived from a combined empirical orthogonal function (EOF) analysis of tropically averaged (15°S-15°N) anomalous daily outgoing longwave radiation (OLR), 200-hPa zonal wind (U200), and 850-hPa zonal wind (U850). As in WH04, we deseasonalize, remove interannual variability, and normalize the anomalies by their global variance. To enable a fairer comparison between the models and reanalysis, we project the anomalous model fields onto the 1959-2022 ERA5 WH04 EOFs; projecting onto each model's respective ENSO simulation instead does not change the conclusions. Daily OLR and U200 were not available for two models (GISS-E2-2-G and LMDz6) so their RMMs are computed using U250 and U850. The number of MJO events within a given data set is tallied like in Pohl and Matthews (2007) by counting the number of times the MJO makes a complete rotation through its RMM1 and RMM2 phase space. Average lifetime and MJO amplitudes ($\sqrt{RMM1^2 + RMM2^2}$) are computed across events. To visualize the MJO's vertical structure, latitudinally averaged 10°S-10°N longitude-pressure cross-section of zonal wind and temperature are projected onto the RMMs using the same steps as Hendon and Abhik (2018), but applied across ENSO years in the present study rather than QBO years.

The MJO is also visualized using two slightly different wavenumber-frequency filtering analyses. The first, available via the MJO US Climate Variability and Predictability (CLIVAR) metrics package (Waliser et al. 2009), is computed by Fourier transforming in time and longitude deseasonalized, tapered, and centered November-April segments of tropical OLR and U850, reorganizing the Fourier coefficients for eastward and westward disturbances (Hayashi 1982) and computing power, Figures 3 and 4 respectively. The second filtering technique is broadly similar, but specializes in resolving convectively coupled waves in addition to the MJO (Wheeler and Kiladis 1999). Prior to this analysis, the multi-year daily-mean fields from ERA5 and each model are linearly detrended, high pass filtered for intraseasonal variability using a 96-day cutoff, grouped into 96-day segments that share 65 days of overlap with neighboring segments, and each segment is linearly detrended and tapered. Successive discrete Fourier transforms are applied in longitude and time, the coefficients are reordered (Hayashi 1982), we retrieve the symmetric and antisymmetric components of a given field's spectra with respect to the equator and then divide each component by a smoothed background spectrum. The resulting power spectrum, shown as the ratio between raw symmetric daily-mean precipitation power and the background spectrum in Figure 2, reveals the modes of organized

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convection with the most power. Model spectra are divided by their respective perpetual ENSO backgrounds, whereas ERA5 El Niño and La Niña spectra are both compared to the 1959-2022 background; conclusions from ERA5 results are not sensitive to using respective El Niño or La Niña backgrounds.

We also implement an MJO diversity analysis in which MJO events are classified into distinct types based on their propagation characteristics using k-means clustering (Wang et al. 2019). Each MJO event is binned as one of four archetypes, "standing" or "jumping" MJOs, which propagate across the Indian Ocean, but are distinguished by reemergence of the MJO over the western Pacific during jumping events, and "slow" or "fast" MJOs, which both continuously propagate across the Maritime Continent, but at different speeds. An MJO event occurs when the 20-70 day bandpass-filtered OLR anomalies (from seasonal cycle) averaged over the equatorial Indian Ocean (10°S-10°N, 75°E-95°E) are smaller than negative one standard deviation for five successive days; the reference day (day 0) is the day of minimum OLR. The MJO events are categorized by a k-means clustering of the enhanced convective signal (OLR anomalies under -5 Wm^{-2}) of the latitudinally averaged 10°S to 10°N time-longitude OLR anomalies taken over 60°E to 180°E and over a 31-day period from day -10 to day 20. For brevity, we omit further diversity analysis methodological details, for which we refer the reader to Back et al. (2024) for all steps. However, it is important to note that unlike Wang et al. (2019), in which initial centroids for clustering are randomly chosen, initial centroids for model MJO events are set to those of the four observation-based clusters to minimize subjective decisions. Because of this step, herein the present study evaluates how well the climate models can reproduce the observed MJO diversity archetypes.

2.5 QBO and analyses

The space-time form of the QBOs varies from model to model as each is generated with different amounts of forcing from resolved waves and parameterized non-orographic gravity wave drag. Properties of these models that are particularly relevant for simulating the QBOs are listed in Butchart et al. (2018), details on QBO morphology (e.g., its amplitude, latitudinal width) given the observed SST record are presented in Bushell et al. (2022), and the relative contribution of resolved and parameterized tropical waves to forcing the QBO is analyzed in detail in Holt et al. (2020). Of note, MIROC-AGCM-LL's QBO is forced solely by resolved waves. As EC-EARTH and GISS-E2-EG did not contribute to some of the earliest QBOi analyses, relevant details on their internal QBOs can be found in Serva et al. (2024) and Rind et al. (2014, 2020), respectively. For a thorough analysis of how the QBO responds to the perpetual ENSO simulations, we refer the reader to Kawatani et al. (in preparation).

To help clarify the ability of the QBOs to interact with the MJOs, we use established metrics to characterize the morphology of the ERA5 and model QBOs. The main field used to document QBO morphology is the monthly zonal-mean zonal wind. "QBO cycles" (consecutive easterly/westerly phases) are identified by marking the first month when the deseasonalized and

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smoothed (5-month running mean) 20 hPa 5°S-5°N wind changes from westerly to easterly, ending one month before the next transition at 20 hPa (Kawatani et al. 2019). From these cycles, we calculate average QBO easterly, westerly, and total amplitudes using the QBO "transition time" methodology of Richter et al. (2020). The easterly (westerly) amplitude is equal to the average of the minimum (maximum) monthly QBO winds from each QBO cycle. The QBO cycles are used further to calculate minimum, mean, and maximum QBO periodicity statistics. These statistics are a key result of Kawatani et al. (in preparation) and are discussed thoroughly there. In short, the periodicity of the QBO decreases in all El Niño simulations and increases in all La Niña simulations. For the purposes of the present study, the minimum and maximum periodicities are required to evaluate the QBO's spatial structure, defined as the latitude-pressure cross sections of each data set's QBO Fourier amplitude. These are made by applying a discrete Fourier transform in time to the multi-year monthly zonal-mean zonal wind at each pressure-latitude grid point and dividing the sum of squares of the amplitudes of the harmonics corresponding to periods between the minimum and maximum QBO periods by the sum of squares of the amplitudes of all harmonics. This ratio is subsequently multiplied by the standard deviation of the zonal-mean zonal wind (Pascoe et al. 2005). Using this QBO Fourier amplitude, the lowest altitude the QBO reaches, its vertical extent (i.e., how tall it is), and its latitudinal extent are defined as in Schenzinger et al. (2017), except that here the QBO's maximum amplitude is assumed to be at 20 hPa for all models and ERA5.

The QBO's capability to impact the tropical tropopause and the MJO is further assessed using the techniques of Klotzbach et al. (2019) and Kim et al. (2020). Following the prior, we make scatterplots of December-February warm-pool (10°S-10°N, 45°E-180°E) averaged tropopause stability (100 hPa minus 200 hPa temperature) versus December-February MJO amplitude as a function of QBO phase (sign of DJF averaged 5°S-5°N 50 hPa zonal mean zonal-wind) for each of the simulations. MJO amplitude is expected to increase as tropopause stability decreases, which happens during the easterly QBO phase. As in Kim et al. (2020), MJO activity is also computed as a function of QBO phase. Specifically, MJO-filtered OLR is calculated following Wheeler and Kiladis (1999) with one exception, the full time series is detrended rather than using 96-day overlapping segments. To minimize spectral leakage, 5% of the data are tapered to zero at the ends of the timeseries. After tapering, a complex Fourier Transform is performed, and the spectral wavenumber-frequency data are filtered to retain only the eastward propagating coefficients for 20-100 day periods and wavenumbers 1-5. MJO activity is then defined as the standard deviation of the MJO-filtered OLR across all December-February days that fall into a particular category, for instance all years, easterly QBO years or westerly QBO years. For this analysis, easterly and westerly QBO years are defined as those which exceed +/- 0.5 standard deviation of the 50 hPa monthly zonal wind anomalies, seasonally smoothed and averaged over 10°S to 10°N. One may notice that the QBO is defined differently between the Klotzbach and Kim et al. analyses. Herein, we have prioritized using the aforementioned metrics in their original form rather than using customized metrics so as to have one uniform definition of, for instance, QBO phase.

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3 Results

3.1 ENSO-MJO coupling

Before examining the influence of ENSO on MJO, we evaluate some of the other large-scale tropical phenomena that the models simulate. Convectively coupled waves are relevant because they comprise the space-time structure of the MJO and can influence its propagation by modulating the tropical circulation and the distribution of moisture that the MJO encounters (Kiladis et al. 2009; Wang et al. 2019; Wei and Ren 2019; Berrington et al. 2022; Wang and Li 2022). Aspects of the waves, such as their phase speed, vary depending on the low frequency circulation (Roundy 2012). Hence, the amplification of the Walker Circulation by La Niña and the weakening of it by El Niño (Fig. S1) provide a pathway for the perpetual ENSO forcings to modulate the waves and perhaps the MJO. Applying similar methods to Wheeler and Kiladis (1999), we visualize the waves by computing the spectral power of ERA5 and model daily-averaged precipitation as a function of wavenumber and frequency. Figure 2 shows the precipitation spectra for phenomena symmetric about the equator, taken over November-April and 15°S-15°N. Three dispersion curves, as in Matsuno (1966), corresponding to equivalent depths of 10, 25, and 50 meters are also superimposed; these curves are derived using the dispersion relations for equatorially trapped waves and they are co-located with modes of organized convection, with larger equivalent depths corresponding to faster phase speeds.

Only six La Niña and eight El Niño events are used to make the ERA5 equivalent figures that are shown in row one, which coincides with these signals being noisy compared to the multi-decade averages from the models. Spectral signals associated with the eastward propagating Kelvin wave move up and to the right on each panel, spanning sub-planetary low frequency (~ k = 3, 25 days) scales to synoptic (k = 4+) sub-weekly scales. Relative to ERA5, the models underestimate the strength of the Kelvin wave and this happens irrespective of the type of ENSO forcing. Power associated with the westward propagating equatorial Rossby wave is evident on the left side of each panel between wavenumbers 1-10 and timescales of 10 days to five weeks. Overall, the models do a reasonable job of simulating the spectral amplitude of equatorial Rossby waves, although it is too strong for some models (EMAC, MIROC-ESM), especially in their La Niña simulations.

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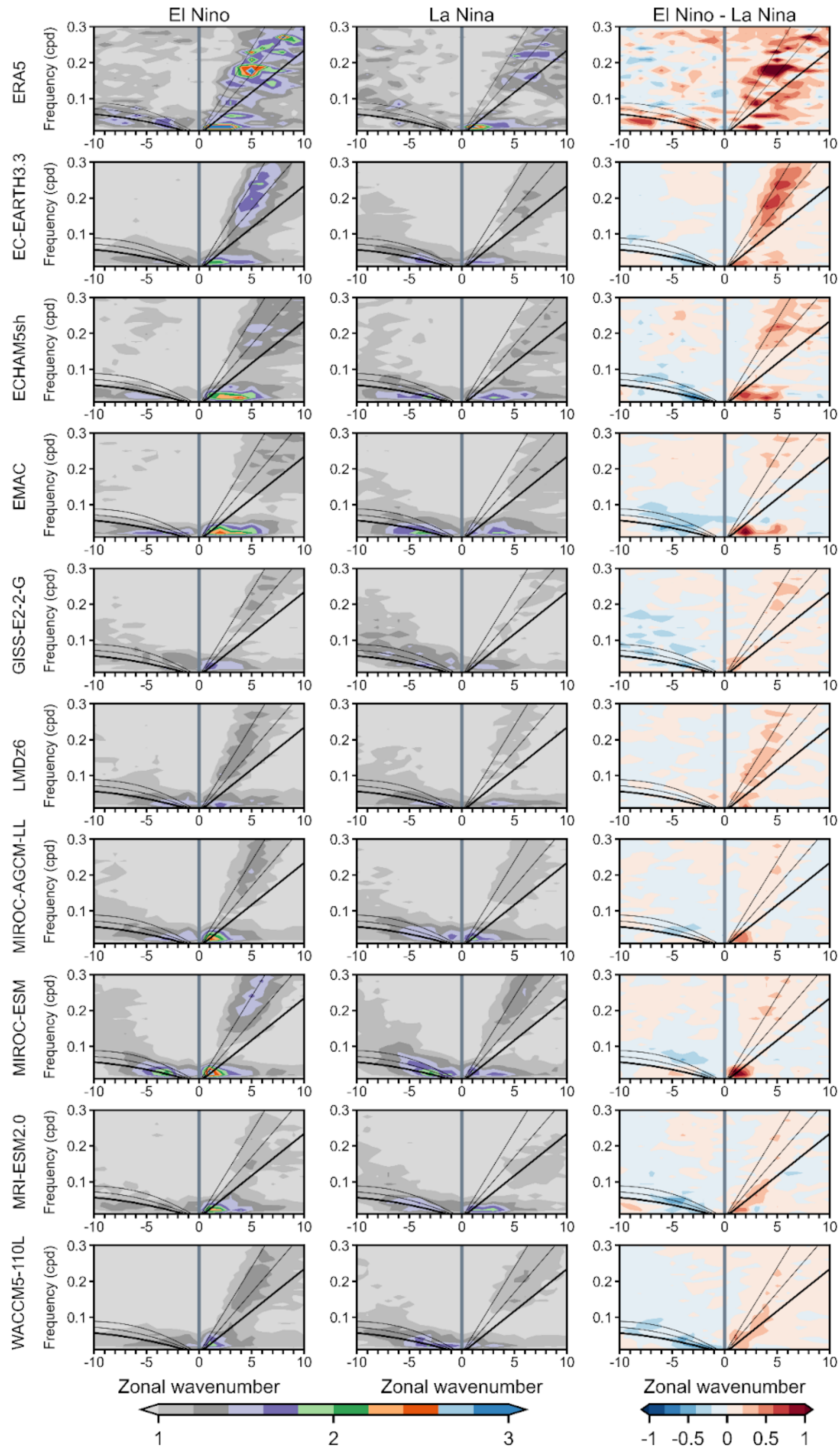
Figure 2: Wavenumber-frequency power spectrum of the symmetric component of 15°S-15°N November-April precipitation plotted as the ratio between raw symmetric precipitation power and a smoothed red noise background spectrum. The eastward (right) side of the spectrum includes three Kelvin wave dispersion curves in black, of which the thickest curve corresponds to the equivalent depth of 12 meters, and the other two correspond to 25 and 50 meters, respectively. Similar dispersion curve plotting conventions are used on the westward (left) side of the spectrum where the curves overlay the equatorial Rossby wave power. Column one corresponds to El Niño, column two to La Niña, and column three to their difference, which is computed as (El Niño symmetric minus El Niño background) minus (La Niña symmetric minus La Niña background). Computing the third column as (El Niño symmetric) minus (La Niña symmetric) yields similar conclusions (not shown).



The effect of ENSO phase on each wave is revealed by the rightmost column of Figure 2, which shows El Niño (column one) minus La Niña (column two) differences, where red means stronger power during El Niño and blue means larger power during La Niña. All models simulate stronger Kelvin waves in their El Niño simulation, particularly along the deeper equivalent depth (n = 25, 50 meters) dispersion curves. This implies faster Kelvin wave phase speeds during El Niño. Examining the El Niño column, the alignment of the Kelvin wave power along these particular curves is demonstrated by EC-EARTH3.3, GISS-E2-E-G, LMDz6, MIROC-AGCM-LL, MIROC-ESM, MRI-ESM2.0 and (CESM1) WACCM5-110L, hereafter just "WACCM5-110L." The remaining models, ECHAM5sh and EMAC (both ECHAM-based models), differ in that their El Niño Kelvin wave power is weighted towards higher zonal

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wavenumbers for frequencies below 0.2 cpd. Similar to the models, ERA5 shows large sporadic increases in Kelvin wave power along deeper equivalent depth dispersion curves during El Niño compared to La Niña. Agreement between ERA5 and the models is less clear when instead considering the westward propagating equatorial Rossby wave. All models simulate stronger equatorial Rossby wave power during La Niña. There is a tendency in some models for this to happen along the deeper equivalent depth dispersion curves (e.g., MIROC-AGCM-LL, MIROC-ESM).

Having found changes in the convectively coupled waves due to ENSO, perhaps the model MJOs are also modulated by ENSO. Broadly speaking, Figure 2 shows that the models do in fact include MJOs as indicated by the maxima in spectral power at intraseasonal timescales (<< 0.1 cpd) between eastward propagating wavenumbers 1-5. Holt et al. (2020) also found MJOs to be simulated by these models. The highest MJO power in ERA5 is concentrated between wavenumbers 1 and 3 irrespective of ENSO phase. EC-EARTH3.3, MIROC-AGCM-LL, MIROC-ESM, MRI-ESM2.0 are closest to reproducing this whereas ECHAM5sh, EMAC, and LMDz6 exhibit spectral power that is incorrectly shifted towards higher wavenumbers. The El Niño minus La Niña differences shown in the rightmost column of Figure 2 highlight that MJO spectral power is stronger in the presence of the El Niño basic state, predominantly between wavenumbers 2 and 3 in ERA5 and wavenumbers 1 and 2 across the majority of the models. Differing from the other models, EC-EARTH3.3, ECHAM5sh, and EMAC have fairly large El Niño minus La Niña MJO power differences at wavenumber 4 and 5.

Irrespective of ENSO phase, the amplitude of the model MJOs as shown in Fig. 2 is systematically weaker than in ERA5. This may have something to do with dividing each simulation's symmetric power by its respective background power, the latter of which is contaminated, in a sense, by the perpetual ENSO conditions. Note that recomputing the third column of Fig. 2 without dividing each El Niño and La Niña composite by their respective background does not change our conclusions (not shown). To get around this potential issue with the background power and further inspect the model MJOs as opposed to the convectively coupled waves, in Figures 3 and 4 we consider the westward and eastward wavenumber-frequency spectra of OLR and U850, respectively, taken over the intraseasonal timescale and over MJO-like zonal wavenumber scales. These analyses yield more holistic views of the MJO than in Fig. 2 because they incorporate the MJO's signals in these fields that are both symmetric and antisymmetric about the equator.

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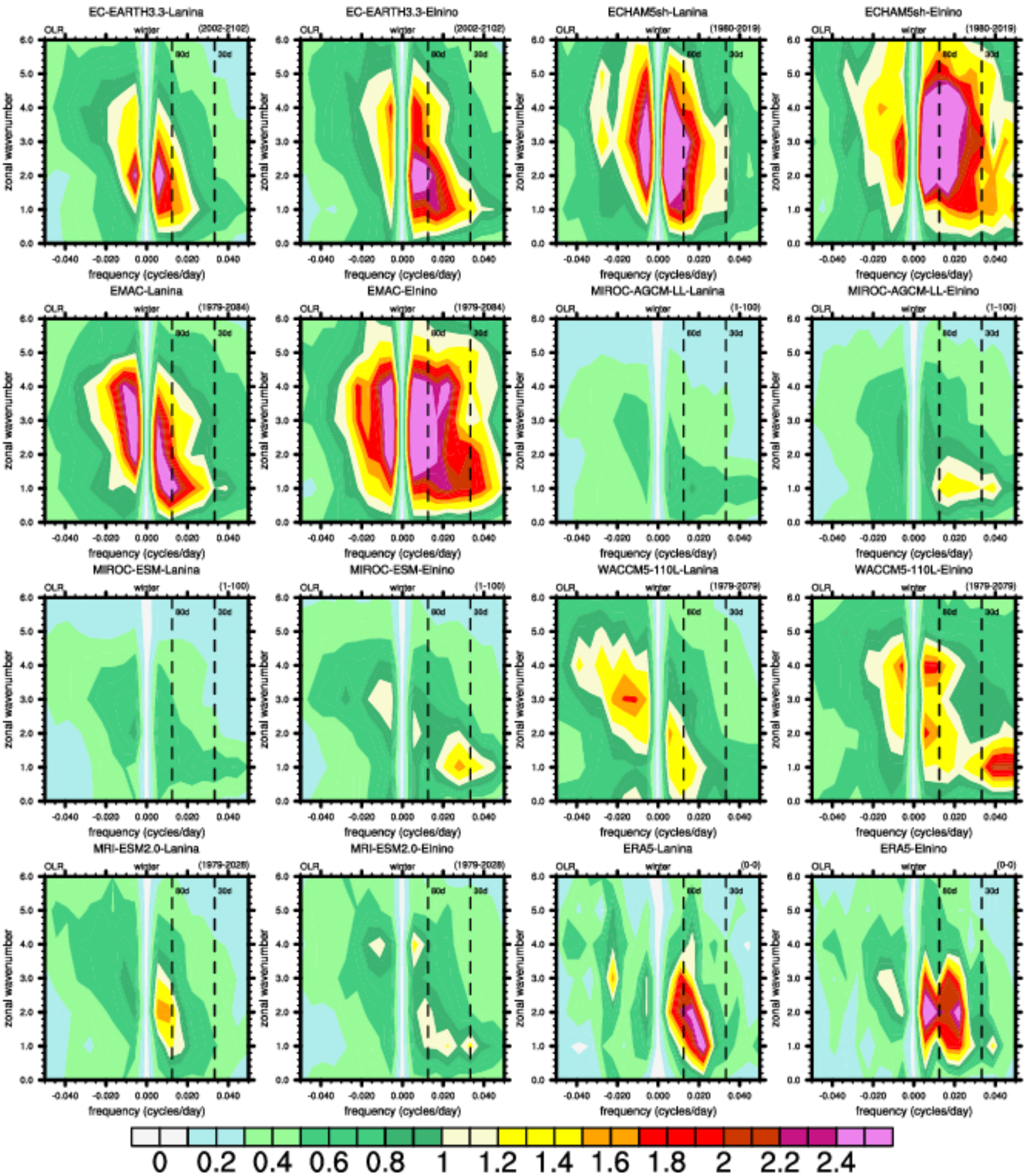

Figure 3: November-April wavenumber-frequency power spectra of 10°S-10°N averaged OLR. Units of the OLR spectrum are W^2/m^4 per frequency interval per wavenumber interval.

Observed variance associated with convective fields like OLR predominantly spans zonal wavenumber 1-3 and frequencies corresponding to periodicities of 1-3 months (Hendon and Salby 1994). Independent of the ENSO phase, ERA5's wavenumber-frequency shows the highest power between wavenumbers 1-3 and frequencies of 30-80 days (vertical dashes),

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a so-called "MJO band" (Ahn et al. 2017). Considering only the MJO band, the MJO is stronger given lower zonal wavenumbers and longer periodicities during La Niña compared to El Niño. Despite La Niña having higher power at lower frequencies within the MJO band, it is actually El Niño that has larger spectral power beyond 80 days, which we conjecture reflects the diversity of El Niño's influence on the MJO (Wei and Ren 2019). There is also strong power at frequencies corresponding to periods of 181 days, especially in the ERA5 El Niño composite, which is likely an artifact of using 181-day NDJFMA segments for this analysis.

There are notable differences in the amplitude of the spectral power between each model and ERA5 for both El Niño and La Niña. Of the models, EC-EARTH3.3's MJO band amplitude is most similar to ERA5. MIROC-AGCM-LL, MIROC-ESM, and WACCM5-110L significantly underestimate the strength of the MJO in this metric whereas ECHAM5sh and EMAC both overestimate it. Another issue is that the models consistently exhibit too large of an MJO signal for zonal wavenumbers three and up, which is unrealistic and common amongst GCMs (Ahn et al. 2017). When MJO power is considered as a function of ENSO phase, all models show that the MJO is stronger during El Niño, especially near the high frequency portion of the MJO band.

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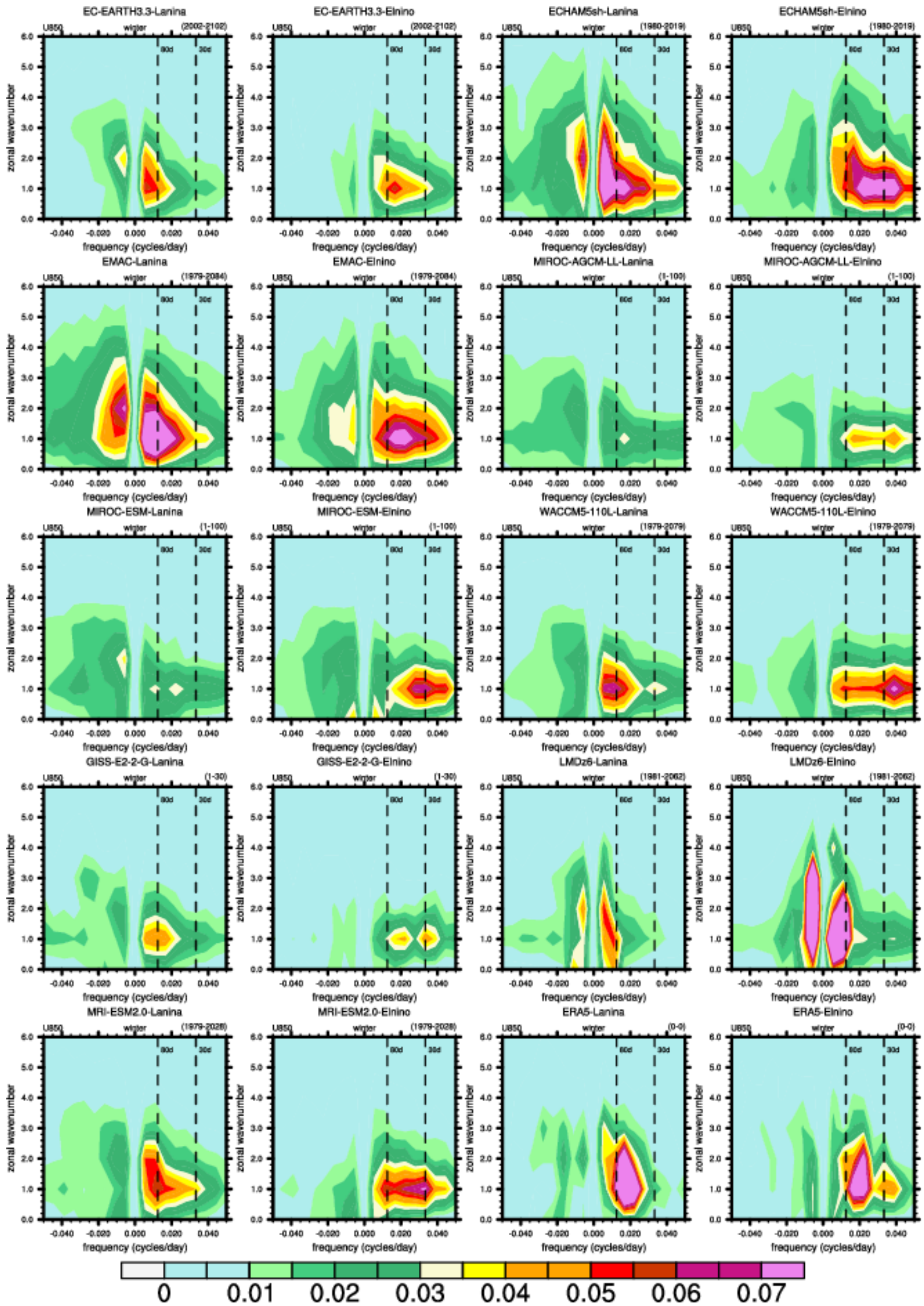

Figure 4: Same as Figure 3, but for U850 across all nine models and ERA5.

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As shown by ERA5, the MJO timescale variance of dynamical fields such as U850 is known to have a much narrower spectral peak around zonal wavenumber-1 (Fig. 4). The models are fairly good at reproducing this. Using U850 allows us to incorporate output from GISS-E2-2-G and LMDz6 for which OLR data is not available. Notwithstanding some of the typical model issues (e.g., amplitude differences compared to observations, and overly large power at high wavenumbers especially in ECHAM5sh, EMAC, and LMDz6), Figure 4 like Figure 3 indicates that the periodicity of the MJO decreases during El Niño and increases during La Niña. The robustness of these results is considered further by using the PM07 MJO statistics including MJO lifetime, which are tabulated in Table 2.

Table 2: The number of MJO events, their mean lifetimes and standard errors (reported in parentheses), and their mean amplitudes given either perpetual El Niño or La Niña conditions in a model. An asterisk (*) next to a model name indicates that the RMMs were retrieved using only 250 and 850 hPa zonal wind. Different from the models, for ERA5, MJO event statistics are calculated using 8 El Niño and 6 La Niña winters subsampled from the entire 1959-2022 RMM record.

	EN events (#/dec)	LN events (#/dec)	EN lifetime (days)	LN lifetime (days)	EN amplitude	LN amplitude
ERA5	25	22	38.25 (2.27)	47.07 (3.97)	1.36	1.41
EC-EARTH3.3	18.07	13.80	37.96 (1.25)	46.73 (2.01)	1.47	1.40
ECHAM5sh	26.20	15.87	28.59 (1.18)	42.94 (3.26)	1.43	1.38
EMAC	23.83	14.75	29.77 (0.88)	45.57 (1.93)	1.37	1.45
GISS-E2-2-G*	20.56	11.46	32.23 (1.87)	37.06 (3.50)	1.42	1.31
LMDz6*	11.30	9.81	37.01 (2.20)	32.47 (1.69)	1.55	1.41
MIROC-AGCM-LL	23.48	19.26	30.31 (0.78)	30.90 (1.11)	1.46	1.49
MIROC-ESM	27.77	18.15	27.96 (0.57)	29.90 (1.15)	1.38	1.34
MRI-ESM2.0	21.53	16.70	35.02 (1.39)	39.35 (1.88)	1.43	1.40
WACCM5-110L	26.00	16.87	27.13 (0.77)	36.99 (1.31)	1.40	1.49

Based on ERA5, La Niña events are roughly nine days longer than El Niño events on average. Wei and Ren (2019) found La Niña to support both high-frequency (lifetime ~40 days) and low frequency (lifetime ~80 days) MJOs, which conceivably explains the much larger ERA5 lifetime standard errors during La Niña compared with El Niño. Strikingly, the difference in lifetime and its standard error between ENSO phases is nearly ubiquitous across the models. With the exception of LMDZ6, La Niña lifetimes are between 0.59 (MIROC-AGCM-LL) and 15.8 (EMAC) days longer than El Niño lifetimes. Models in similar families, for instance ECHAM5sh and EMAC as well as MIROC-AGCM-LL and MIROC-ESM, typically have similar

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magnitude differences in their Pohl and Matthews (2007) statistics between ENSO phases. All models simulate more MJO events during El Niño, which is consistent with ERA5, however the difference in the number of events between ENSO phases is generally larger in the models than in ERA5. MJO amplitude is only marginally larger during La Niña based on ERA5 whereas six of the nine models have larger amplitudes during El Niño.

Analyzing MJO diversity can provide further insight into its speed and propagation. K-means clustering of MJO convection tracks from empirical OLR Hovmöller diagrams reveal four major MJO propagation archetypes: standing, jumping, slow propagating, and fast propagating events (Wang et al. 2019). Composites of the background SSTs associated with these archetypes show standing MJOs to be concurrent with La Niña, fast MJOs overlap with El Niño, and jumping and slow events have no clear association with either ENSO phase. The experimental setup here enables us to test if in fact some of the MJO archetypes predominate given a background ENSO forcing. Note that fast and slow events can occur during either ENSO phase and so there is at least some sensitivity of the previous results to sampling variability (Yadav and Straus 2017).

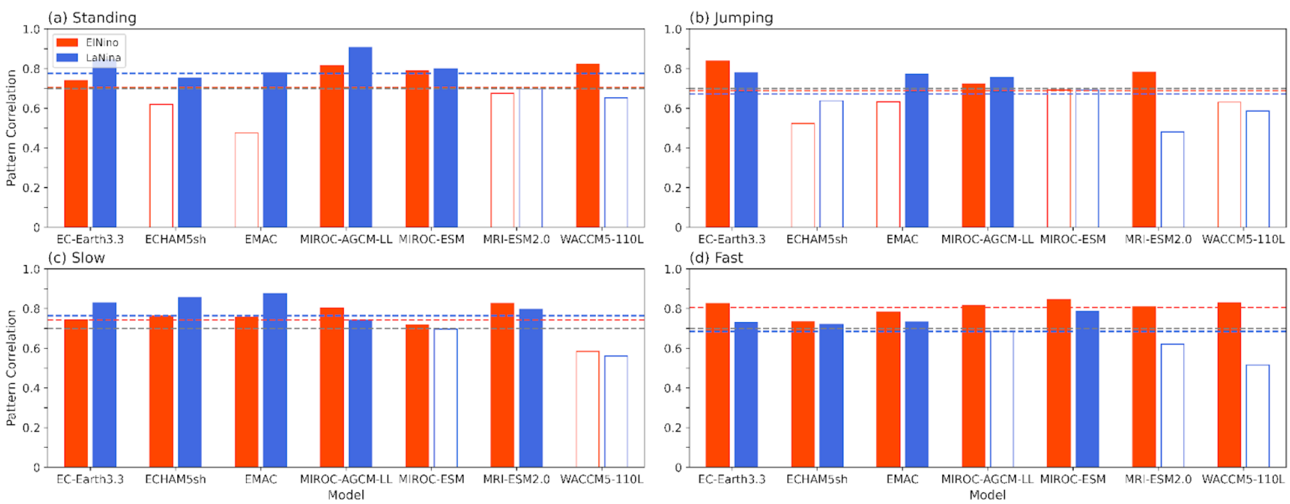

Figure 5: Pattern correlations between the ERA5 and simulated time-longitude (Hovmöller) 10°S-10°N convective OLR anomaly composites (OLR < -5 W/m^2) corresponding to each of the four K-means clusters MJO archetypes defined in Wang et al. (2019). Multi-model average El Niño and La Niña correlations are shown by red and blue dashed lines, respectively, and shaded (non-shaded) bars exceed (fall beneath) these multi-model means. The gray dashed line marked at a correlation of 0.7 is a heuristic threshold used here and elsewhere (Back et al. 2024) to decide when a particular model's MJO archetype is well captured by a model.

To gauge how similar the model archetypes are to those in reanalysis, pattern correlations are calculated between the ERA5 and model time-longitude tropical OLR convective anomaly composites corresponding to a given cluster. This measures how well the models represent the various observed MJO archetypes and helps to assess whether or not the representation of a given archetype improves in the presence of either ENSO forcing. Offline multi-model assessments of MJO diversity (Back et al. 2024) have revealed that a pattern correlation of 0.7 is a reasonable threshold to distinguish between good and poorly

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simulated OLR Hovmöllers. For the standing MJO (Fig. 5a), five of the 14 models have correlations below 0.7, hence we shade their bar white. Although the representation of the standing cluster is poor in roughly a third of the simulations, the representation of the standing MJO is notably better during La Niña, with the multi-model pattern correlation exceeding its El Niño equivalent by 0.09. The pattern correlation between the observed and simulated jumping MJOs falls beneath 0.7 for over half of the simulations, indicating that the models really struggle to represent this archetype (Fig. 5b). However, jumping MJOs are not currently thought to be influenced by ENSO and so are not considered further. Observations indicate that slowly propagating MJOs are typically concurrent with La Niña, however the associated SST pattern is weak and not statistically significant (Wang et al. 2019; Back et al. 2024). Similarly, we find the representation of slowly propagating MJOs to be slightly better amongst the La Niña simulations, but likely statistically indistinguishable from the El Niña correlations (Fig. 5c). In stark contrast, for fast events, every model's El Niño simulation represents this archetype better than the La Niña equivalent, culminating in the El Niño multi-model mean correlation exceeding the La Niña mean by 0.11 (Fig. 5d). In summary, the diversity analysis affirms that the fast and standing MJO archetypes are closely associated with El Niño and La Niña, respectively.

The vertical structure of the MJO differs between slow and fast propagating events (Wang et al. 2019). To consider this further, we regress the latitudinally averaged 10°S-10°N zonal wind and temperature from ERA5 and the models onto their phase 3/4 RMM indices as in Hendon and Abhik (2018) and form pressure-longitude cross-sections (Figure 6). Phases 3/4, when the MJO convection is over the western Maritime Continent, are of interest because ENSO modulates the low-frequency circulation here through its effect on the Walker Circulation, giving it a pathway to influence MJO propagation (Sun et al. 2019; Suematsu and Miura 2022). Irrespective of the ENSO phase, the MJO in ERA5 exhibits a quadrupole structure in zonal wind, all of which is centered around a tropospheric warming at 140°E that peaks in amplitude near 300 hPa (cf. Jiang et al. 2015).

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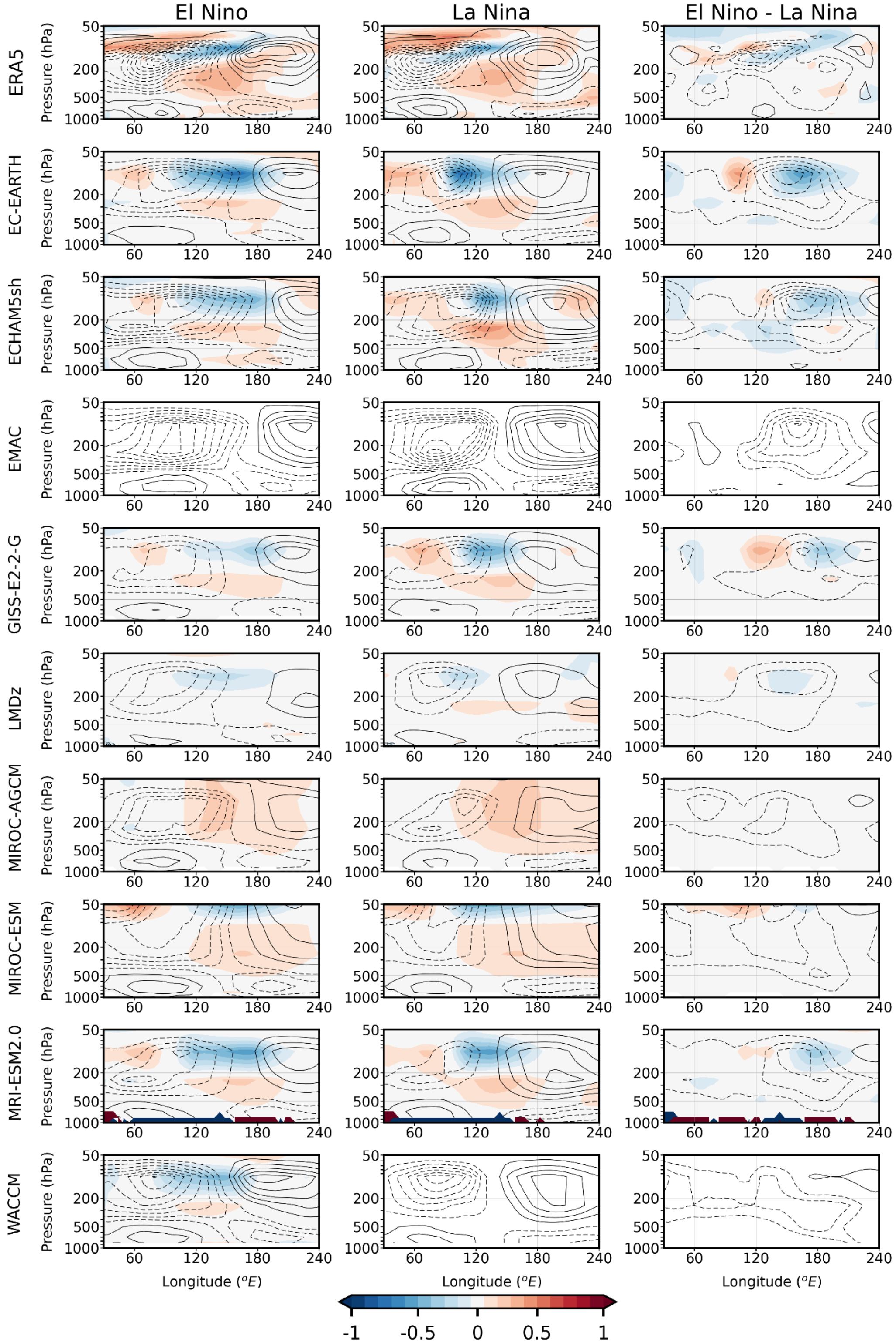

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Figure 6: Pressure-longitude cross-sections of the 10°S-10°N zonal wind and temperature regressed onto the Phase 3/4 RMMs as in Hendon and Abhik (2018). Black contours show zonal wind (intervals of +/- 0.5, 1.5, 2.5 m/s…) and temperature is shaded between -1 and 1 °C. EMAC is missing temperature and WACCM's La Nina temperature includes a conspicuous artifact that we are still looking into.

Although the ERA5 El Niño and La Niña composites are similar overall, subtracting the two reveals that they differ due to the El Niño composite including a stronger Kelvin wave (cf. Fig. 2). The characteristic features of the wave include its cold cap temperature anomaly in the UTLS, which is in quadrature with easterly zonal wind anomalies, all of which tilt eastward with increasing height above ~200 hPa and westward with increasing height below (Straub and Kiladis 2002; Kim et al. 2013; Yuni et al. 2019; Nakamura and Takayabu 2022). Judging by the longitude of the ERA5 100 hPa cold cap maximas, the Kelvin wave embedded in the composite El Niño MJO is shifted further east compared to its La Niña equivalent, evidence that it is propagating faster. This corresponds to the alignment of ERA5 Kelvin wave spectral power along the deepest equivalent depth dispersion curves during El Niño in Fig. 2.

Consistent with recent studies, the surface easterlies positioned east of the MJO convection are indeed stronger during El Niño in reanalysis (Wang et al. 2019; Wei and Ren 2019). We attribute the amplification of these easterlies to the Kelvin wave's planetary scale signature in wind, which better bridges the MJO lower tropospheric easterlies over the Pacific with the upper tropospheric easterly outflow over the Indian Ocean; compare the 500 hPa zonal winds at 150°E between El Niño and La Niña. This enhanced continuity of the MJO easterlies during El Niño is a robust feature amongst the models and is particularly clear in the El Niño minus La Niña composites of EC-EARTH3.3, ECHAM5sh, MIROC-AGCM-LL, MIROC-ESM and MRI-ESM2.0. The models, however, struggle to represent the detailed temperature structure of the Kelvin wave and they exhibit MJO temperature anomalies that can differ significantly from ERA5 (e.g., MIROC family).

The vertical structure of the MJO zonal wind anomalies is more baroclinic during La Niña. This may be attributed to a weaker and slower propagating Kelvin wave during La Niña. However, it is also possible that the amplification of the equatorial Rossby wave during La Niña (cf. Figure 2) projects onto the MJO's vertical structure. For instance, similar to the western portion of the phase 3/4 MJO winds, these waves (when located in the eastern hemisphere) have a first baroclinic structure in zonal wind that consists of low-level westerlies and upper-level easterlies (Kiladis et al. 2009; Yuni et al. 2019; Nakamura and Takayabu 2022). Following from the robust amplification of the equatorial Rossby wave across the models during La Niña, it was hypothesized that the low-level westerlies west of the MJO convection would be stronger during La Niña than El Niño like in Wei and Ren (2019). This does not appear to be the case though and no first baroclinic zonal wind structure stands out in the El Niño minus La Niña composites. The signal of the equatorial Rossby wave does, however, appear to be visible in the temperature field. These waves are associated with a mid to upper tropospheric warming that is centered around 300 hPa (Kiladis et al. 2009, Fig. 18c). This region of the upper troposphere is warmer in all of the La Niña simulations, with the exception of MIROC-ESM in which the warming is marginally stronger in the El Niño composite.

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3.2 The lack of QBO-MJO coupling

The results in the previous section indicate that ENSO modulates the MJO's propagation, promoting faster MJOs during El Niño and the opposite during La Niña. However, it is possible that aliased signals from the spontaneously generated QBOs are embedded in the aforementioned results. Therefore, in this section we look for evidence of QBO-MJO coupling. As a first step, the representation of the QBO is documented using previously defined metrics, with a specific interest in quantifying the "lowest level" that the QBO descends to in the lower stratosphere. Insufficient descent is a known bias, which may hinder the QBO from modulating other potentially important variables near the tropopause such as temperature (Richter et al. 2020; Kim et al. 2020). Similar to Schenzinger et al. (2017), the lowest level that QBO reaches is found by averaging the QBO Fourier amplitude (see Methods) over 5°S-5°N, identifying the maximum amplitude (fixed at 20 hPa here), and then finding the isobar in the lower stratosphere where the amplitude equals 10% of the maximum.

Table 3: From left to right, QBO easterly, westerly, and total amplitude, the lowest level that the QBO descends to, its vertical extent, and its latitudinal extent. These statistics are computed using the same "QBO cycles" (see Methods) and QBO periodicity statistics that are reported in Kawatani et al. (2024, in preparation). Vertical extents listed as "N/A" were missing data at middle stratospheric isobars, which prevents the calculation. ECHAM5sh's El Niño simulation QBO Fourier amplitude is split into two parts above and below ~10 hPa (not shown), which is why its vertical extent is only 10.4 km.

	EN easterly amplitude (m/s)	LN easterly amplitude (m/s)	EN westerly amplitude (m/s)	LN westerly amplitude (m/s)	EN QBO amplitude (m/s)	LN QBO amplitude (m/s)	EN lowest level (hPa)	LN lowest level (hPa)	EN vertical extent (km)	LN vertical extent (km)	EN latitudinal extent (degrees lat.)	LN latitudinal extent (degrees lat.)
EC-EARTH3.3	-15.5	-15.6	16	16.7	15.8	16.2	70.4	67.5	17.5	15.6	21.4	20.8
ECHAM5sh	-16.2	-24.4	17.4	21.8	16.8	23.1	64.6	70.3	10.4	20.2	21	21.5
EMAC	-22.3	-24	21.2	17.8	21.8	20.9	66.2	64.7	19	21.2	21.2	21.9
LMDz6	-16.7	-16.1	19.1	14.3	17.9	15.2	68.1	54.3	N/A	N/A	17.7	16.9
GISS-E2-E-G	-24.3	-18.9	23.1	16.6	23.7	17.8	74.7	59.7	19.9	14	20.5	19.4
MIROC-AGCM-LL	-15.4	-16.4	14.8	15.3	15.1	15.8	68.1	66.9	N/A	N/A	20.3	21.1
MIROC-ESM	-18.4	-18.5	16.9	17.5	17.6	18	66.2	68.9	20.5	24.9	19.9	20.2
MRI-ESM2.0	-20.6	-21.7	24.6	24.4	22.6	23	82.4	82.8	17.7	17.3	19.5	20.5

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WACCM5-110L	-23.4	-23.4	24	24	23.7	23.7	69.5	87	17.6	18.5	19.7	21.4
ERA5	-24.1		24.5		24.3		92.2		18.1		23.9	

The QBO descends to 92.2 hPa in ERA5 (Table 3). Of the simulated QBOs, the majority do not reach beneath 70 hPa, indicating that they are likely too high in altitude to influence the tropical atmosphere beneath 100 hPa as observed (Tegtmeier et al. 2020). One outlier is the WACCM5-110L's La Niña simulation whose lowest isobar of 87 hPa is fairly similar to the ERA5 benchmark. Nonetheless, sensitivity tests with this simulation in which MJO amplitude is computed as a function of lower stratospheric QBO phase reveals its MJO to be insensitive to the QBO in the observed way (not shown). ENSO phase does not have consistent effects on what lowest isobar a given model's QBO reaches. For example, GISS-E2-E-G and LMDz6 favor much stronger descent of the QBO into the lower stratosphere during El Niño whereas WACCM5-110L's ENSO simulations reflect a strong opposite signed response.

In general, the metrics do not change systematically by ENSO phase. For example, QBO amplitude is stronger during La Niña in five of the nine models. El Niño and La Niña QBO amplitudes differ by less than 1 m/s for all models except ECHAM5sh, GISS-E2-EG, and LMDz6. ECHAM5sh favors a stronger QBO amplitude during La Niña, owing to intensified QBO easterlies and westerlies during this ENSO phase. Conversely, GISS-E2-EG, and LMDz6 favor stronger easterly, westerly, and total QBO amplitudes during El Niño. Of the 12 simulations corresponding to the six other models, EC-EARTH3.3, EMAC, MIROC-AGCM-LL, MIROC-ESM, MRI-ESM2.0, and WACCM5-110L, the magnitude of their easterly and westerly QBO amplitudes is stronger during La Niña in eight of the 12 simulations. The effect of ENSO phase on vertical extent is inconsistent across the models and difficult to evaluate entirely because of missing data in two models and an unrealistic QBO Fourier amplitude structure in ECHAM5sh's El Niño simulation. Although the models ubiquitously underestimate the latitudinal extent of the QBOs relative to ERA5, it may be noteworthy that six of nine models have wider QBO latitudinal extents during La Niña. The boreal winter polar stratospheric wind response to the QBO is stronger when the QBO is wider (Hansen et al. 2013) and there is a preference for this teleconnection to happen during La Niña over the observed record (Kumar et al. 2022).

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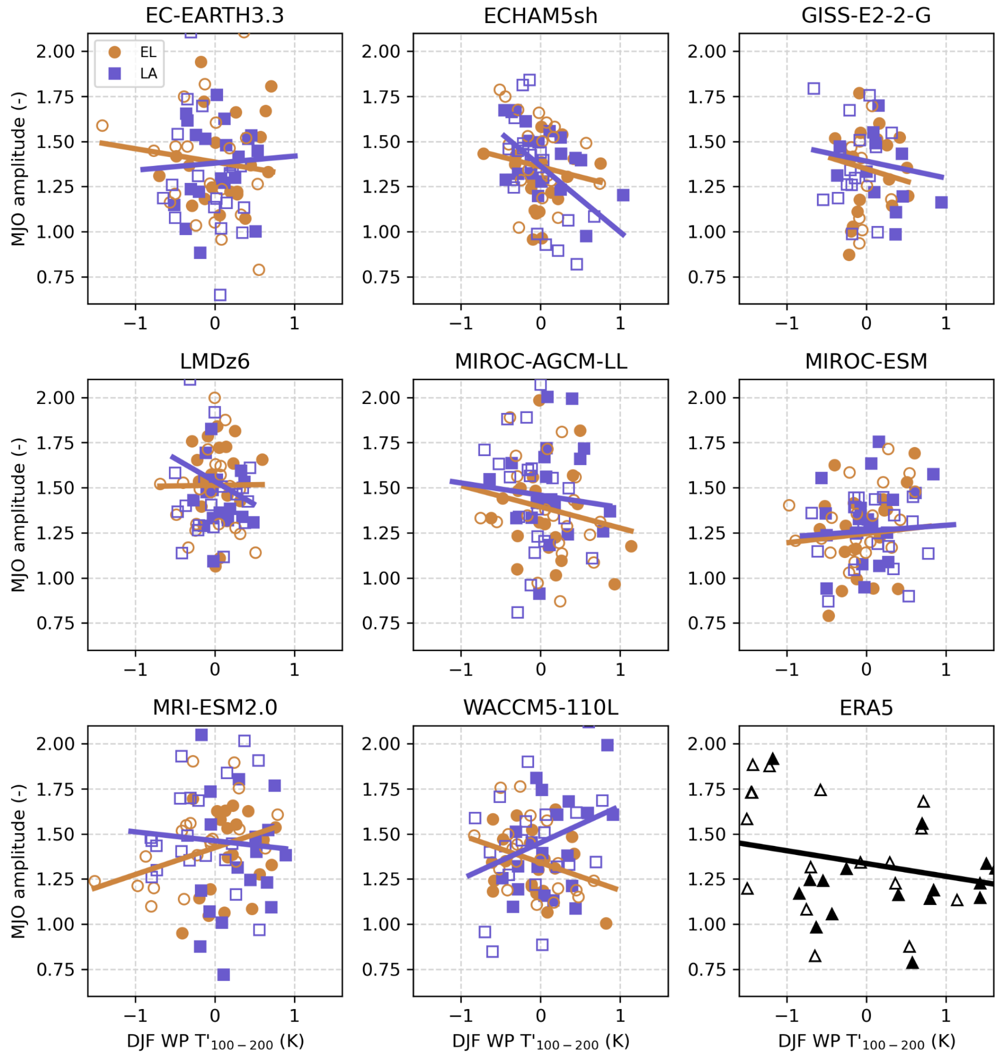

Figure 7: Scatter plot of warm-pool averaged (10°S-10°N, 45°E-180°E) tropopause stability anomalies (100 hPa minus 200 hPa temperature) versus December-February MJO amplitude. Lines represent the slope of the regression line during El Niño (orange) or La Niña (purple). Easterly and westerly QBO phases, which are delineated by the sign of the December-February 5°S-5°N 50 hPa zonal mean zonal-wind, are denoted by open and filled markers, respectively.

While the aforementioned QBO metrics help to broadly characterize the form of each model's QBO, they are non-time-varying quantities and have less value for better understanding seasonal phenomena such as the predominantly boreal winter QBO-MJO interaction. To incorporate the effects of seasonality, scatterplots of December-February warm-pool averaged tropopause stability versus December-February MJO amplitude are made as a function of QBO phase for each of the simulations (Klotzbach et al. 2019). MJO amplitude is expected to increase as tropopause stability decreases (Son et al. 2017; Klotzbach et al. 2019), as is apparent based on ERA5 (Fig. 7). This metric is relevant for considering QBO-MJO coupling because the QBO's effect on lower stratospheric stability (e.g., Densmore et al. 2019) is one of the suspected physical mechanisms coupling

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the QBO and MJO. In general, the models do not reproduce the observed inverse relation between MJO amplitude and 100-200 hPa stability and stratifying the results either by ENSO phase or QBO phase does not change this. The linear response of the MJO amplitude to the tropopause stability, which is negative in observations, does not change consistently with the ENSO phase. It is worth noting that the mean DJF stability in the models is generally close to that of ERA5 (-28.7 K) except for the GISS model, which showcases a smaller gradient (-23.3 K), and all models appear to underestimate its interannual variability, as evident by the smaller range compared to ERA5. Furthermore, the stratification by QBO phase (with eQBO associated with lower stability values, and vice versa for the wQBO) is also small or absent in models, possibly due to a limited influence of the QBO at tropopause heights (Serva et al., 2022). Further sensitivity tests were done to see if the model QBOs simulate a QBO-MJO amplitude relationship when the MJO is in a particular phase (e.g., Lim and Son 2020; Lawrence et al. 2023); no systematic effect was detected (not shown).

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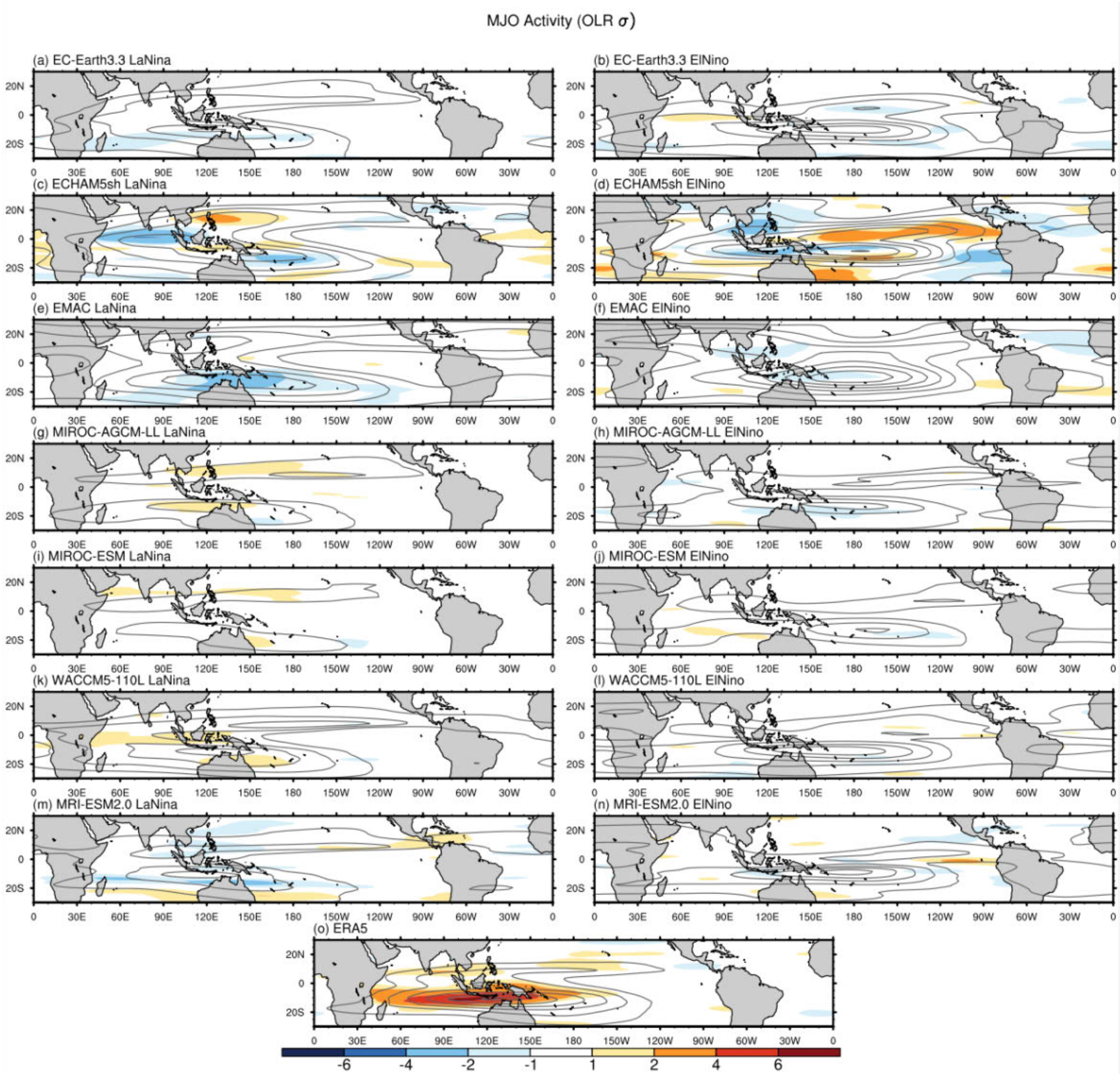

Figure 8: Gray contours show the MJO activity defined as the standard deviation of MJO-filtered OLR for each model and ENSO phase, as well as for ERA5 (6n). The color-filled contours show the MJO-QBO relationship as the difference in MJO activity for the eastward minus westward QBO phases for each model and ERA5.

To further evaluate the representation of QBO-MJO coupling in the models, Figure 8 presents the effect of QBO phase on MJO activity (see Methods). As shown in previous studies (e.g., Kim et al. 2020), the models do not capture the observed QBO-MJO relationship, which has maximum signal over the maritime continent region (Fig. 8m) illustrating the enhancement

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of MJO activity during easterly QBO phase. With La Niña forcing, MIROC-AGCM-LL and WACCM5-110L show a weak positive signal over the Maritime Continent (Fig. 8g, k), however EC-EARTH3.3, ECHAM5sh, and EMAC exhibit rather different responses. No change in the MJO activity by QBO phase is evident in the El Niño simulations either. There is, however, a clear eastward shift of the MJO activity towards the Pacific during El Niño, corroborating the observational work of Kessler (2001) and the climate model based study of Tam and Lau (2005).

4 Discussion and conclusions

The observed interannual variability of the MJO is influenced by multiple parts of the climate system. Due to their impact on the tropical troposphere and prominent fluctuations at interannual timescales, ENSO and the QBO are known drivers of the MJO's year to year variability, however it is difficult to definitively isolate their influence on the MJO because of how short and noisy the observational record is (Randall et al. 2023). Building on previous work, we have analyzed the representation of the MJO in nine climate models that are forced by prescribed perpetual El Niño and La Niña conditions and which include spontaneously generated QBOs. Although the models exhibit difficulties simulating the MJO, several previously reported effects of the ENSO phase on the MJO are corroborated by this coordinated set of experiments. These include faster propagation of the MJO during El Niño versus slower propagation during La Niña, manifesting as shorter and longer lifetimes, respectively, stronger amplitude of the MJO during El Niño, and east-west shifting of the MJO timescale variance towards the east Pacific during El Niño and towards the west Pacific and Indian Ocean during La Niña. As in the observational record, it is possible that aliasing from the QBO is superimposed on what are thought to be MJO changes due to ENSO. However, we find that the climate models considered here include nearly no evidence of QBO-MJO coupling. While this hampers further understanding of the mechanisms responsible for coupling the QBO and MJO, in all likelihood this eliminates the QBO as a driver of the MJO in this set of experiments, which increases our confidence that the aforementioned changes in the MJO are arising due to ENSO. Experiments with specified rather than internally generated QBOs can help understanding the processes at play, which remain elusive (Martin et al., 2023).

These results highlight that the interannual variability of the MJO is sensitive to ENSO in several regards, in contrast with Slingo et al. (1999) and Hendon et al. (1999). These studies reported a weak simultaneous relationship between ENSO and MJO activity. Hendon et al. (1999) clarified that increased MJO activity coincides with an increased number of MJO events and enhanced intraseasonal convective activity around the Maritime Continent. While these attributes of the MJO were largely insensitive to SSTs in their study, the models here unambiguously simulate more events during El Niño (Table 2), which are of stronger MJO activity than their La Niña equivalents (Figure 8). We suspect that the distinction between our results and the aforementioned studies is related to the timescale over which the oceanic component of ENSO modulates the atmosphere. Recent studies show that while the likelihood of MJO occurrence and its propagation speed are only weakly correlated with tropical intraseasonally filtered SSTs (agreeing with the aforementioned studies), they are strongly correlated with low-

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frequency (e.g., > 90 days) SSTs (Suematsu and Miura 2018; 2022). Along the same lines, Newman et al. (2009) found air-sea coupling to have weak effects on subseasonal atmospheric variability, but strong influence on the long-term atmospheric circulation. In light of this and our use of a simplified climate system in which smoothed monthly SSTs are prescribed, intraseasonal and interannual SST fluctuations are explicitly ignored, and the downward impact of the MJO on intraseasonal SSTs (Zhang and Gottschalk 2002; Hendon et al. 2007; Newman et al. 2009) is not simulated, we deduce that the different basic state circulations set up by the indefinite ENSO forcings enables distinct MJOs. This interpretation of the low-frequency SSTs as an important modulator of the MJO aligns with studies which have attributed variability in the MJO's propagation to ENSO (Wei and Ren 2019; Wang et al. 2019; Dasgupta et al. 2021; Back et al. 2024) as well as studies employing climate models in which MJO propagation can be modulated by changing the horizontal gradients of the background SST field (Kang et al. 2013; Jiang et al. 2020).

Compared with the La Niña simulations, all El Niño simulations include amplified Kelvin waves whereas equatorial Rossby waves intensify in the presence of perpetual La Niña conditions. Consistent with the reported relationship between these waves and the MJO, all models simulate faster MJO propagation in their El Niño simulation. This is further supported by the MJO diversity analysis, which reveals that models simulate the fast and standing MJO archetypes well in the presence of perpetual El Niño and La Niña conditions, respectively. In addition, the MJO's phase 3/4 vertical structures highlight that lower tropospheric easterlies do intensify to the east of the MJO's major convection during El Niño across most models, which we interpret to result from the intensification of the Kelvin wave.

While the relationship between Kelvin waves, equatorial Rossby waves, and ENSO is well established by previous studies employing empirical data and reanalysis, this is the first time, to the best of our knowledge, that this relationship has been ubiquitously affirmed by a coordinated set of climate model experiments with prescribed ENSO forcings. The robustness of this result across models suggests that it is worthwhile considering how these wave responses to ENSO influence other parts of the climate system. For instance, Kelvin waves are a source of resolved wave forcing for the QBO (Baldwin et al. 2001; Taguchi 2010; Pahlavan et al. 2021) and more rapid descent of the QBO's westerly shear zones during El Niño in observations has been attributed to their intensification (Das and Pan 2016). The periodicity of the QBO in the El Niño simulations is in fact shorter than in the La Niña simulations across all models considered here (Kawatani et al., in preparation), however, the extent to which Kelvin waves are responsible for this as opposed to other waves (e.g., Kawatani et al. 2019), is yet to be quantified across all of the models. The convectively coupled wave responses presented here may also be relevant for better understanding ENSO diversity. El Niño events vary in type and intensity due to the influence of westerly wind bursts, which introduce asymmetry and irregularity into ENSO's phase changes (Chen et al. 2015). Westerly wind bursts are more frequent during the convective phases of equatorial Rossby waves and the MJO, especially strong MJOs (Puy et al. 2016). Hence, the atmospheric responses to ENSO, such as the amplifications of the MJO during El Niño (Figs. 2-4) and of the convectively coupled Rossby wave during La Niña, have a pathway to influence ENSO's oceanic component.

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Code availability

The code used for the wavenumber-frequency analysis is publicly available through the National Center for Atmospheric Research (NCAR) Command Language (NCL): https://www.ncl.ucar.edu/Applications/mjoclivar.shtml. A reproduction of NCL's Wheeler-Kiladis (1999) routine in Python is available here: https://github.com/brianpm/wavenumber_frequency. Python code, which assesses QBO morphology is available here: https://github.com/NOAA-GFDL/MDTF-diagnostics/blob/main/diagnostics/stc_qbo_enso/stc_qbo_enso.py.

Data availability

Storage for the QBOi multi-model data set is provided by the Centre for Environmental Data Analysis (CEDA) whose data and processing service is called JASMIN. Interested users must obtain a JASMIN login account and take the necessary steps to access the QBOi group workspace within JASMIN, which contains the perpetual ENSO simulations. Certain derived model products (e.g., the MJO RMMs) may be made available upon request.

Author contributions

DE, FS, JC, SYB, CO, and JR contributed to the conceptualization of this study. DE, FS, JC, and SYB performed the data analyses and produced the figures and tables. All authors contributed to the review and editing of this manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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