## Is the Madden-Julian Oscillation a Moisture Mode?

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#### Abstract

The governing thermodynamics of the Madden-Julian Oscillation (MJO) are examined using sounding and reanalysis data. On the basis of four objective criteria, results suggest that the MJO behaves like a moisture mode –a system whose thermodynamics is governed by moisture– only over the Indian Ocean. Over this basin, the small effective gross moist stability, i.e., a slow moist static energy (MSE) export by convection, and slow convective adjustment timescale allows moisture modes to exist for all zonal wavenumbers except 1. Elsewhere, the faster-propagating wavenumber 1-2 components are more prominent and the effective gross moist stability is higher, preventing weak temperature gradient (WTG) balance to be established and causing temperature and moisture to play similar roles in the MJO's thermodynamics.





### Is the Madden-Julian Oscillation a Moisture Mode?

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# Key Points: The MJO satisfies the criteria to be defined as a moisture mode only over the eastern Indian Ocean (60-110°E). The unique climatological features of the Indian Ocean allow moisture modes to exist near the planetary scale. The MSE export in this basin is slow enough to allow for WTG balance and for moisture to govern convection evolution.

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#### 11 Abstract

The governing thermodynamics of the Madden-Julian Oscillation (MJO) are ex-12 amined using sounding and reanalysis data. On the basis of four objective criteria, re-13 sults suggest that the MJO behaves like a moisture mode –a system whose thermody-14 namics is governed by moisture- only over the Indian Ocean. Over this basin, the small 15 effective gross moist stability, i.e., a slow moist static energy (MSE) export by convec-16 tion, and slow convective adjustment timescale allows moisture modes to exist for all zonal 17 wavenumbers except 1. Elsewhere, the faster-propagating wavenumber 1-2 components 18 are more prominent and the effective gross moist stability is higher, preventing weak tem-19 perature gradient (WTG) balance to be established and causing temperature and mois-20 ture to play similar roles in the MJO's thermodynamics. 21

#### <sup>22</sup> Plain Language Summary

The Madden-Julian Oscillation is one of the most important phenomena that oc-23 cur at the subseasonal to seasonal timescale and is a source of weather predictability at 24 this timescale. In spite of its importance, many features of the MJO remain elusive and 25 many theories have been proposed to understand its behavior. Arguably, the most well-26 known MJO theory is the moisture mode theory. The theory posits that moisture gov-27 erns the evolution of the MJO. Here we show that this theory is applicable only over the 28 Indian Ocean, where low atmospheric stability and long-lasting convection allow for mois-29 ture modes to exist. Elsewhere, temperature fluctuations in the MJO become as impor-30 tant as moisture, a feature that is inconsistent with moisture mode theory. 31

#### 32 1 Introduction

The Madden-Julian oscillation (MJO) is the dominant and most well-known mode 33 of intraseasonal variability over the tropics (Madden & Julian, 1971; Zhang, 2005). Its 34 planetary-scale structure, intraseasonal time-scale, and slow eastward propagation at  $\sim 5$ 35 m s<sup>-1</sup> make this wave stand out from other forms of equatorial variability such as the 36 equatorial waves (Kiladis et al., 2009). Recently, it has become clear that interactions 37 between moisture, convection, radiation, and circulation are important for the dynam-38 ics of the MJO (Sobel et al., 2001; Raymond, 2001; Sobel & Maloney, 2013; A. Adames 30 & Kim, 2016; Gonzalez & Jiang, 2019; A. Adames & Maloney, 2021; Ahmed, 2021; Wang 40 & Sobel, 2021). These interactions can cause the dynamics of the MJO to significantly 41 42 differ from those described by dry shallow water theory. Indeed, the MJO does not correspond to any of Matsuno's solutions (Matsuno, 1966). 43

Many theoretical models have been proposed to explain the MJO's features. These 44 theories have been recently documented by Zhang et al. (2020) and Jiang et al. (2020). 45 Among these theories, the moisture mode theory has arguably gained the most atten-46 tion (Å. Adames & Maloney, 2021). In this theory, the evolution of moisture governs the 47 evolution of the wave. The primary signatures of moisture modes are (a) a strong mois-48 ture tendency and (b) a weak temperature tendency (A. Adames et al., 2019; Ahmed 49 et al., 2021; A. Adames & Maloney, 2021). The first condition manifests as a tight cou-50 pling between moisture and precipitation. The second condition ensures that the weak 51 temperature gradient approximation (WTG; Sobel et al., 2001) is the dominant column 52 energy balance. These two conditions underpin the criteria proposed in Mayta et al. (2022) 53 to classify different tropical systems. By using these criteria, Mayta and Adames (2023) 54 found that the MJO over the Western Hemisphere does not satisfy the conditions to be 55 a moisture mode. Other studies have also argued that the circumnavigating MJO signature-56 where it is weakly coupled with convection– agrees with the convectively-coupled Kelvin 57 wave rather than a moisture mode (Sobel & Kim, 2012; Powell, 2017; A. Adames et al., 58 2019; Emanuel, 2020; Ahmed et al., 2021). However, other studies have shown that the 59

MJO's signature over the Indo-Pacific warm pool has the features of moisture modes (e.g., 60

Myers & Waliser, 2003; A. Adames & Kim, 2016; Kim et al., 2017; A. Adames, 2017; Snide 61 et al., 2022, ; among others).

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These results give us the main scientific question of this study: Is the MJO a mois-63 ture mode? Is it possible that the MJO is a moisture mode only in some regions of the 64 tropics? The structure of this paper is as follows: In section 2, we discuss the data and 65 statistical methods used to explore moisture mode conditions associated with the MJO. 66 In section 3, we examine the leading thermodynamic properties and assess its consistency 67 with moisture mode theory (A. Adames et al., 2019; Ahmed et al., 2021; Mayta et al., 68 2022). In section 4, we will employ a recent theory by Ahmed et al. (2021) to show that 69 the MJO exhibits moisture mode behavior in regions where the atmosphere favors this 70 behavior near the planetary scales. A concluding discussion is offered in section 5. 71

#### 2 Data and Methods 72

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#### 2.1 Satellite CLAUS $T_b$ and Reanalysis dataset

Satellite-observed brightness temperature  $(T_b)$  data is used in this study as a proxy 74 for convection. The satellite data is obtained from the Cloud Archive User System (CLAUS) 75 (Hodges et al., 2000). Three-dimensional (27 pressure levels) fields from the European 76 Centre for Medium-Range Weather Forecasts ERA-5 reanalysis (ERA5; Hersbach et al., 77 2019) are used to explore moist thermodynamics associated with the MJO. The ERA5 78 dataset uses a  $1.0^{\circ}$  horizontal resolution grid, with four times daily analyses that match 79 the CLAUS  $T_b$  data for the 36-yr time period 1984 through 2015. We make use of the 80 zonal (u), meridional (v), and vertical winds  $(\omega)$ , specific humidity (q), temperature (T), 81 diabatic heating rate  $(Q_1)$ , surface and top of the atmosphere radiative fluxes, surface 82 sensible and latent heat fluxes (SH and LE, respectively), and precipitation (P). 83

#### 2.2 Field campaign data

To further analyze the moist process in the MJO and verify the accuracy of reanal-85 ysis data, we used observed data from three field campaigns around the tropical belt: 86 (i) Over the Indian Ocean, we use data from the Dynamics of the Madden-Julian Os-87 cillation (DYNAMO) field campaign, conducted from October 2011 through March 2012 88 (Yoneyama et al., 2013). We used data from the northern sounding array (NSA) aver-89 ages from observations, located in the central equatorial Indian Ocean for a 3-month pe-90 riod from 10 October through 31 December 2011. The sounding array dataset was quality-91 controlled and bias corrected to create a DYNAMO legacy dataset (Ciesielski et al., 2014). 92 (ii) In the Western Pacific, we used data collected during intensive operating period (IOP) 93 of TOGA-COARE for a 4-month period from 1 November through 28 February 1993. 94 A detailed description of sounding stations and quality control procedures for TOGA-95 COARE was documented in Webster and Lukas (1992). All calculations we present are 96 average vertical profiles for grid points within Intensive Flux Array (IFA), which is an 97 array of sounding stations centered near 2°S,155°E (Fig. 1). (iii) For tropical South Amer-98 ica, the Observations and Modeling of the Green Ocean Amazon (GoAmazon 2014/15) 99 are used. The field campaign was carried out in central Amazonia, Brazil for a two-year 100 time period from 1 January 2014 through 31 December 2015. For this study, we make 101 use of the constrained variational analysis product for GoAmazon (VARANAL; Tang et 102 al., 2016). VARANAL is derived from the ECMWF analysis fields and Atmospheric Ra-103 diation Measurement's (ARM) observations during GoAmazon 2014/15 using the con-104 strained variational analysis proposed in Zhang and Hendon (1997). This product as-105 similates the top of the atmosphere and surface observations to produce thermodynamic 106 budgets. The surface observations assimilated include surface radiative, latent, and sen-107 sible heat fluxes and precipitation from the System for the Protection of Amazonia (SIPAM) 108

radar. Additional details about VARANAL products during GoAmazon 2014/15 are found
 in Tang et al. (2016).

Finally, we make use of the all-season OLR MJO index (OMI; Kiladis et al., 2014) as a measure of MJO activity. This index represents the circulation and convection MJO features and is commonly used to track the life cycle of an MJO event.

#### 2.3 Linear regression

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115 Thermodynamic anomaly fields associated with the MJO are obtained by projecting raw ERA5 data at each grid point onto the associated first principal component (OMI1) 116 time series. Then, all fields are scaled to one standard deviation OMI1 perturbation as 117 made in previous studies (e.g., Mapes et al., 2006; A. Adames et al., 2021; Snide et al., 118 2022; Mayta et al., 2022). The same approach is applied to data from campaigns. The 119 area-average of filtered  $T_b$  or data at the same grid base point of the observations is used 120 to calculate regressions instead. The statistical significance of these results is then as-121 sessed based on the two-tailed Student's t-test. This method takes into account the cor-122 relation coefficients and an effective number of independent samples (degrees of freedom) 123 based on the decorrelation timescale (Livezey & Chen, 1983). 124

#### <sup>125</sup> 3 Moist Thermodynamics of the MJO

We will now examine three criteria first described by Ahmed et al. (2021), applied to the entire tropical belt. In Mayta et al. (2022), these criteria were modified to make them more suitable for their diagnosis in observational and reanalysis data. These criteria are:

 (a) Criterion 1 (C1): The wave must exhibit a large moisture signature that is highly correlated with the precipitation anomalies
 For the MJO to be considered a moisture mode, its signature in column water va-

por  $(\langle q \rangle')$  must be large enough to explain the majority of the surface rainfall variance (P'), given the following relation,

$$P' \propto \langle q \rangle' \tag{1}$$

- This results in a strong correlation (~0.9 rounded) between P' and  $\langle q \rangle'$  (Mayta et al., 2022; Mayta & Adames, 2023). In this study,  $\langle \cdot \rangle \equiv 1/g \int_{surf.}^{top} (\cdot) dp$  denotes the mass-weighted vertical integral and primes (') represent intraseasonal anomalies.
- We apply this criterion by constructing a scatterplot between P' and  $\langle q \rangle'$  at each 139 grid point in the reanalysis (Fig. 1a) and at the corresponding base point for the 140 field campaign data (Fig. 2). The correlations between P' and  $\langle q \rangle'$  from ERA5 141 are plotted in Fig. 1a, and the latitudinal averages in Fig. 1d. Results show that 142 only over the Indo-Pacific warm pool region passes the first criterion, with cor-143 relations ranging close to  $\sim 1.0$ . An exception occurs in the Maritime Continent, 144 where correlations are beneath 0.9. Correlations decay drastically outside of the 145 warm pool, from 150°W to 40°E, where the mean correlation value is of  $\sim 0.5$  (Fig. 146 1d). 147
- When data from the field campaigns are analyzed instead, we see that a strong 148 correlation between P' and  $\langle q \rangle'$  is seen for the DYNAMO data (Fig. 2a). As the 149 MJO moves away from the warm pool, correlations decrease as depicted in the TOGA-150 COARE data, where a correlation between P' and  $\langle q \rangle'$  is about ~0.75 (Fig. 2d). 151 The cyclical appearance of the cloud of points is suggestive of a lead/lag relation-152 ship between the two fields, rather than an in-phase one. A high correlation of  $\sim 0.98$ 153 (Fig. 2h) is seen once again at the GoAmazon base point, in disagreement with 154 ERA5. 155



Figure 1. Geographical variations of the moisture mode criteria. Maps of (a) P' vs  $\langle q \rangle'$ , (b)  $\nabla \cdot \langle s \mathbf{v} \rangle'$  vs  $\langle Q_1 \rangle'$ , and (c)  $\langle m \rangle'$  vs  $\langle L_v q \rangle'$ . Anomalies are obtained by projecting ERA5 data at each grid point onto the associated first principal component (OMI1) time series. Panel (a) shows the correlation coefficient, and panels (b) and (c) are the slopes of the linear fitting. (d) Represents the average value of each criterion computed from 10°S to 10°N at each longitude. The gray shading represents the threshold (0.85 to 1.1) necessary to satisfy the moisture mode criteria. The red dashed lines indicate the longitude domain where the three criteria are satisfied. Panel (e) shows the geographical variation of the dimensionless  $N_{mode}$  parameter. Shadings represent base 10 logarithm of  $N_{mode}$ , where blue represents  $N_{mode}$  values categorized as moisture modes, yellow can be considered inertio-gravity waves, and white represents mixed systems. The location of the DYNAMO, TOGA-COARE, and GO-Amazon sites is indicated by a yellow, red, and green circle, respectively.

(b) Criterion 2 (C2): The mode must be in weak temperature gradient (WTG) balance WTG balance is the leading thermodynamic balance in the tropics (Sobel et al., 2001). This balance states that vertical dry static energy (DSE) advection approximately balances heating  $\nabla \cdot \langle s \mathbf{v} \rangle' \simeq \langle Q_1 \rangle'$  (2)

where 
$$s = C_p T + \phi$$
 is DSE,  $\mathbf{v} = u\mathbf{i} + v\mathbf{j}$  is the horizontal vector wind field,  
 $C_p = 1004$  is the specific heat at constant pressure, and  $T$  is the temperature.  
 $\langle Q_1 \rangle' \simeq \langle Q_r \rangle' + L_v P' + SH'$  is the apparent heating rate and can be calculated  
from reanalysis and observations following Yanai and Johnson (1993), where  $Q_r$ 

- is the radiative heating rate, SH is the surface sensible heat flux, and  $L_v$  repre-165 sents the latent heat of vaporization  $(2.5 \times 10^6 \text{ J kg}^{-1})$ . To pass this criterion, 166 the MJO must exhibit a slope of the linear least-square fit within the margin of 167  $\sim 0.9-1.1$  (rounded). 168 Fig. 1b shows the value of the slope of the linear least-square fit at each grid point. 169 We can see that the slope is  $\sim 1$  from the Indian Ocean towards the Western Pa-170 cific. Regions over the mean climatological ITCZ position, including the Amazon 171 basin, are also places where this criterion is satisfied. The meridionally-averaged 172 values (Fig. 1d) show that the criterion largely prevails from  $50^{\circ}E$  to  $180^{\circ}$ . Ob-173 servations are also in agreement with reanalysis. Results show a high correlation 174 between  $\nabla \langle s \mathbf{v} \rangle'$  and  $\langle Q_1 \rangle'$ , with a slope of ~0.99, ~0.97, and ~0.99 for DYNAMO, 175 TOGA-COARE, and GoAmazon, respectively (Figs. 2b, e, i). 176
- (c) Criterion 3 (C3): Moisture must govern the distribution of moist static energy (MSE)
  - If the MJO is a moisture mode, moisture should be the main contributor to MSE, implying that

$$\langle m \rangle' \approx L_v \langle q \rangle' \tag{3}$$

where  $m = s + L_v q$  is MSE. As in C2, a slope of the linear least-square fit within 181 the margin of  $\sim 0.9-1.1$  (rounded) is needed to guarantee the balance of Eq. (3). 182 From Fig. 1c, we see that the slope of the linear fit is  $\sim 1$  only over the Indian Ocean. 183 According to the average values presented in Fig. 1d (solid magenta line), this cri-184 terion is satisfied from 45°E to 130°E. Results from ERA5 can be verified with 185 observations at different base points. From DYNAMO (Fig. 2c) it is possible to 186 see that the slope is about  $\sim 1$  over the Indian Ocean. The slope diminishes at the 187 TOGA-COARE base point (0.88, Fig. 2f), and completely falls outside the thresh-188 old over GoAmazon (1.66, Fig. 2i). 189

190 (d) N<sub>mode</sub>

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In addition to the three aforementioned criteria, we can also estimate the value of  $N_{mode}$ , which can be computed as in Á. Adames et al. (2019),

$$N_{mode} \simeq \frac{c_p^2 \tau}{c^2 \tau_c} \tag{4}$$

193	where c is the phase speed of a first baroclinic free gravity wave $(c \simeq 50 \ ms^{-1})$ ,
194	$c_p$ is the phase speed of the MJO, $\tau_c$ is the convective moisture adjustment time
195	scale, and $\tau$ is the temporal time scale. When $N_{mode} \ll 1$ , moisture governs the
196	thermodynamics of the MJO, resulting in moisture modes; but if $N_{mode} \gg 1$ the
197	thermodynamics of a wave are predominantly driven by thermal fluctuations, re-
198	sulting in gravity waves. When $N_{mode} \approx 1$ the MJO will exhibit the behavior of
199	both moisture mode and gravity wave.
200	Figure 1e shows the geographical variation of the base 10 logarithm of the dimen-
201	sionless $N_{mode}$ parameter. From Eq. (4), $\tau_c$ varies at each longitude (Fig. S1a),
202	$\tau$ is assumed to be 45 days, the average value throughout the tropics and $c_p$ is com-
203	puted for different regions (see Table S1). The zonal distribution of $N_{mode}$ is in
204	qualitative agreement with the three criteria discussed above. Values of $N_{mode}$ smaller
205	than 0.3 are observed exclusively from 60°E throughout 180°. The smallest value
206	of $N_{mode}$ is found over the Eastern Indian Ocean (60°E–90°E, Fig. 1e), where the
207	MJO propagates slowly at about $\sim 4.1 \text{ m s}^{-1}$ (Table S1). In contrast, larger val-
208	ues of $N_{mode}$ are observed over the Eastern Pacific, in a region where the wave prop-
209	agates faster.

When all conditions are examined together, we conclude that the MJO is a moisture mode only over the eastern Indian Ocean (60°E to 110°E; Fig. 1d ). Elsewhere, it is not a moisture mode but rather a so-called quasi-equilibrium mode (Ahmed et al., 2021)



Figure 2. Scatterplots of P' vs  $\langle q \rangle'$  (first column),  $\nabla \cdot \langle s \mathbf{v} \rangle'$  vs  $\langle Q_1 \rangle'$  (second column), and  $\langle m' \rangle$  vs  $\langle L_v q' \rangle$  (third column) for the DYNAMO (top panels), TOGA-COARE (middle panels), and GoAmazon (bottom panels), respectively. Anomalies are obtained by regressing all fields against the time series of the filtered  $T_b$  at the corresponding base point of the field campaign (See Fig. 1). The linear least squares fit is shown as a solid red line. The slope of the linear fit and the correlation coefficient are shown in the top-left of each panel.

or a mixed-moisture gravity wave (Á. Adames et al., 2019; Á. F. Adames, 2022), as will be discussed in the following section.

In order to objectively quantify the regional dependence of the moisture mode fea-215 tures of the MJO, the seasonal (Nov-Apr) space-time spectra of  $T_b$  for two different sec-216 tors of the tropics is shown in Figure 3: Indo-Pacific  $(10^{\circ}N-10^{\circ}S, 60^{\circ}E-180^{\circ})$  and East-217 ern Pacific - Atlantic (10°N–10°S, 120°W–0°). More details about the calculation of re-218 gional spectra can be found in the figure caption. The wavenumber-frequency distribu-219 tion of base 10 logarithms of  $N_{mode}$ , following a similar procedure of A. F. Adames (2022), 220 is also depicted as shading. Areas shaded in blue are moisture modes. Each spectrum 221 shows clear evidence of the differences in the intraseasonal time scale (periods more than 222 20 days). In the Indo-Pacific spectrum (Fig. 3a), a wide range of zonal wavenumbers ( $k \approx$ 223 (0-7). The peaks are centered at wavenumbers k = 2-3, in a region where moisture 224 modes are expected according to the  $N_{mode}$  spectrum. However, the story is quite dif-225 ferent in the Eastern Pacific and Atlantic spectrum (Fig. 3b), where stronger power spec-226 tra are mainly concentrated in planetary wavenumbers  $k \approx 1-2$  and frequencies of 227

 $\sim 20-50$  days. According to the N<sub>mode</sub> wavenumber-frequency spectra, the intraseasonal

signal over these regions is clearly located in the mixed moisture-gravity wave regime (Å. F. Adames,
 20022).

#### 4 The Moisture Mode Cutoff Wavenumber $(k_{moist})$

**Table 1.** Table of constants used in this study with their units and values. The calculation wasconducted considering two separate regions, over and outside the warm pool region.

Parameter	Description	Value		Units
		Indo-Pacific	E. Pacific-Atlantic	
c	Dry gravity wave speed	50	50	${\rm m~s^{-1}}$
$m_{eff}$	Effective gross moist stability	0.05	0.28	_
$ au_q$	Moisture sensitivity	27.2	13	h
$ au_t$	Temperature sensitivity	16.1	9.7	h
r	Cloud-radiative feedback parameter	0.13	0.07	—

In order to better understand the differences in the spectral signal shown in Fig. 232 3, we will employ the linear theory of Ahmed et al. (2021) to assess whether the differ-233 ent behavior is a result of mean state differences. Their theory examined the dispersion 234 relation of an MJO-like mode without assuming moisture mode a-priory. They found the 235 existence of a "moisture mode cutoff wavenumber"  $(k_{moist})$ , which describes the wavenum-236 ber in which longwave quasi-equilibrium (QE) modes (or mixed moisture-gravity waves) 237 transition to WTG moisture modes. According to Ahmed et al. (2021) moisture modes 238 exist when  $k > k_{moist}$ . The value of  $k_{moist}$ , is determined from the following relation, 239

$$k_{moist} \approx \frac{2}{c} \sqrt{\frac{m_{eff}(\tau_t + \tau_q)}{\tau_q^2 \tau_t}} \tag{5}$$

where  $m_{eff}$  is the effective gross moist stability (GMS), defined as a measure of the GMS that includes the impact of the radiative heating in the export of MSE (e.g., Inoue et al., 2020). The terms  $\tau_t$  and  $\tau_q$  are the sensitivity of convection to temperature and moisture fluctuations, respectively. A detailed derivation and scale analysis of Eq. (5) is explained in the supplementary material. The values of  $\tau_t$  and  $\tau_q$  in Eq. (5) are estimated as in Ahmed et al. (2020), where precipitation can be related to moisture and temperature by using a multiple linear regression model as follows,

$$P' = \frac{\langle q \rangle'}{\tau_q} - \frac{C_p}{L_v} \frac{\langle T \rangle'}{\tau_t} \tag{6}$$

By using Eq. (6), we obtain the values of the convective sensitivities  $\tau_t$  and  $\tau_q$  for the 247 warm pool region of about 16.1 and 27.2 hours (Table 1), respectively. These values are 248 longer than those used in Ahmed (2021). Outside the warm pool, the values of  $\tau_t$  and 249  $\tau_a$  decrease to 9.7 and 13.0 hours, respectively. Thus, the cooler tropospheric temper-250 ature outside the warm pool quantitatively impacts the convection moisture sensitivity 251 (Ahmed et al., 2020). In addition, considering that the moisture mode cutoff wavenum-252 ber depends on  $m_{eff}$  (Ahmed et al., 2021), we also computed the value of  $m_{eff}$  from 253 reanalysis for two distinct regions over the tropics. For the MJO, we found a value of 254

 $m_{eff} \sim 0.05$  over the Indo-Pacific warm pool region (Fig. S2c and Table 1). In con-255

trast, the value of  $m_{eff}$  is larger outside of the warm pool ( $m_{eff} \sim 0.28$ ), causing  $k_{moist}$ 256 to be larger.

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Figure 3. Regional wavenumber-frequency power spectrum (contours) of the symmetric component of CLAUS  $T_b$  calculated for (a) Indo-Pacific [10°N–10°S, 60°E–180°E] and (b) Eastern Pacific - Atlantic  $[10^{\circ}N-10^{\circ}S, 120^{\circ}W-0^{\circ}]$  and for the extended boreal winter (November-April). The functional form of the tapering window is the same as described in Wheeler and Kiladis (1999). Background spectra were estimated separately for the regional domain, using the smoothing procedure of Dias and Kiladis (2014). Contour interval is 0.05. Shadings represent wavenumber-frequency distribution of base 10 logarithm of  $N_{mode}$  following similar procedure of Á. F. Adames (2022). Blue shading represents tropical systems that can be categorized as moisture modes, yellow can be considered inertio-gravity waves, and white represents mixed systems. The red dashed lines in both panels indicate the moisture mode cutoff wavenumber  $(k_{moist})$ .

Replacing all these values into Eq. (5), we obtain a value of  $k_{moist} \approx 1.1$  for the 258 warm pool region and  $k_{moist} \approx 4.0$  elsewhere (dashed red lines in Fig. 3). That  $k_{moist} \approx$ 259 1.1 over the warm pool means that moisture modes can extend to the planetary length 260 scale (except for k = 1) since to  $m_{eff}$  is nearly to zero. Spectral peaks are observed 261 at wavenumbers k = 2-3 (Fig. 3a), indicating that the peak MJO signal is expected 262 to behave as a moisture mode in this region, consistent with the  $N_{mode}$  analysis. In con-263 trast, outside the warm pool region (Fig. 3b)  $k_{moist} \approx 4.0$  because of the larger effec-264 tive GMS ( $m_{eff} \approx 0.28$ ). Over the Eastern Pacific-Atlantic region, the signal strength 265 is mainly concentrated in planetary wavenumbers  $k \approx 1-3$ . The strongest MJO sig-266 nal in this region is concentrated over the mixed gravity wave spectrum (white shading 267 in Fig 3). Thus the result of the  $k_{moist}$  analysis is largely consistent with the results of 268 the four criteria discussed in the previous section. 269

#### 5 Summary and conclusions 270

On basis of four criteria to identify moisture modes proposed in previous works (A. Adames 271 et al., 2019; Ahmed et al., 2021; Mayta et al., 2022), we demonstrated that the MJO can 272

<sup>273</sup> be considered a moisture mode only over the Indian Ocean (60°E to 110°E; Fig. 1d). <sup>274</sup> Elsewhere, the MJO has properties of both moisture mode and gravity wave. By using <sup>275</sup> the theory proposed by Ahmed et al. (2021), we found that two factors explain why the <sup>276</sup> MJO behaves like a moisture mode over the Indian Ocean: (i) a small effective gross moist <sup>277</sup> stability ( $m_{eff} \rightarrow 0$ ); and (ii) a slow convective adjustment timescale. These two fea-<sup>278</sup> tures allow moisture modes to exist at the largest zonal scales in this region (except wavenum-<sup>279</sup> ber 1; Fig. 3a ).

The opposite occurs outside the Indian Ocean; most of the MJO signal is observed 280 in wavenumbers  $k \sim 1-2$ , falling in the mixed moisture-gravity wave part of the N<sub>mode</sub> 281 spectrum (Fig. 3b). Over this region, the effective gross moist stability is almost five times 282 larger than over the warm pool  $(m_{eff} \approx 0.28)$  and the convective adjustment timescale 283 is faster. Under these conditions, WTG balance is not achieved at the MJO scale and 284 temperature and moisture fluctuations play comparable roles. These results are in agree-285 ment with previous works that posited that the planetary-scale component of the MJO 286 is not a moisture mode (Powell, 2017; A. Adames et al., 2019; Ahmed et al., 2021; Chen, 287 2022; Mayta & Adames, 2023). In other words, the circumnavigating MJO component 288 outside of the warm pool exhibits features that are more akin to a Kelvin wave (e.g., So-289 bel & Kim, 2012). 290

The results of this study have several implications. First, more theoretical work 291 must be done to understand how a zonally-varying mean state affects the MJO. These 292 results could also help us understand the scale selection mechanism of the MJO, which 293 is likely not determined by moisture mode processes. Furthermore, the transition from moisture mode to a mixed wave should be examined further, especially with more GCMs. 295 While not discussed here, this transition may help us further understand the Maritime 296 Continent barrier effect (Zhang & Ling, 2017), and the MJO-QBO connection (Son et 297 al., 2017), both of which occur in the region where the MJO begins to exhibit a tran-298 sition from a moisture mode to a mixed mode. Lastly, it is curious that MJO initiation 299 occurs in the region where moisture mode behavior is observed. It is possible that de-300 viations from WTG balance play an important role in exciting moisture modes, as Snide 301 et al. (2022) posited. All of these outstanding questions may be fruitful directions for 302 future research. 303

#### <sup>304</sup> 6 Open Research

The dataset used in this study are available at ECWF (ERA5; https://doi.org/ 305 10.24381/cds.adbb2d47), the Atmospheric Radiation Measurement (ARM) program 306 archive (VARANAL; https://iop.archive.arm.gov/arm-iop/0eval-data/xie/scm 307 -forcing/iop\_at\_mao/GOAMAZON/2014-2015/) [registration is required to access data]. 308 TOGA-COARE dataset are available at https://data.eol.ucar.edu/dataset/dsproj 309 **?TOGA\_COARE**, and the interpolated CLAUS  $T_b$  data is available at https://catalogue 310 .ceda.ac.uk/uuid/ce476101711ce73107c9e90265ec6d9a. DYNAMO NSA array av-311 erages from observations data (Version 3a) are available at http://johnson.atmos.colostate 312 .edu/dynamo/. The OMI index is available at https://psl.noaa.gov/mjo/mjoindex/. 313

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# Supporting Information for "Is the Madden-Julian Oscillation a Moisture Mode?"

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#### a. Wave-type filtering of CLAUS $T_b$

To isolate individual components of the MJO,  $T_b$  is filtered following the method proq posed by Wheeler and Kiladis (1999) using the same frequency-wavenumber boxes docu-10 mented in previous works (Kiladis et al., 2009). This is accomplished in the wave number-11 frequency domain by retaining only those spectral coefficients within a specific range cor-12 responding to the spectral peaks associated with a given mode. The filter settings for the 13 20-96-days period and wavenumbers k = 0 - 2, k = 3 - 10, and k = 0 - 10. 14

#### b. Phase speed calculation: A Radon Transform Approach 15

The Radon Transform was been used in recent years as more objective way to calculate 16 the phase of the waves (e.g., Yang et al., 2007; Mayta et al., 2021; Mayta & Adames, 17 2021; Mayta et al., 2022). The Radon Transform of g(x, y) is the integral of g along the 18 line L oriented at angle  $\theta$ , with angles ranging from 0° to 180°. A detailed schematic and 19 explanation of each variable can be found in Fig. A1 of Mayta et al. (2021). Thus, the 20 Radon Transform can be defined as a projection of q(x, y) on L as follows: 21

$$P(s,\theta) = \int_{u} g(x,y) du \tag{S1}$$

where u is the direction orthogonal to L, and s is the coordinate on L. Thus, for a 22 given angle  $\theta$ , the Radon Transform is a function of the line coordinate s. From these 23 considerations and rewriting equation S1 above in terms of coordinates x and y, 24

$$p(x',\theta) = \int_{y'} f(x,y) \Big|_{\substack{x = x'\cos\theta - y'\sin\theta\\x = x'\sin\theta - y'\cos\theta}} dy'$$
(S2)

the phase speed is expressed by finding the value of  $\theta$  or  $\theta_{max}$ , for which  $\int p^2 f(s, \theta) ds$ , when p from equation S2 is a maximum. Finally, the phase speed  $c_p$  is then calculated as follows,

$$c_p = \frac{tan(\theta_{max}) \times \Delta x \times 111.319km \times cos(\varphi)}{\Delta t}$$
(S3)

where 111.319 km ×  $cos(\varphi)$  is the length of a degree longitude at latitude  $\varphi$ . The phase speed  $c_p$  is obtained based on the temporal ( $\Delta t$ ) and spatial ( $\Delta x$ ) resolution of the data considered in the time-longitude calculation. Table S1 summarizes the phase speed calculated for different regions.

# c. Calculation of cloud-radiation feedback parameter (r) and Effective Gross Moist Stability $(m_{eff})$

In this study, we calculated  $m_{eff}$  from a scatterplot of anomalous  $\langle \omega \partial_p m \rangle$  and  $\langle Q_r \rangle$ against  $\langle \omega \partial_p s \rangle$  as in Inoue and Back (2017):

$$m_{eff} = \underbrace{\frac{\langle \omega \partial_p m \rangle}{\langle \omega \partial_p s \rangle}}_{\Gamma} - \underbrace{\frac{\langle Q_r \rangle}{\langle \omega \partial_p s \rangle}}_{r} \tag{S4}$$

Figure S2 shows scatterplots for the calculation of  $m_{eff}$  for two distinct regions: Indo-Pacific warm pool (60°E–180°) and Eastern Pacific-Atlantic (120°W–0°).  $\Gamma$  shows relatively different values in both regions with a higher value over Eastern Pacific- Atlantic ( $\Gamma \approx 0.35$ ) than Indo-Pacific ( $\Gamma \approx 0.18$ ). The cloud-radiation feedback parameter is depicting close values in both regions, with r = 0.13 and r = 0.07 for the warm pool and Eastern Pacific - Atlantic region, respectively. Thus, from Eq. (S4) and Figures S2c, f, is possible to infer that the  $m_{eff}$  results in different values associated with the MJO over

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<sup>43</sup> both regions. We obtain a value of  $m_{eff} = 0.05$  for the warm pool region (Fig. S2c) and <sup>44</sup>  $m_{eff} = 0.28$  for the Eastern Pacific - Atlantic region (Fig. S2f).

#### <sup>45</sup> d. The Moisture Mode Cutoff Wavenumber $(k_{moist})$ definition

To determine the cutoff wavenumber  $(k_{moist})$  in which the transition occurs between 47 convective quasi-equilibrium (QE) and WTG, we use the relation proposed in recent work 48 (see Eq. 51 in Ahmed et al., 2021),

$$k_{moist} \approx 2 \frac{\sqrt{m_{eff} \varepsilon_a \varepsilon_q}}{c} \tag{S5}$$

where  $m_{eff}$  is the effective gross moist stability,  $\varepsilon_q = 1/\tau_c$  is the convective moisture sensitivity, and

$$\varepsilon_a = \varepsilon_q + \varepsilon_t (1+r) \tag{S6}$$

<sup>51</sup> is the inverse of the effective convective adjustment time scale. In Eq. (S6)  $\varepsilon_t$  is temper-<sup>52</sup> ature sensitive and r cloud-radiative feedback parameter. In the section above, we found <sup>53</sup> values of r close to zero for the MJO (Figures S2c, f), which is also in agreement with <sup>54</sup> previous studies (e.g., Inoue et al., 2020). By considering this approximation, Eq. (S6) <sup>55</sup> takes the form of

$$\underbrace{\varepsilon_a}_{\tau_a^{-1}} \approx \underbrace{\varepsilon_q}_{\tau_q^{-1}} + \underbrace{\varepsilon_t}_{\tau_t^{-1}}$$
(S7)

<sup>56</sup> with these definitions, Eq. (S5) takes the following form

$$k_{moist} \approx \frac{2}{c} \sqrt{\frac{m_{eff}(\tau_t + \tau_q)}{\tau_q^2 \tau_t}}$$
(S8)

<sup>57</sup> Eq. (S8) represents a simplified version of the calculation of the moisture mode cutoff

:

 $_{\mbox{\tiny 58}}$  wavenumber  $(k_{moist})$  after scale analysis associated with the MJO.

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**Table S1.** Phase speeds propagation of the MJO considering different regions of propagation. The  $\theta_{max}$  values used in the Eq. (S3) are shown for each corresponding longitude.

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Region	Convection (Lon)	$ heta_{max}$	Phase speed (m $s^{-1}$ )
Western Pacific	$180^\circ$ to $140^\circ \mathrm{W}$	58.8 °	5.95
Eastern Pacific	$140^{\circ}\mathrm{W}$ to $95^{\circ}\mathrm{W}$	$74.3^{\circ}$	12.80
Atlantic	95°W to 0°	67.0°	8.50
Africa	$0^{\circ}$ to $55^{\circ}E$	61.3°	6.60
Western Indian Ocean	55°E to 100°E	48.8°	4.12
Eastern Indian Ocean	$100^\circ \mathrm{E}$ to $140^\circ \mathrm{E}$	51.3°	4.50
Maritime Continent	$55^{\circ}\mathrm{E}$ to $100^{\circ}\mathrm{E}$	49.6°	4.24



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Figure S1. (Top) Geographical variation of the convective moisture adjustment time scale ( $\tau_c = \langle q' \rangle / P'$ ) and the dimensionless N<sub>mode</sub> parameter (bottom). Shadings in panel (b) represent base 10 logarithm of N<sub>mode</sub> as in Adames (2022), where blue represents N<sub>mode</sub> values categorized as moisture modes, yellow can be considered inertio-gravity waves, and white represents mixed systems.



Figure S2. Scatterplot of (a, d) vertical advection of MSE ( $\langle \omega \partial_p m \rangle'$ ), (b, e) column radiative heating ( $\langle Q_r \rangle'$ ), and (c, f) their difference ( $\langle \omega \partial_p m \rangle' - \langle Q_r \rangle'$ ) as a function of column DSE ( $\langle \omega \partial_p s \rangle'$ ). The slope of the linear least squares fitting represents the gross moist stability ( $\Gamma$ ), cloud-radiation feedback (r), and the effective GMS ( $m_{eff}$ ). The shading represents the base-10 logarithm of the number of points within 0.5 W m<sup>-2</sup> × 5 W m<sup>-2</sup> bins. Anomalies are computed over the tropical belt domain (10°S–10°N) and for two separated regions: (a)-(c) Indo-Pacific Warm pool (60°E–180°); and (d)-(f) Eastern Pacific - Atlantic . The slope of the linear fit and the correlation coefficient are shown in the top-left of each panel.



Figure S3. Time-longitude diagram of  $10^{\circ}\text{S}-10^{\circ}\text{N}$  of CLAUS  $T_b$  (shading) regressed onto PC1 (normalized) of (a) k = 0 - 2, (b) k = 3 - 10, and (c) k = 0 - 10. The contour interval for  $T_b$  is 1 K. The phase speed of the MJO over the Indo-Pacific warm pool region (50°E–160°W) by using the Radon Transform is shown in each plot.