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Impact of MJO Propagation Speed on Active Atlantic Tropical Cyclone Activity Periods

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Key Points:

- The Atlantic basin sees the most subseasonal tropical cyclone activity when the Madden-Julian Oscillation (MJO) is moving slowly prior to entering phase 2
- Under normal MJO propagation higher shear occurs in the main development region than during slow propagating MJOs
- Under slow propagating MJO regimes the 500 mb geopotential height pattern has smaller wavelengths and weaker anomalies over the Atlantic

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The Madden-Julian Oscillation (MJO) is often used for subseasonal forecasting of tropical cyclone (TC) activity. However, TC activity still has considerable variability even given the state of the MJO. This study evaluates the connection between MJO propagation speed with Atlantic TC activity and possible physical mechanisms guiding this relation. We find the Atlantic sees the highest accumulated cyclone energy (ACE) during MJO phase 2. However, the odds of above average ACE in the Atlantic is greatest during slow MJO propagation. We find that slow propagation of the MJO results in lower vertical wind shear anomalies over the Caribbean and main development region compared with typical MJO propagation. Typical MJO propagation produces an amplified height pattern and lower height anomalies along the region of the tropical upper tropospheric trough which is known to impede Atlantic TC activity. Slow MJO propagation sees weaker height anomalies over the Atlantic.

Plain Language Summary The Madden-Julian Oscillation (MJO) is a large region of storminess and winds that moves slowly eastward from the Indian ocean eastward into the Pacific over the course of 40–90 days. When the MJO is over the Indian Ocean it produces more hurricanes in the Atlantic because it reduces wind shear which is the difference in winds at different heights of the atmosphere. When the MJO moves slowly or is nearly stationary over the Indian Ocean there is even more hurricane activity in the Atlantic. When the MJO moves at a normal pace, it influences the jet stream which can then dip into the Atlantic creating high wind shear. When the MJO moves slowly there is less shear over the Atlantic.

1. Introduction

Subseasonal forecasts of tropical cyclones (TCs) are important because these storms have considerable subseasonal variability and are high impact events. The difficulty in making skillful predictions has led some scientists to call the subseasonal range the "predictability desert" (Vitart et al., 2012). However, recent improvements to dynamical models (Camargo et al., 2019) and implementation of novel techniques like statistical-dynamical prediction have resulted in an increase of skill (Hansen et al., 2022; Maier-Gerber et al., 2021; Vecchi et al., 2014).

On subseasonal timescales, the primary source of predictability comes from the Madden-Julian Oscillation (MJO) (Janiga et al., 2018; Waliser et al., 2003; Zhang, 2005). The MJO is a global wave pattern centered on the equator that propagates eastward at 3–6 m s^{-1} with a period of 40–90 days (Jones et al., 2004; Kim et al., 2018; Knutson et al., 1986; Madden & Julian, 1971; Xie et al., 1963). During the westerly phase of the MJO in the Atlantic, or phases 1, 2 and 3 of the widely used Real-time Multivatiate MJO (RMM) index of Wheeler and Hendon (2004), enhanced TC genesis was found to occur in the tropical Atlantic (Maloney & Hartmann, 2000). Other measures of TC activity also vary with MJO phase; accumulated cyclone energy (Bell et al., 2000, ACE) in the Atlantic basin was found to increase by 25% during MJO phases 2 and 3 (Vitart, 2009). The MJO is hypothesized to directly modify environmental conditions in the Atlantic by decreasing vertical wind shear and increasing relative vorticity and relative humidity (RH) (Camargo et al., 2009; Klotzbach, 2010; Maloney & Hartmann, 2000).

However, even given a favorable MJO phase, there is significant variability in TC activity. The MJO may also influence environmental conditions over the Atlantic indirectly through mid-latitude teleconnections, although this relationship, particularly in boreal summer is weak and not well established (Tseng et al., 2019; Zhou et al., 2012). The MJO has been shown to impact Rossby wave breaking (RWB) over the Atlantic which can influence Atlantic TC activity (Li et al., 2018; Papin et al., 2020). The MJO also influences Pacific TC activity (Liebmann et al., 1994), and recurving TCs in this basin have been shown to amplify RWB events altering height anomalies over North America and western Atlantic (Archambault et al., 2015). Given the multi-faceted influence of the MJO on Atlantic TC activity, using just the instantaneous phase of the MJO overlooks important aspects of predictability. The combined influence of MJO remote teleconnections and local environmental influence in influencing TC activity is not well understood.

Hence, in this study we investigate how the propagation speed of the MJO can provide additional information on Atlantic TC activity and explores potential physical mechanisms guiding this relation. In Section 2 we explain methodology and datasets. In Section 3 we present findings on MJO influence on Atlantic TC activity and environmental patterns. We summarize our findings and discuss the implications of this study in Section 4.

2. Methods

2.1. Reanalysis Data

Thermodynamic and dynamic fields are calculated or taken directly from the ECMWF Reanalysis version 5 (ERA5) (Hersbach et al., 2020). Hourly data are available at 137 vertical levels on a 0.25° grid, although for this study only 0000 UTC data at four vertical levels and 1.25° horizontal resolution are used for faster computation. We use 500 hPa geopotential height, vertical wind shear calculated using the 200 and 850 hPa zonal and meridional winds, and 200 hPa potential vorticity (PV) fields. Reanalysis data during August, September, and October (ASO) periods from 1979 to 2020 are used in this study to focus on peak hurricane season in the Atlantic.

2.2. Madden-Julian Oscillation

For this study we quantify the MJO using outgoing longwave radiation (OLR) which serves as a proxy for convective activity. In particular we use the values of the two principal components (PCs) of the OLR MJO Index (OMI) from NOAA (Kiladis et al., 2014) during ASO periods from 1979 to 2020. OMI is used as the OLR MJO indices are able to capture seasonally dependent MJO features during boreal summer and better captures propagation than other indices (Wang et al., 2018).

The magnitude of the MJO is determined by the square root of the sum of the squares of the two PCs and is visually represented as the distance from the center in the Wheeler Hendon diagrams. From the PCs the MJO can be classified as one of eight phases or in a neutral/inactive state if the MJO is below the standard 1.0 magnitude threshold.

2.3. Tropical Cyclone Activity

Six-hourly TC data from the National Hurricane Center best track database (Landsea & Franklin, 2013, HURDAT2) are retrieved from the International Best Track Archive for Climate Stewardship (Knapp et al., 2010, IBTrACS). TC activity is quantified using accumulated cyclone energy (ACE), defined as the summation of the square of the maximum sustained surface winds (in knots) in a TC at each six-hour interval (Bell et al., 2000). For this study, ACE is calculated for TCs with maximum sustained winds exceeding 34 kt in the North Atlantic south of 30°N. We select ACE because of its utility as a continuous function and for the added weight toward more intense TCs.

To find subseasonal patterns in environmental fields that indicate enhanced subseasonal TC activity we use the compositing method ACE by Year (ABY) from Hansen et al. (2020, hereby known as H20). ABY was shown to highlight patterns associated with the MJO and other subseasonal factors while removing signals from ENSO. The selection of periods to go into an ABY composite is done by taking 5-day periods with the top 33% of normalized ACE anomalies from each year. The running mean of ACE smooths out weather signals, and the normalized anomaly removes the seasonal cycle. Equal selection of periods from each year ensures that oscillations that affect Atlantic hurricane activity on seasonal scales, such as ENSO, are averaged out. See H20 for more detail on this method. While (Hansen et al., 2020, 2022) used ABY to create composites of spatial environmental conditions associated with subseasonal TC activity, here we use ABY to highlight subseasonally active TC periods in MJO phase space.

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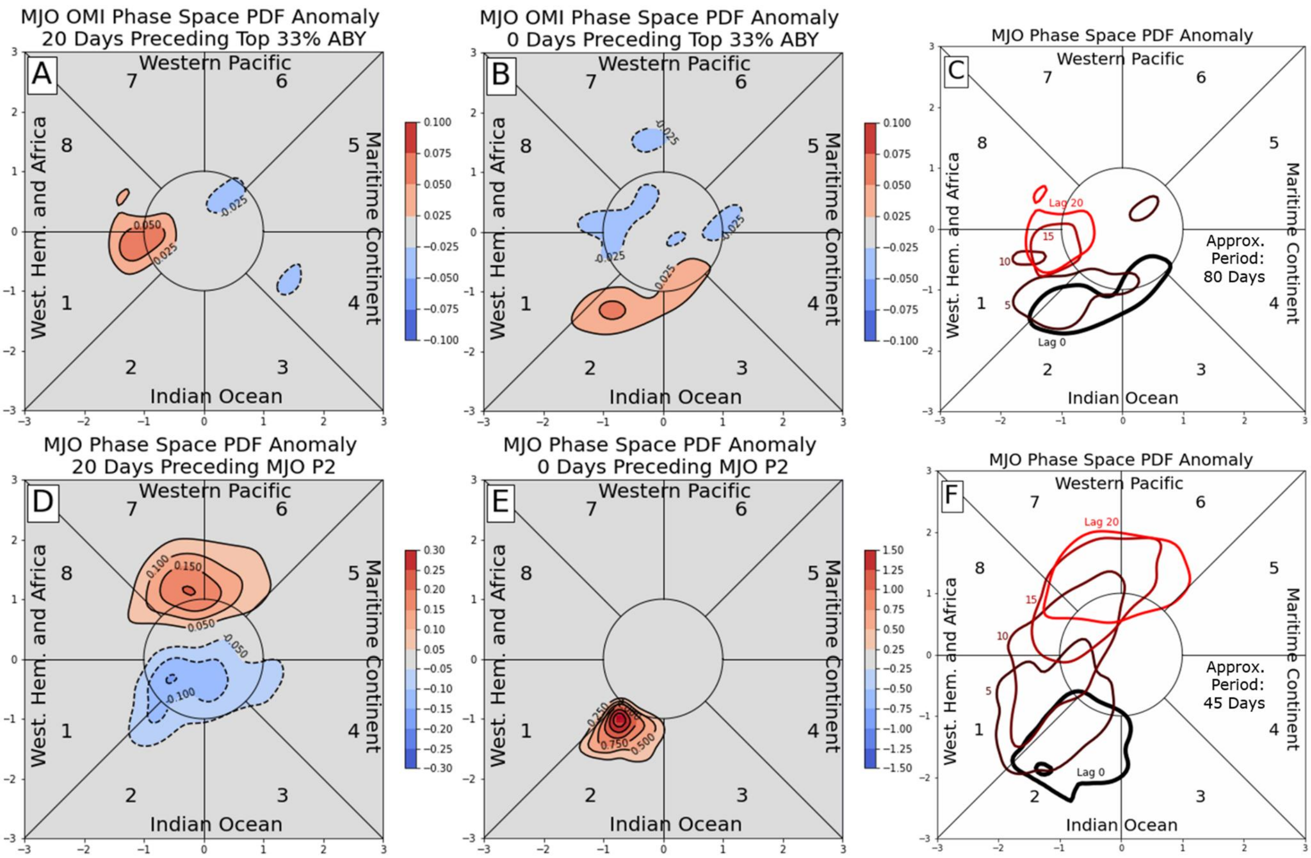

Figure 1. The PDF anomalies in MJO phase space of (a) MJO state concurrent with ABY periods, (b) MJO state 20 days prior to ABY periods, (c) MJO state 20 days prior to MJO phase 2. Note the difference in scale for each plot.

3. Results

Figure 1 uses probability density function (PDF) anomalies of the MJO on the Wheeler Hendon phase space. To calculate the PDFs, the MJO phase space is separated into 10,000 bins (100 × 100 for each EOF dimension) and the relative frequency of occurrence is calculated for each bin and put through a Gaussian smoothing function. PDF anomalies are calculated as the difference of the subsample PDF from the total climatological PDF. From Figure 1a, we can see that active subseasonal TC periods (using ABY as defined in H20) in the Atlantic are most likely to occur during MJO phase 2, with above average activity occurring to a lesser extent in MJO phase 3. This is consistent with previous studies like Maloney and Hartmann (2000); Klotzbach (2007); Vitart (2009); and H20.

Based on the PDF anomaly in Figure 1b, 20 days prior to active subseasonal Atlantic TC periods the MJO is more likely to be in phases 8 and 1. This is corroborated by Table 1; 20 days prior to ABY periods, phases 8 or 1 of the MJO occur in 18% of cases compared with a climatological rate of 13%. In fact, the MJO phase 20 days prior to an active period appears to have a stronger connection to Atlantic TC activity than the concurrent MJO phase as

Table 1
The Percent Frequency of the MJO Occurring in Phases 8, 1, 6, and 7 for Periods 20 Days Prior to ABY (Column 2), 20 Days Prior to MJO Phase 2 (Column 3) and for All MJO Cases (Column 4)

MJO phase	Twenty days prior to ABY	Twenty days prior to MJO phase 2	Climatological occurrence
8	6	6	4
1	12	7	9
6	5	19	7
7	5	22	5

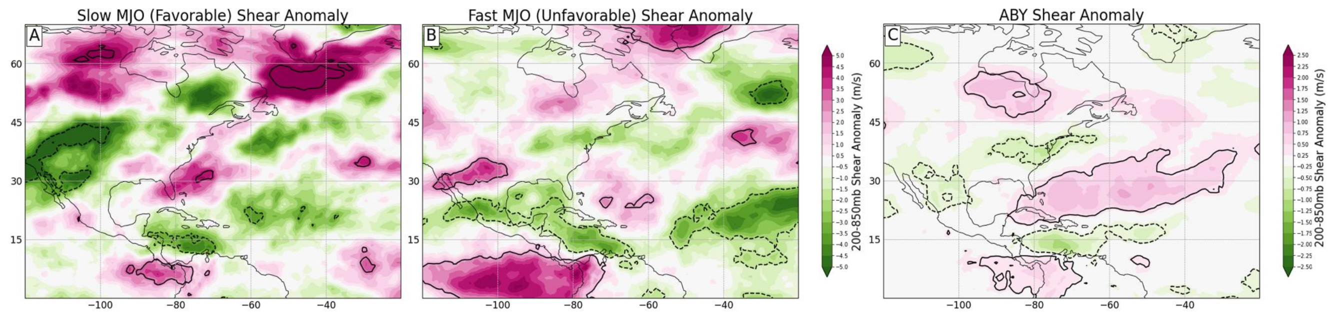

Figure 2. Conditional composites of 200–850 mb shear anomalies (m/s) over the Atlantic during (a) MJO phase 2 with an MJO of phase 6 or 7 occurring 20 days prior, (b) MJO phase 2 with an MJO phase 8 or 1 occurring 20 days prior, and (c) ABY composite of vertical wind shear. Bold contours indicate regions that are statistically different from the daily climatological mean ($p < 0.05$) using a two tailed t-test.

indicated by the higher PDF anomalies in Figure 1b than in Figure 1a. Figure 1c shows a slow progression of the MJO prior to active periods as compared to climatological progression in Figure 1f. This is corroborated by the slow evolution of OLR anomalies in Figure 4a. Twenty days prior to MJO phase 2 the MJO exists in phases 6 and 7 in 41% of cases compared with the climatological rate of 12% demonstrating that typical MJO propagation is faster which is in agreement with the PDF anomalies in Figure 1c. The significance of the anomalous frequency of MJO occurring in these phases (MJO phases 8 and 1, 20 days prior to ABY periods and phases 6 and 7, 20 days prior to MJO phase 2) was evaluated using a chi squared test in comparison to climatological values and was found to be significantly different ($p < 0.001$).

One caveat we considered is that MJO propagation speed is influenced by ENSO. Wei and Ren (2019) suggest MJO propagation is slower during La Niñas (although their study is based on boreal winter) and this relation could explain why subseasonally active Atlantic TC periods appear to occur when the MJO is propagating slowly. However, ABY should remove the influence of seasonal oscillations like ENSO. As an extra precaution, we recalculated the PDF anomalies only considering cases with SST anomalies in the Niño 3.4 region less than 0.5°C in magnitude (not shown) which produced very similar results to those in Figure 1, suggesting that ENSO is not responsible for slower MJO propagation prior to active TC periods.

To evaluate potential mechanisms linking MJO propagation to Atlantic TC activity, we looked at conditional composites of vertical wind shear (Figure 2). For periods in MJO phase 2 that, 20 days prior, were preceded by MJO phase 6 or 7 (representing typical MJO propagation, Figure 2a) there is a pattern of anomalously low shear in the Caribbean and main development region (MDR) which indicates favorable conditions for TC activity. There is a region of anomalously high shear to the north of the Caribbean which is similar to the favorable pattern for TC activity in H20 and the ABY composite in Figure 2c. Periods of MJO phase 2 that were preceded by MJO 8 or 1 20 days prior (representing slow MJO propagation associated with active Atlantic TC activity, Figure 2b) produce a similar pattern of shear anomalies, although there are some key distinctions. Shear anomalies are even more pronounced during slow MJO propagation compared with typical MJO propagation. Shear anomalies in slow MJO propagation cases are also displaced further north which places high shear anomalies well north of the Caribbean. Overall, the slow MJO propagation shear composite more closely matches the shear signal for enhanced subseasonal TC activity (Figure 2c) than the typical MJO propagation composite.

The subseasonal shear patterns may be linked to mid-latitude phenomena such as negative PV anomalies as shown in Chang et al. (2023) and Hansen et al. (2022). To evaluate the influence of MJO propagation on extratropical features, we take conditional composites of 500 hPa height anomalies shown in Figure 3. We can see that the mid-latitude response to typical MJO propagation (Figure 3a) is characterized by large ridges and troughs. Low height anomalies centered over the northeast Atlantic extend into the tropical Atlantic. This suggests an enhanced Tropical Upper Tropospheric Trough (TUTT) that may increase shear and thus reduce Atlantic TC activity. In contrast, the slow propagating MJO (Figure 3b) is characterized by a shorter wavelength pattern with weaker anomalies over the tropical Atlantic. While there are negative height anomalies along the TUTT region these are generally north of 30°N. These results are also true using 15-day lags although those composites do not demonstrate the trough as clearly.

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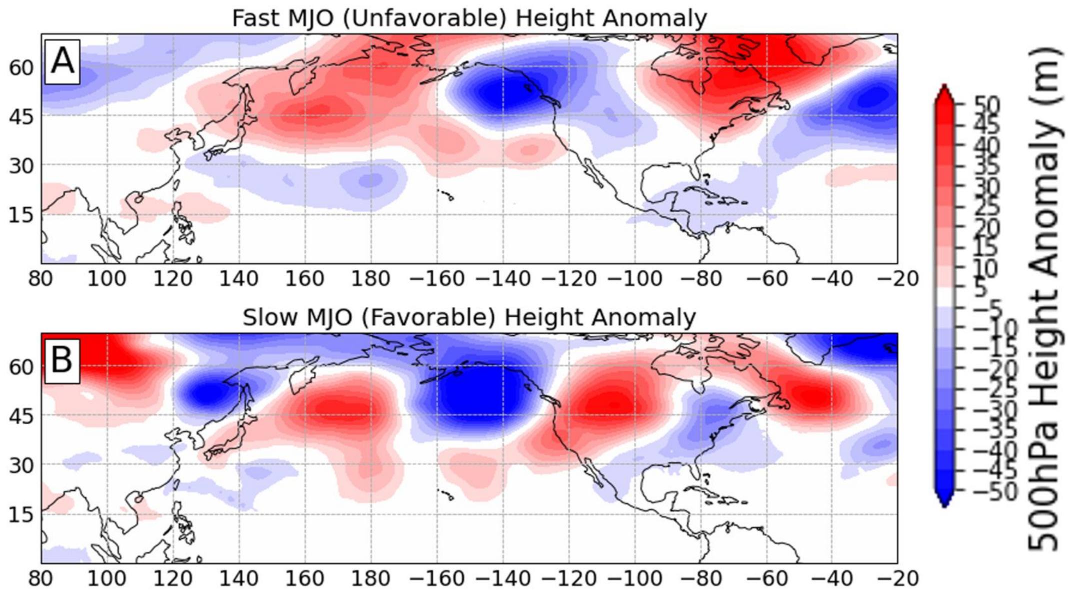

Figure 3. Conditional composites of 500 mb height anomalies over the north Pacific and Atlantic basins (a) MJO phase 2 with an MJO of phase 6 or 7 occurring 20 days prior and (b) MJO phase 2 with an MJO phase 8 or 1 occurring 20 days prior.

These results are supported by a one-dimensional Fourier analysis of height anomalies averaged over 30–60N (Figure S1 in Supporting Information S1). For the slow propagating MJO (Figure 3b), the power spectrum peaks for height oscillations with wavelength of 72° longitude indicating a wavenumber 5 pattern. For typical MJO propagation (Figure 3a), the power spectrum peak occurs for height oscillations with a wavelength of 120° longitude indicating larger oscillations and a wavenumber 3 pattern. The power spectrum peak is higher for the slow propagation, but this seems to be because of the lower number of cases and thus higher apparent magnitude of anomalies. A sub-sample of the typical MJO propagation is taken so that the composite sample size is equal, and the typical MJO propagation was found to have a higher peak in the power spectrum and thus stronger oscillations in the mid-latitude height pattern.

Matthews et al. (2004), Gloeckler and Roundy (2013), Li et al. (2018), and Chang et al. (2023) have shown that the MJO influences North American and Atlantic weather through Rossby wave breaking events that are initiated by convection in the Pacific. During and immediately prior to MJO phase 2 (Figure 4h) convection is suppressed around the near-equatorial north Pacific as we would expect. Ten to 20 days preceding MJO phase 2 (Figures 4e–4g) the signal of suppressed convection shifts over the Indian Ocean and convective activity can be seen in portions of the Western North Pacific (WNP) particularly the northern South China Sea (SCS) at 15 days prior. Five days prior to ABY periods (Figure 4d) the OLR signal shows more convective activity over the maritime continent and suppressed convection to the north around coastal China. This signal is relatively constant through 10 and 15 days prior to ABY events. It is at 15–20 days prior (Figures 4a and 4b) that the suppressed convective signal over the SCS begins to fade.

4. Discussion and Conclusion

The MJO is associated with enhanced TC activity in the Atlantic basin during phase 2 when there is enhanced convection over the Indian Ocean. However, there is significant variability in TC activity even given this condition. More information can be gained by assessing the prior state of the MJO. This study shows that there is a significant discrepancy in the MJO propagation speed occurring in seasonally active versus inactive TC periods in the Atlantic. The MJO is most likely to be in phases 6 or 7, with convective activity over the West and Central Pacific, 15 to 20 days prior to reaching phase 2. However, this typical propagation is not most favorable for Atlantic TC activity. Even though active TC periods in the Atlantic also occur most frequently in MJO phase 2, 15 to 20 days prior to active TC periods, the MJO is more likely to be in phases 8 and 1 which see convective activity over Africa and the western Indian Ocean. These suggest that slow propagating or nearly stationary MJOs in the Indian Ocean create favorable conditions for Atlantic TC activity.

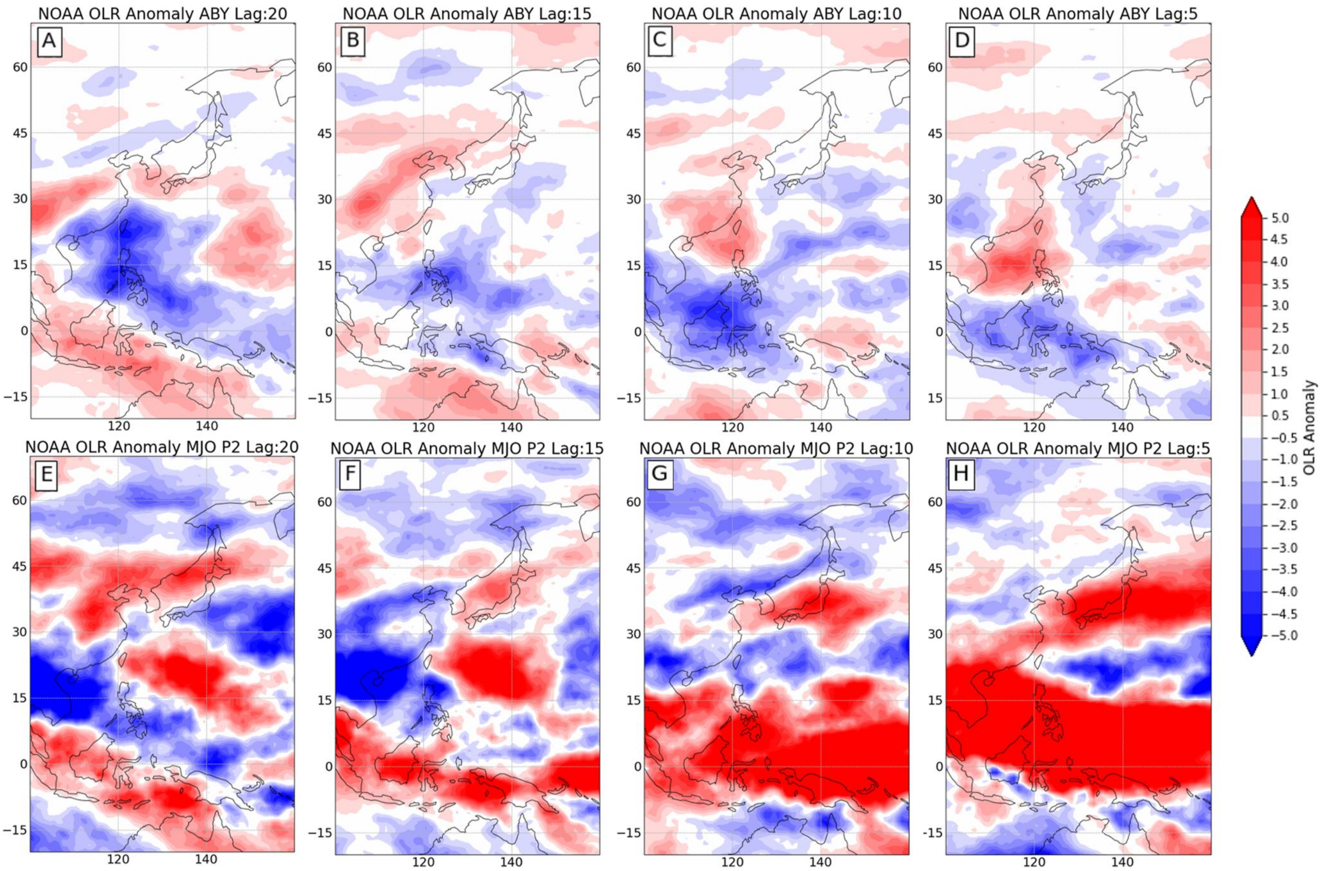

Figure 4. Composites of NOAA OLR anomalies preceding ABY events by 20, 15, 10, and 5 days (a–d) and preceding MJO phase 2 by 20, 15, 10, and 5 days (e–h).

MJO phase 2 is associated with anomalously low shear in the Caribbean and higher shear to the north. This dipole pattern is similar to the subseasonal shear signal that favors enhanced Atlantic TC activity found in H20. When the MJO propagates to phase 2 from phases 6 and 7 this dipole shear pattern is not as apparent and higher shear encroaches into the Caribbean. When the MJO propagates from phase 8 and 1 into phase 2, low shear anomalies centered over the Caribbean are higher in magnitude.

We investigated the connection between the propagation of the MJO and Atlantic TC activity. It is reasonable to hypothesize that ENSO state is responsible for both the enhanced TC activity (Goldenberg & Shapiro, 1996) and the slower speed of MJO as suggested by Wei and Ren (2019). However, our metrics for measuring subseasonal TC activity should remove the influence of ENSO and other long period oscillations, and we have verified that these results are consistent even when only considering neutral ENSO years. Instead we suggest that the MJO modulates Atlantic TC activity through amplification of mid-latitude wave patterns which influence shear anomalies over the Atlantic. We showed that typical MJO propagation produces high amplitude and long period wave patterns in geopotential height anomalies. Anomalous troughing occurs over the Atlantic under these conditions, which likely produces higher shear that counteracts the low shear anomalies produced by the MJO circulation itself. When the MJO moves slowly from phase 8 and 1 to phase 2 the corresponding height anomaly pattern has lower amplitude and higher spatial frequency waves that do not extend into the tropical western Atlantic. These findings are also corroborated by 200 hPa PV anomalies (not shown) which indicate an absence of PV over the Bahamas during slow propagating MJO periods which corresponds to less intrusion of mid-latitude air. Typical MJO propagation also sees negative PV anomalies over this region but of lower magnitude than slow propagating MJO cases. Enhanced PV anomalies are usually characterized by increased shear equatorward, which are in line with the findings from Figure 2.

We suggest that when the MJO is active in the Pacific, enhanced convection initiates a Rossby wave train that triggers an extratropical response over the Atlantic at nearly the same timeframe that the MJO circulation reaches the Atlantic. Our OLR composites in Figure 4 support this notion as there is enhanced convection over the SCS 15 days prior to the MJO reaching phase 2. We note that there is suppressed convection in the north SCS prior to ABY events that are not seen in periods prior to MJO phase 2, thus it is possible that the SCS is a particularly crucial region that determines the initiation or path of Rossby wave trains. It is also possible that unfavorable RWB patterns over the Atlantic during typical MJO phase 2 are initiated by recurving typhoons (Archambault et al., 2015; Ferreira & Schubert, 1999). The MJO is often in phase 6 and 7, which favor WNP TC activity (Klotzbach & Oliver, 2015), 15–20 days prior to MJO phase 2. The mechanism that initiates Rossby wave trains could be another feature entirely, for instance OLR plots lagging MJO phase 2 by 20 and 25 days (not shown) indicate large convective anomalies off the coast of Japan. These findings are somewhat counter to previous studies such as Li et al. (2018) which finds anti-cyclonic Rossby wave breaking (AWB) decreases in the Atlantic during MJO phases 2 and 3. However, there is a significant difference in methodology; our study suggests mid-latitude responses counteract the favorable conditions produced by the MJO although they may not fall under the category of AWB.

Regardless of the exact method by which the mid-latitude response is initiated, there is clear evidence linking MJO propagation to TC activity in the Atlantic. Thus, in the case of slow propagating MJOs, suppressed convection in the SCS, reduced Typhoon activity, or perhaps another mechanism results in an altered downstream trough amplification which leads to more favorable shear anomalies seen in Figure 2b. If subseasonal Atlantic activity is dependent on WNP typhoon activity (a relatively noisy parameter), this may explain the low correlation between MJO phase and Atlantic TC activity as compared to other basins. This relationship could be further explored in several ways. A statistical analysis looking at WNP convection of recurving typhoon occurrence and resulting Atlantic shear and geopotential height anomalies would be helpful in determining the nuances of the Pacific-Atlantic teleconnection. A linear baroclinic model (like in Watanabe and Kimoto (2000)) could be used to diagnose the impact of forcing from MJO features in the Pacific, or potentially higher latitude forcing from WNP TCs on Atlantic environmental conditions.

The results from this study demonstrate that the MJO phase several weeks prior to a given period may be just as important as the current MJO phase in determining subseasonal TC activity in the Atlantic, which suggests that the relation between the MJO and Atlantic TC activity is more complicated than the MJO producing favorable or unfavorable conditions in the Atlantic. We hypothesize and provide evidence that a delayed response from the MJO in the WNP through mid-latitude interactions is important for subseasonal TC activity in the Atlantic, although this requires more analysis. Most importantly this work can be used to improve subseasonal TC prediction. By understanding the propagation paradigm of the MJO, we have gained a new source of predictability not currently used in subseasonal forecasts and we can potentially use this to predict active TC periods in the Atlantic with higher confidence.

Data Availability Statement

MJO EOF data are available from Kiladis et al. (2014). The IBTrACS data set that was used to calculate TC metrics can be found at Knapp et al. (2010). The ERA5 data set used to calculate ABY and shear composites can be found at Hersbach et al. (2020). OLR data are available from Lee (2011).

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