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Key Points:

- The Madden-Julian oscillation (MJO) significantly impacts continental US hurricane landfall frequency
- Gulf Coast hurricane landfalls are favored when the MJO is enhancing Western Pacific/Western Hemisphere convection
- East Coast hurricane landfalls are favored when the MJO is enhancing Indian Ocean/Maritime Continent convection

Supporting Information:

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

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Influence of the Madden-Julian Oscillation on Continental United States Hurricane Landfalls

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Abstract The Madden-Julian oscillation (MJO) significantly impacts North Atlantic hurricanes, with increased hurricane activity occurring when the MJO enhances convection over Africa and the tropical Indian Ocean and suppressed hurricane activity occurring when the MJO enhances convection over the tropical Pacific. Using data from 1905 to 2015, we find more tropical cyclones (TCs) make landfall in the continental United States when the MJO enhances tropical Indian Ocean convection. In addition, when the MJO enhances Western Pacific and Western Hemisphere convection, TC activity is preferentially favored in the Caribbean, leading to more Gulf Coast landfalls. As MJO-enhanced convection moves to the Indian Ocean and Maritime Continent, more storms form in the tropical Atlantic, favoring Florida Peninsula and East Coast landfalls. The MJO's TC steering wind modulation appears to be secondary to its genesis location modulation.

Plain Language Summary The Madden-Julian oscillation (MJO) is a large-scale atmospheric signal of winds, rainfall, and surface pressure along the equator that circles the globe every 30–70 days. The MJO's location affects wind patterns that can then increase or decrease North Atlantic hurricane activity. When the MJO increases thunderstorms (convection) over Africa and the Indian Ocean, there tend to be more North Atlantic hurricanes. We show that the MJO patterns that increase North Atlantic hurricane activity also make hurricane landfalls more likely in the continental United States. We are likely to see more landfalls from Texas to the Florida Panhandle than from the Florida Peninsula to Maine when the MJO increases thunderstorms over the Western Pacific and Western Hemisphere. Landfalls from the Florida Peninsula to Maine tend to increase compared with Texas to Florida Panhandle landfalls when the MJO increases thunderstorms over the Indian Ocean. We believe this shift in landfall location is related to where the MJO helps storms form and less related to how the storms move after they form.

1. Introduction

The Madden-Julian oscillation (MJO) is a large-scale atmospheric mode that propagates around the globe approximately every 30–70 days (Jiang et al., 2020; Madden & Julian, 1972). As it propagates, it alters large-scale vertical wind shear, pressure, and moisture patterns, all of which have been shown to be critical for tropical cyclone (TC) formation and intensification (e.g., Bruyère et al., 2012; Camargo et al., 2007). In the North Atlantic (hereafter Atlantic), the MJO tends to increase hurricane (1-min maximum sustained winds ≥ 64 kt) activity when MJO-enhanced convection is occurring over Africa and the Indian Ocean, while decreased Atlantic hurricane activity occurs when the MJO enhances tropical Pacific convection (Klotzbach, 2010; Kossin et al., 2010; Mo, 2000; Ventrice et al., 2011). MJO-associated variations in vertical wind shear, mid-level moisture, low-level vorticity, and vertical motion are important contributors to the observed response in Atlantic hurricane activity (Camargo et al., 2009; Klotzbach, 2010). The robustness of this relationship has been documented with >100 years of historical hurricane data using a reconstructed MJO time series based on mean sea level pressure (MSLP) (Klotzbach & Oliver, 2015a).

When Kossin et al. (2010) examined Atlantic TC track clusters, they found that the MJO significantly modulated a cluster of TCs forming in the Gulf of Mexico and western Caribbean. More TCs formed in this cluster when the MJO enhanced Western Hemisphere and Indian Ocean convection, and fewer TCs formed there when the MJO enhanced western North Pacific convection.

Though prior studies have identified relationships between the MJO and TC activity around the globe, the relationship with continental United States (CONUS) landfalling TC activity has not been fully explored. Using data from 1974 to 2007, Klotzbach (2010) showed that when the MJO enhanced Indian Ocean convection, significantly more hurricanes made landfall in the CONUS than when the MJO enhanced Pacific Ocean convection. In this study, we expand upon Klotzbach (2010) and other studies by conducting an in-depth examination of the relationship between the MJO and CONUS landfalling hurricanes. Specifically, we use a 111-year MJO data set (see Section 2) to explore this relationship over 1905–2015. We then assess whether spatially-preferred locations exist for CONUS hurricane landfalls based on MJO phase. We also investigate whether changes in large-scale steering currents, formation locations, or a combination of both factors are responsible for the observed changes in landfalling hurricanes.

2. Data and Methodology

We obtained CONUS hurricane landfalls from the Atlantic Oceanographic and Meteorological Laboratory's (AOML's) website: https://www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html. Tropical storm (1-min maximum sustained winds between 34 and 63 kt) landfalls were obtained from: https://www.aoml.noaa.gov/hrd/hurdat/uststorms.html. These landfalls were aggregated from the National Hurricane Center's official Atlantic TC database (HURDAT2; Landsea & Franklin, 2013) and are currently available from 1851 to 1970 and 1983 to present. Because the Atlantic hurricane best track reanalysis project has not yet been completed for 1971–1982, we identify CONUS tropical storm and hurricane landfalls during this period from HURDAT2 following Klotzbach et al. (2018).

We subdivide the CONUS coastline into two regions: the Gulf Coast and the Florida Peninsula and East Coast (FP + EC), with the Gulf Coast/FP + EC dividing line drawn near Tarpon Springs (~28°N along the Florida west coast), similar to Klotzbach and Gray (2008). This dividing line is also used by AOML to delineate between northwest and southwest Florida landfalls. If a storm made landfall in both regions, we counted landfalls in both regions, but only the strongest landfall was counted if the TC made multiple landfalls in the same region. We focus on July–October landfalls, a period which accounts for all CONUS hurricane landfalls during the most recent 30-year NOAA climatological period (1991–2020). Atlantic July–October hurricane and Accumulated Cyclone Energy (ACE; Bell et al., 2000) data are obtained from HURDAT2. ACE is an integrated metric accounting for storm frequency, intensity, and duration.

We use a surface pressure-based index (Oliver & Thompson, 2011) to identify MJO phase and amplitude. This index was shown to successfully replicate the canonical Wheeler and Hendon (2004) MJO index with reasonable fidelity. The current version of the surface pressure-based index uses the 20th Century Reanalysis version 3 (20CRv3, Slivinski et al., 2019, 2021) and is available from 1905 to 2015 (when the 20CRv3 currently ends). The Oliver and Thompson (2011) index has been used in previous TC studies (e.g., Klotzbach & Oliver, 2015a, 2015b). Here, we restrict our examination of the MJO-TC relationship to days where the MJO amplitude exceeds 1 (~60% of July–October days from 1905 to 2015). Since the MJO does not spend the same number of days in each phase, we calculate normalized rates of hurricane activity—observed hurricane activity divided by the number of days that the MJO spends in a particular phase. Throughout the manuscript, we display the percentage of normalized TC metrics generated in each MJO phase pair. We investigate the MJO phase pairs from Klotzbach and Oliver (2015b): phases 1–2 (MJO enhancing Africa and western Indian Ocean convection), phases 3–4 (MJO enhancing convection over the eastern Indian Ocean and western portions of the Maritime Continent), phases 5–6 (MJO enhancing convection over the eastern part of the Maritime Continent and the western Pacific), and phases 7–8 (MJO enhancing central and eastern Pacific and Western Hemisphere convection). The phases examined in this study are based on this particular MJO index and may slightly vary from phases identified via other MJO indices.

We use the 20CRv3 daily-averaged ensemble mean to analyze large-scale environmental fields. The 20CRv3 system assimilates surface and sea level pressure observations, including TC reports, and prescribes monthly sea ice concentration and pentad sea surface temperature fields as boundary conditions. The reanalysis is available on a $1° \times 1°$ grid.

Normalized CONUS hurricane damage is provided by Weinkle et al. (2018). Normalization estimates the damage a hurricane would cause today by adjusting its observed damage by current values of exposure and wealth. In this analysis, we use the normalization method of Pielke and Landsea (1998) that adjusts for inflation, population,

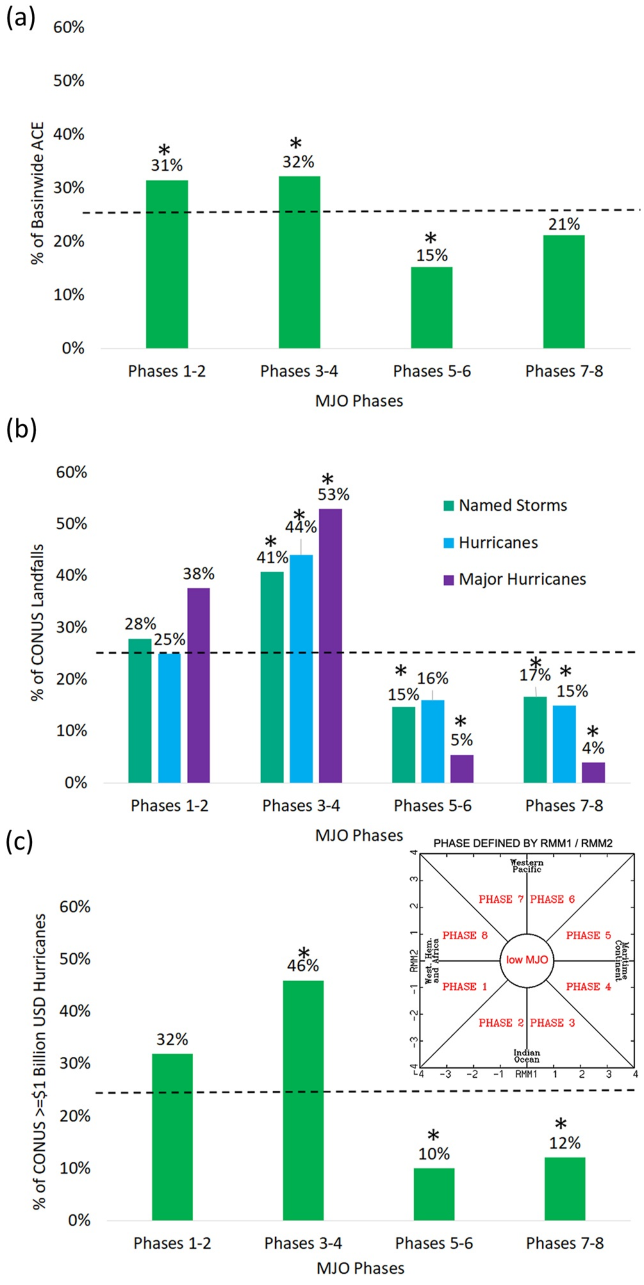

Figure 1. Madden-Julian oscillation (MJO) modulation of basinwide Atlantic ACE and continental US landfalling hurricane activity. (a) Percentage of normalized Atlantic ACE generated in each MJO phase pair. (b) Percentage of normalized CONUS named storm, hurricane, and major hurricane landfalls generated in each MJO phase pair. (c) Percentage of normalized billion-USD CONUS hurricane landfalls in each MJO phase pair. Asterisks denote statistically-significant percentages. The dashed line denoting 25% of all tropical cyclone (TC) activity in each MJO phase pair represents the null hypothesis; that is, that the MJO does not modulate TC activity. The panel (c) inset highlights where convection is favored by MJO phase, adapted from Wheeler and Hendon (2004).

and wealth per capita. Since damage from individual landfalls is not always available in Weinkle et al. (2018), when a storm made multiple landfalls, we count all damage as occurring when the storm made its strongest landfall.

We test for statistically-significant TC activity differences via bootstrap resampling using a 10% significance level threshold (Efron, 1979). We randomly select, with replacement, the number of days where the MJO is observed in a particular phase from the full sample of MJO phase days when its amplitude is greater than 1. We then calculate the rate of the phenomenon being tested (e.g., landfalling hurricanes). This resampling is repeated 1,000 times, and if the observed rate lies outside of 950 of the 1,000 samples, it is significant at the 10% level using a two-sided test. Statistical significance for composites is calculated at the 10% level using a Monte Carlo method as in Schreck et al. (2013).

3. Relationship Between the MJO, Atlantic ACE, and CONUS Landfalling Hurricane Activity

We begin by re-examining the relationship between basinwide Atlantic ACE and the MJO. Corroborating Klotzbach and Oliver (2015b), we find increased Atlantic ACE in phases 1–4 and suppressed Atlantic ACE in phases 5–8 (Figure 1a). This result is consistent with other MJO-Atlantic TC studies using shorter records (e.g., Hansen et al., 2020; Klotzbach, 2010; Kossin et al., 2010; Ventrice et al., 2011; Ventrice et al., 2013). These papers highlighted increased Atlantic TC activity when the MJO favors Africa and Indian Ocean convection (phases 1–3), with decreased Atlantic TC activity when the MJO favors the eastern part of the Maritime Continent and Pacific Ocean convection (phases 5–7).

Continental US landfalls show similar modulation by the MJO (Figure 1b), as noted in Klotzbach (2010). Phases 3–4 show significant enhancement for CONUS landfalls of all categories of named storms, that is, tropical storm or hurricane (≥34 kt), hurricane (≥64 kt), and major hurricane (Category 3 or higher on the Saffir-Simpson Hurricane Wind Scale; ≥96 kt), while phases 5–8 show a significant decrease for all landfall metrics except for hurricane landfalls in phases 5–6. As one would expect from the basinwide modulation of Atlantic hurricane activity, we also find that the MJO significantly modulates CONUS landfalling TCs.

We next examine the relationship between the MJO and CONUS hurricanes that caused ≥$1 billion USD in normalized damage (Figure 1c). We find a statistically significant increase in billion-USD CONUS hurricane landfalls in phases 3–4, with significant decreases in phases 5–6 and 7–8. More than three-quarters (78%) of normalized billion-USD CONUS landfalling hurricanes appear in phases 1–4, highlighting the increased likelihood of significant impacts in these four MJO phases relative to phases 5–8, similar to what Ventrice et al. (2013) found for Atlantic tropical cyclogenesis and hurricane days.

4. Spatial Modulation of CONUS Landfalling Hurricane Activity by the MJO

We next examine the relationship between the MJO and TCs making CONUS landfall. Figures 2a–2d displays landfalling hurricane locations during MJO

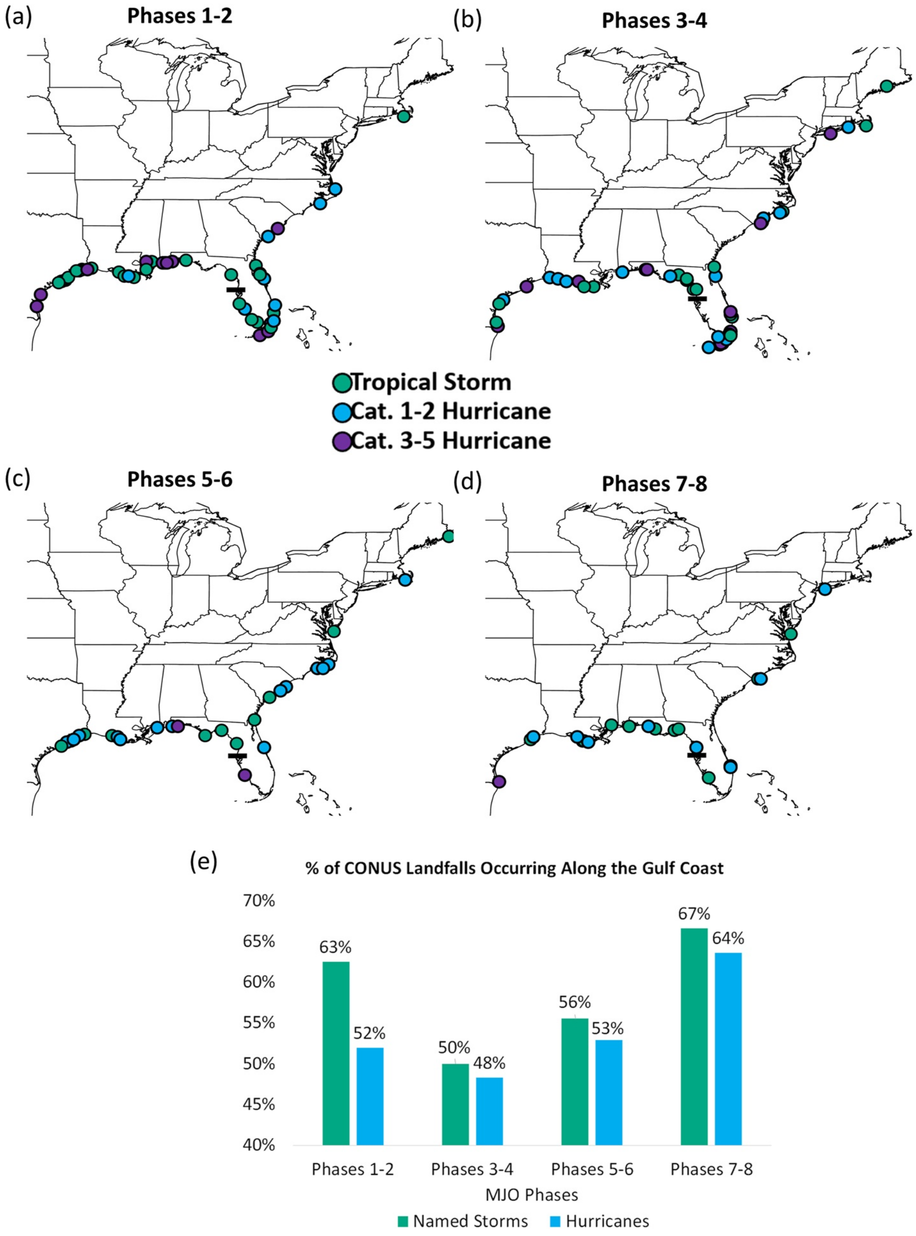

Figure 2. Continental US landfalling tropical cyclone locations by Madden-Julian oscillation (MJO) phase. Tropical storm (green), category 1–2 hurricane (blue), and category 3–5 (purple) CONUS landfalling hurricane locations during (a) MJO phases 1–2, (b) MJO phases 3–4, (c) MJO phases 5–6, and (d) MJO phases 7–8. The black line denotes the Gulf Coast/FP + EC landfall delineator (Tarpon Springs, Florida). (e) Percentage of CONUS named storms and hurricanes making Gulf Coast landfall by MJO phase.

phase pairs, highlighting the previously-noted increase in CONUS landfalls during MJO phases 1–4 relative to phases 5–8. For example, 25 major hurricanes made CONUS landfall in phases 1–4, while only 3 major hurricanes made CONUS landfall in phases 5–8.

It also appears that the preferential landfall location shifts based on MJO phase (Figures 2a–2d). Gulf Coast landfalls are favored relative to FP + EC landfalls in phases 7–8 and 1–2, while FP + EC landfalls are favored in phases 3–4 and 5–6. Figure 2e displays the percentage of CONUS named storm and hurricanes making Gulf Coast landfall. We evaluate ratios of named storms and hurricanes because the sample size of major hurricanes is limited. Of 21 CONUS landfalling named storms in phases 7–8, 14 (67%) made Gulf Coast landfall. In contrast, of 46 CONUS named storms in phases 3–4, 24 (50%) made Gulf Coast landfall. We find that phases 3–4 and

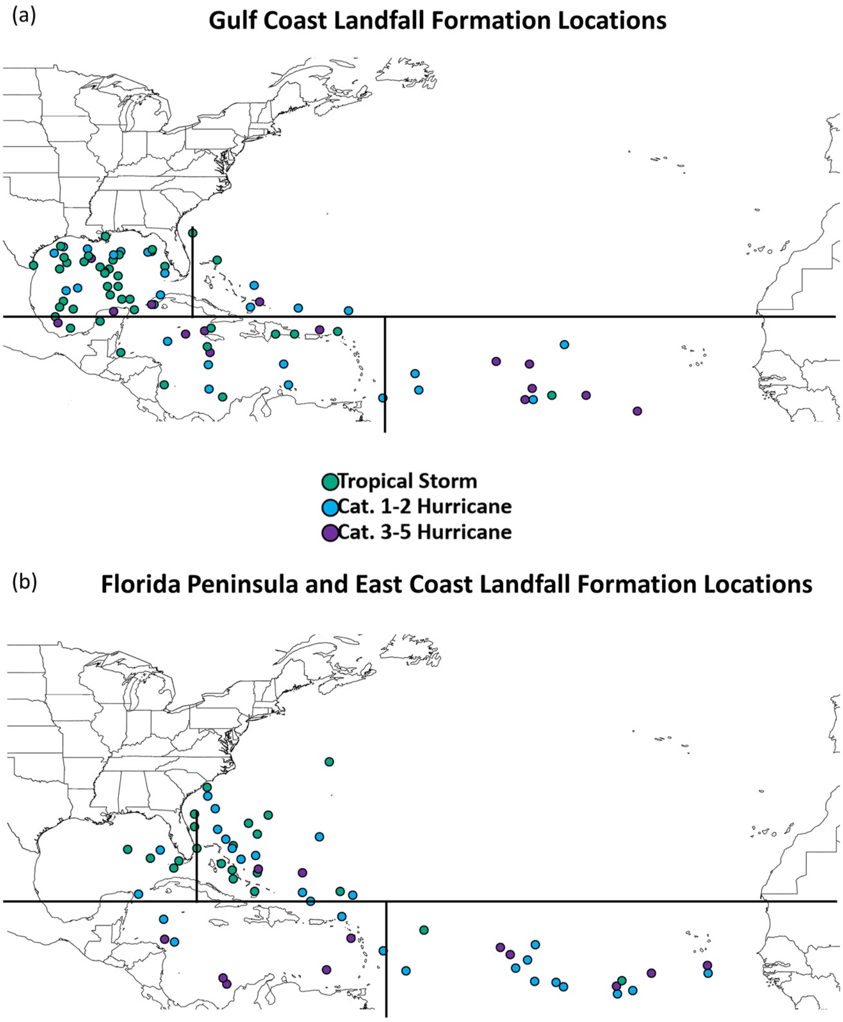

Figure 3. Formation location of tropical storms (green), category 1–2 hurricanes (blue), and category 3–5 hurricanes (purple) that made landfall along (a) the Gulf Coast and (b) the FP + EC. Black lines delineate the four formation regions discussed in the text.

phases 5–6 generally show a decrease in the ratio of Gulf Coast to all CONUS named storm and hurricane landfalls, while phases 1–2 and phases 7–8 generally show an increase in the ratio of Gulf Coast to all CONUS named storm and hurricane landfalls.

Hurricanes making Gulf Coast landfall tend to form farther west in the Atlantic basin than hurricanes making FP + EC landfall (Klotzbach et al., 2018), so we next explore whether the MJO modulates where Atlantic TCs tend to form. Maps of the genesis locations of named storms that made CONUS landfall (Figure 3) highlight a westward shift in named storm formation for Gulf Coast landfalls relative to FP + EC landfalls, corroborating Klotzbach et al. (2018).

We next separate the Atlantic basin into four regions: tropical Atlantic (≤20°N, ≤60°W), Caribbean (≤20°N, >60°W), Gulf of Mexico (>20°N, >80°W) and open Atlantic (>20°N, ≤80°W) to evaluate the percentage of Gulf and FP + EC named storms and hurricanes forming in each region (Figures 4a and 4b). The sample size for major hurricanes making landfall is small, reduced further when split into four formation regions. Consequently, we choose to focus on named storms and all hurricanes (e.g., Category 1–5) in this analysis.

Corroborating visual inspection, 37% of Gulf hurricane landfalls and 51% of Gulf named storm landfalls form in the Gulf of Mexico—a significant increase from the CONUS landfall average. Only 9% of Gulf named storm landfalls and 12% of Gulf hurricane landfalls form in the open Atlantic—a significant decrease. In contrast, a

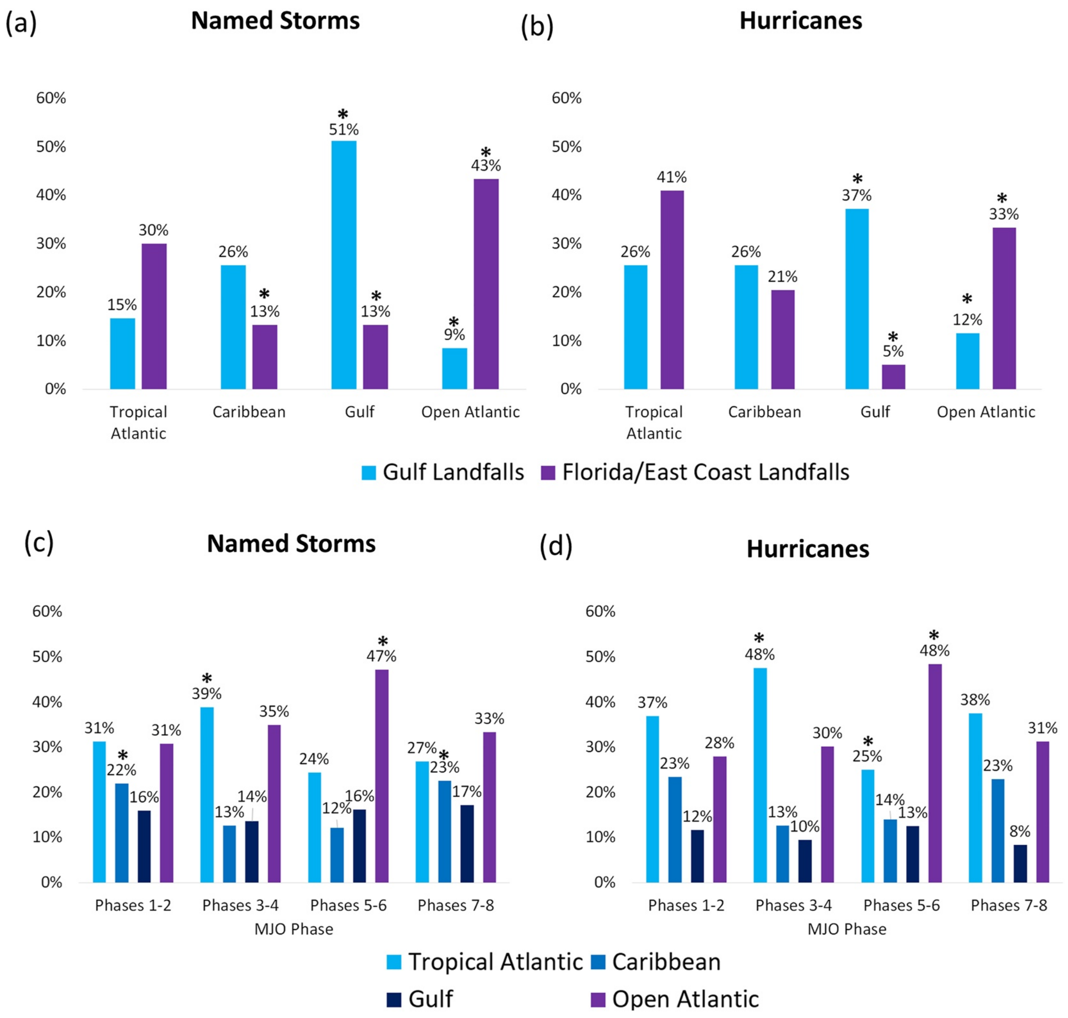

Figure 4. Percentage of CONUS landfalling TCs categorized first by Atlantic formation region and then by Madden-Julian oscillation (MJO) modulation of each region. (a) Percentage of named storm landfalls for the Gulf and FP + EC by formation region. (b) As in panel a but for hurricane landfalls. (c) Percentage of Atlantic named storms by formation region as modulated by the MJO. (d) As in panel c but for Atlantic hurricanes. Asterisks denote statistically-significant percentages.

significantly higher percentage of FP + EC named storm and hurricane landfalls (43% and 33%, respectively) form in the open Atlantic.

Gulf hurricane landfalls have a higher chance of originating in the tropical Atlantic than named storm landfalls (26% vs. 15%), while as noted earlier, Gulf hurricane landfalls have a lower chance of originating in the Gulf than named storm landfalls (37% vs. 51%). In addition, while 30% of FP + EC named storm landfalls form in the tropical Atlantic, 41% of FP + EC hurricane landfalls form in the same region. These changes in formation region for named storm versus hurricane landfalls indicate that hurricane landfalls tend to form farther from where they make landfall than do named storms. This increased distance provides increased residence time over the warm waters of the western Atlantic and thus a greater likelihood of intensification.

Figure 4c displays the percentage of all Atlantic named storms, regardless of whether they made CONUS landfall, occurring in each formation region divided by MJO phase. We focus on the difference in named storm formation percentage between MJO phases 7–8 and phases 3–4 since this is the largest difference observed in the percentage of Gulf relative to FP + EC landfalls (Figure 2e). As seen in Figures 4a, 77% of all Gulf named storm landfalls form in either the Gulf or the Caribbean. While there is only a modest decrease in the percentage of Gulf formations from phases 7–8 to phases 3–4 (17%–14%), there is a larger decrease in the percentage of Caribbean formations (23%–13%), likely due to the MJO beginning to suppress convection over the Carib-

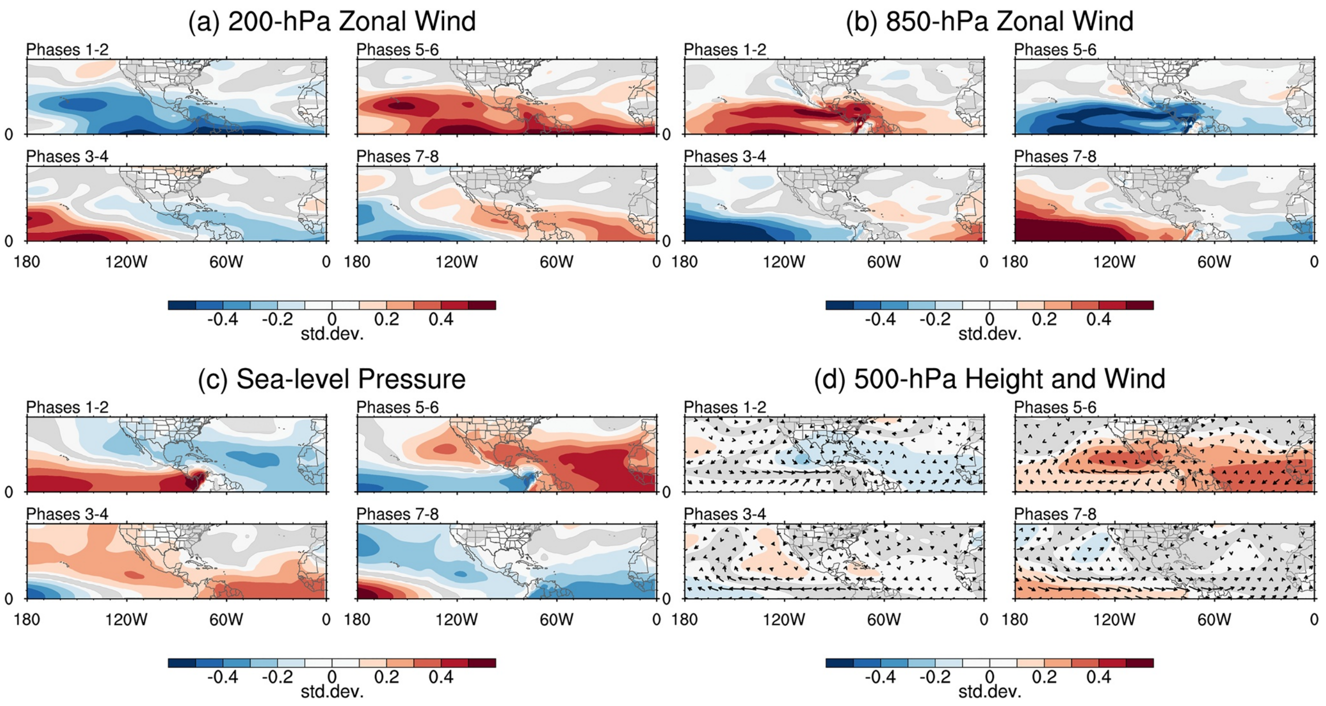

Figure 5. Large-scale atmospheric composite standardized anomalies by Madden-Julian oscillation phase pair: (a) 200-hPa zonal wind, (b) 850-hPa zonal wind, (c) mean sea level pressure, and (d) 500-hPa geopotential height and wind vectors. Significant regions are shaded. Vectors are displayed when either the zonal or meridional component is significant.

bean during these phases (Ventrice et al., 2013). The smaller reduction for Gulf formations may be due to multiple genesis pathways for Gulf storms including stalled fronts, which given their midlatitude origin are less likely to be impacted by the MJO. The decrease in storms forming in the Caribbean is likely one of the reasons why we observe a decrease in the ratio of Gulf landfalls to all CONUS landfalls during phases 3–4. Another reason is the significant increase in tropical Atlantic named storm formations in phases 3–4. This would tend to favor FP + EC landfalls relative to Gulf landfalls. Results for hurricanes resemble those for named storms (Figure 4d).

5. MJO Modulation of the Large-Scale Atmospheric Environment

The MJO appears to modulate Atlantic storm formation locations, but another potential reason for differences in Gulf landfalls relative to FP + EC landfalls is changes in the large-scale atmospheric environment. We thus investigate July–October 1905–2015 atmospheric composites from 20CRv3 of 200-hPa zonal wind, 850-hPa zonal wind, sea level pressure, and 500-hPa geopotential height and vector wind (Figure 5).

As found in prior research (Klotzbach, 2010; Klotzbach & Oliver, 2015b; Ventrice et al., 2011), MJO phases 1–2 show the most conducive dynamic conditions for Atlantic TC formation, with anomalous upper-level easterly flow and anomalous lower-level westerly flow counteracting the prevailing vertical wind shear over the Caribbean and tropical Atlantic. The strongest vertical shear modulations occurred in the Caribbean, corroborating Klotzbach and Oliver (2015b). In addition, lower MSLP is present across the tropical Atlantic and Caribbean in phases 1–2 but higher MSLP in phases 5–6.

The tropical Atlantic generally exhibits lower 500-hPa heights in phases 1–2 and higher 500-hPa heights in phases 5–6. However, there do not appear to be notable MJO-driven large-scale changes in the subtropical and mid-latitude steering flow that would tend to favor Gulf versus FP + EC landfalls (or vice versa), especially in phases 3–4 and phases 7–8 where we observe the most notable differences in landfall percentages for the Gulf versus FP + EC. Consequently, we find that the primary driver of MJO-driven variations in the ratio of Gulf Coast versus FP + EC landfalls is variations in the preferred formation regions for Atlantic TCs.

Figures S1–S4 in Supporting Information S1 show monthly large-scale atmospheric composites for July, August, September and October. Broadly speaking, we find similar anomaly patterns for each month as for the 4-month average, indicating that MJO-modulated anomalies do not substantially change during the peak months of the Atlantic hurricane season.

6. Summary and Conclusions

This study examined the relationship between the MJO and CONUS landfalling TC activity during the period 1905–2015. We find a significant increase in CONUS landfalling hurricane activity in phases 3–4 when the MJO enhances convection over the eastern Indian Ocean and western portions of the Maritime Continent. We also find suppressed CONUS landfalling hurricane activity in phases 5–6 when the MJO enhances convection over the eastern part of the Maritime Continent and the western Pacific and in phases 7–8 when the MJO enhances convection over the central and eastern Pacific and Western Hemisphere. These modulations generally agree with MJO modulations of Atlantic basinwide TC activity, with a slight shift toward later MJO phases for CONUS landfalls. This finding makes sense given that several days often pass between when a TC forms and when it makes CONUS landfall. This time passage may result in a shift of one (or more) MJO phases between when a TC forms and when it makes landfall.

We find a decrease in Gulf Coast landfalls relative to FP + EC landfalls in phases 3–4 with increases in Gulf Coast landfalls relative to FP + EC landfalls in phases 7–8. We suggest that most of the difference in the ratio of Gulf Coast to FP + EC landfalls is due to changes in where TCs form, with phases 7–8 favoring TC formation in the Caribbean and phases 3–4 favoring TC formation in the tropical Atlantic. These shifts in storm formation favor Gulf Coast and FP + EC landfalls, respectively.

Though studies have examined the relationship between the MJO and TC activity for all TC basins, this is one of the first studies to our knowledge that specifically examines the relationship between the MJO and landfalling TC activity. As the MJO has predictability several weeks in advance (e.g., Kim et al., 2018; Newman et al., 2003), our analysis suggests that TC landfall risk may have similar predictability. Our results could be used by forecasters to provide advanced notice to coastal stakeholders of varying hurricane risks when the MJO is active. In the future, we plan to extend this analysis to examine how the MJO modulates landfalling TC activity for other Atlantic landmasses as well as for landmasses in other TC basins.

Data Availability Statement

Atlantic basin hurricane data from 1905 to 2015 and CONUS landfalling TC data from 1970 to 1982 were extracted from the HURDAT2 data set: https://www.aoml.noaa.gov/hrd/hurdat/hurdat2.html. Continental US landfalling hurricane data from 1905 to 1970 and 1983 to 2015 were taken from: https://www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html. Continental US landfalling named storm data from 1905 to 1970 and 1983 to 2015 were taken from: https://www.aoml.noaa.gov/hrd/hurdat/uststorms.html. All atmospheric and were obtained from the 20th Century Reanalysis version 3: https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html, which is supported by the U.S. DOE, BER (http://science.energy.gov/ber/), by NOAA's Physical Sciences Laboratory and Climate Program Office, and used resources of the DOE National Energy Research Scientific Computing Center (http://www.nersc.gov/) managed by Lawrence Berkeley National Laboratory and of NOAA's Remotely Deployed High Performance Computing Systems. The Oliver and Thompson (2011) MJO index is available at: http://passage.phys.ocean.dal.ca/~olivere/data/mjoindex_IHR_20CRV3.dat. Normalized hurricane damage data are available from the Weinkle et al. (2018) supplemental material: https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-018-0165-2/MediaObjects/41893_2018_165_MOESM2_ESM.xlsx.

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