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

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November 23, 2022

Abstract

The Madden-Julian oscillation (MJO) significantly impacts North Atlantic hurricanes, with more hurricane activity occurring when the MJO favors enhanced convection over Africa and the tropical Indian Ocean and suppressed hurricane activity occurring when the MJO favors enhanced convection over the tropical Pacific. Using data from 1905-2015, we find more hurricanes make landfall in the continental US when the MJO enhances convection over the tropical Indian Ocean. In addition, when the MJO enhances convection over the Western Hemisphere, tropical cyclones tend to form in the Gulf of Mexico or the Caribbean, leading to more Gulf Coast landfalls. As the MJO moves to the Indian Ocean, more storms form in the tropical Atlantic, increasing the number of Florida and East Coast landfalls. The MJO's modulation of tropical cyclone steering winds appears to be secondary to its effects on genesis locations.

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Key Points:

- The Madden-Julian oscillation significantly impacts continental US hurricane landfall frequency.
- Gulf Coast hurricane landfalls are favored when the Madden-Julian oscillation is enhancing convection over the Western Hemisphere.
- Florida and East Coast hurricane landfalls are favored when the Madden-Julian oscillation is enhancing convection over the Indian Ocean.

Abstract

The Madden-Julian oscillation (MJO) significantly impacts North Atlantic hurricanes, with more hurricane activity occurring when the MJO favors enhanced convection over Africa and the tropical Indian Ocean and suppressed hurricane activity occurring when the MJO favors enhanced convection over the tropical Pacific. Using data from 1905-2015, we find more hurricanes make landfall in the continental US when the MJO enhances convection over the tropical Indian Ocean. In addition, when the MJO enhances convection over the Western Hemisphere, tropical cyclones tend to form in the Gulf of Mexico or the Caribbean, leading to more Gulf Coast landfalls. As the MJO moves to the Indian Ocean, more storms form in the tropical Atlantic, increasing the number of Florida and East Coast landfalls. The MJO's modulation of tropical cyclone steering winds appears to be secondary to its effects on genesis locations.

Plain Language Summary

The Madden-Julian oscillation (MJO) is a large-scale atmospheric signal of winds, precipitation, and pressure that loops around the equator every 30–70 days. As it moves, it alters wind patterns that can then enhance or suppress North Atlantic hurricane activity. When the MJO is aiding convection (e.g., thunderstorm activity) over Africa and the Indian Ocean, there tend to be more North Atlantic hurricanes. We show that the patterns that tend to make conditions more active for the North Atlantic basin also make conditions more conducive for continental United States hurricane landfalls. We are likely to see more landfalls from Texas to Alabama than from Florida to Maine when the MJO helps convection over the Western Hemisphere, but Florida to Maine landfalls tend to increase compared with Texas to Alabama landfalls when the MJO is helping convection over the Indian Ocean. We believe this shift in landfall location is related to where the MJO helps storms form.

1 Introduction

The Madden-Julian oscillation (MJO) is a large-scale atmospheric mode that propagates around the globe approximately every 30–70 days (Madden & Julian, 1972; Jiang et al., 2020). As it propagates, it alters large-scale wind shear, pressure and moisture patterns, all of which have been shown to be critical for tropical cyclone (TC) formation and intensification (e.g., Camargo et al., 2007; Bruyere et al., 2012). Specifically for the North Atlantic (hereafter Atlantic), the MJO tends to increase hurricane (one-minute 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 (Mo, 2000; Klotzbach, 2010; Kossin et al., 2010; 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 using over 100 years of historical hurricane data using a reconstructed MJO time series based on mean sea level pressure (MSLP) (Klotzbach & Oliver, 2015a). Both Klotzbach and Oliver (2015a) and Hansen et al. (2020) have shown that ENSO can significantly modulate the MJO influence.

Kossin et al. (2010) examined various Atlantic TC track clusters and 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 was enhancing Western Hemisphere and Indian Ocean convection, and fewer TCs formed there when the MJO was enhancing western North Pacific convection.

While prior studies have identified several relationships between the MJO and TC activity around the globe, the relationship with landfalling TC activity in the continental US (CONUS) has not been fully explored. Using data from 1974-2007, Klotzbach (2010) showed that when the MJO was enhancing Indian Ocean convection, significantly more hurricanes make landfall in the CONUS than when the MJO was enhancing Pacific Ocean convection. In this study, we expand upon Klotzbach (2010) and other prior studies by conducting an in-depth examination of the relationship between the MJO and CONUS landfalling hurricanes. Specifically, we use a long-term MJO dataset (see Section 2) to explore this relationship over an ~110 year period (1905–2015). We then assess whether there are spatially-preferred locations for 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 CONUS hurricanes.

The remaining manuscript is arranged as follows. We discuss the datasets and methodology in section 2. In section 3, we demonstrate that the MJO significantly modulates CONUS landfalling hurricane activity. Section 4 examines impacts of the MJO on formation regions. Section 5 discusses the MJO's modulation of the large-scale tropical Atlantic atmospheric environment. Section 6 provides a summary and ideas for future work.

2 Data and Methodology

We obtained continental US hurricane landfalls from the Atlantic Oceanographic and Meteorological Laboratory's website: https://www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html. Tropical storm (one-minute maximum sustained winds between 34 and 63 kt) landfalls were obtained from: https://www.aoml.noaa.gov/hrd/hurdat/uststorms.html. These landfalls are aggregated from the National Hurricane Center's official Atlantic TC database (HURDAT2; Landsea & Franklin, 2013) and are currently available from 1851–1970 and 1983–present. The Atlantic hurricane best track reanalysis project has not yet been completed for 1971–1982, so for this time period, we identify CONUS tropical storm and hurricane landfalls directly from HURDAT2 following Klotzbach et al. (2018). If storms made multiple CONUS landfalls, we only counted the strongest landfall by maximum sustained wind for each storm. We focus on July–October landfalls, a period which accounts for all CONUS hurricane landfalls during the most recent 30-year NOAA climatological period from 1991–2020. Atlantic basinwide July–October hurricane data are obtained from HURDAT2. We calculate Accumulated Cyclone Energy (ACE; Bell et al., 2000), an integrated metric accounting for storm frequency, intensity and duration directly from HURDAT2.

We use the surface pressure-based index of Oliver and 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 1905–2015 (when the 20CRv3 currently ends). The Oliver and Thompson (2011) index has been used in previous TC studies (e.g., Klotzbach & Oliver, 2015a,b). Here we restrict our examination of the MJO-TC relationship to days where the MJO amplitude exceeds 1.0 (~60% of July–October days from 1905–2015). Since the MJO does not spend the same amount 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. Here we investigate the same MJO phase pairs as used in Klotzbach and Oliver (2015b), that is, 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).

We use the 20CRv3 daily-averaged ensemble mean for all large-scale environmental field analysis. The 20CRv3 system assimilates surface and sea level pressure observations, including tropical cyclone reports, and prescribes monthly sea ice concentration and pentad SST fields as boundary conditions. The reanalysis is available on a 1° x 1° grid.

Normalized CONUS hurricane damage is provided by Weinkle et al. (2018). The normalization estimates how much 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, and wealth per capita.

We test for statistically significant TC activity differences via bootstrap resampling (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 one. We then calculate the rate of the phenomenon being tested (e.g., landfalling hurricanes). This resampling is repeated 1000 times, and if the observed rate lies outside of 950 of the 1000 samples, it is significant at the 10% level using a two-sided test. Statistical significance for composites is calculated using a Monte Carlo method as in Schreck et al. (2013) and is reported at the 5% level. Each composite is created using more than 1200 days, making the averages more robust and significant.

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. As was found in Klotzbach and Oliver (2015b), we find increased Atlantic ACE in phases 1–4 and suppressed Atlantic ACE in phases 5–8 (Fig. 1a). This result is also consistent with other MJO-

Atlantic TC studies using shorter records (e.g., Kossin et al., 2010; Klotzbach, 2010; Ventrice et al., 2011; Hansen et al., 2020). 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 Pacific Ocean convection (phases 5–7).

Continental US landfalls show similar modulation by the MJO (Fig. 1b), as first noted in Klotzbach (2010). Phases 3–4 show significant enhancement for CONUS landfalls of all categories of named storms, i.e., 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. Broadly speaking, 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 (Fig. 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 (77%) 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.

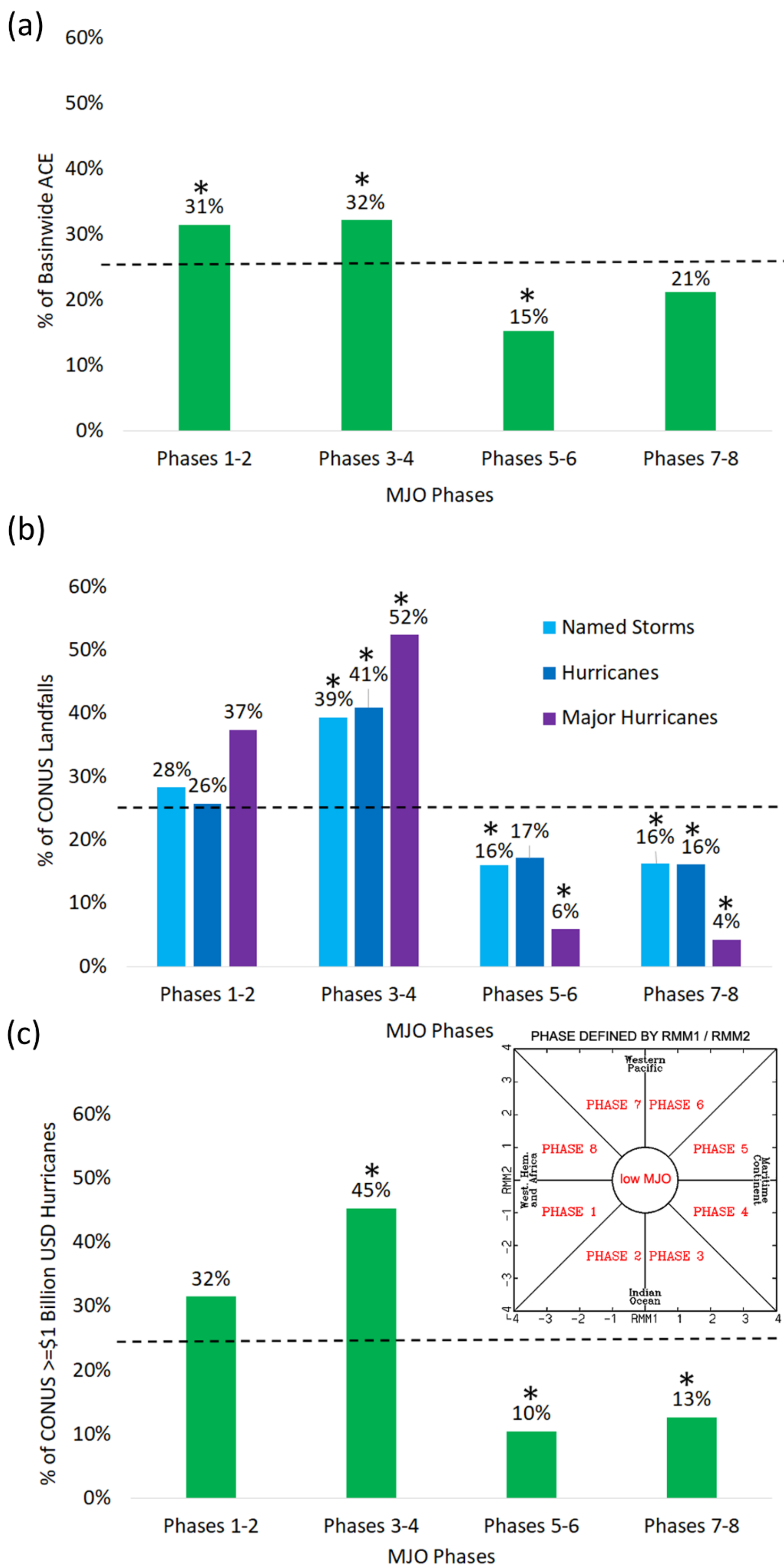

(a)
% of Basinwide ACE
60%
50%
40%
30%
20%
10%
0%
*
31%
*
32%
*
15%
21%
Phases 1-2
Phases 3-4
Phases 5-6
Phases 7-8
MJO Phases
(b)
% of CONUS Landfalls
Named Storms
Hurricanes
Major Hurricanes
28%
26%
37%
* 39%
* 41%
* 52%
* 16%
17%
* 6%
* 16%
* 16%
* 4%
Phases 1-2
Phases 3-4
Phases 5-6
Phases 7-8
MJO Phases
(c)
% of CONUS >=$1 Billion USD Hurricanes
32%
* 45%
* 10%
* 13%
Phases 1-2
Phases 3-4
Phases 5-6
Phases 7-8
MJO Phases
PHASE DEFINED BY RMM1 / RMM2
Western Pacific
Indian Ocean
West. Hem. and Africa
Maritime Continent
PHASE 1
PHASE 2
PHASE 3
PHASE 4
PHASE 5
PHASE 6
PHASE 7
PHASE 8
low MJO
RMM1
RMM2

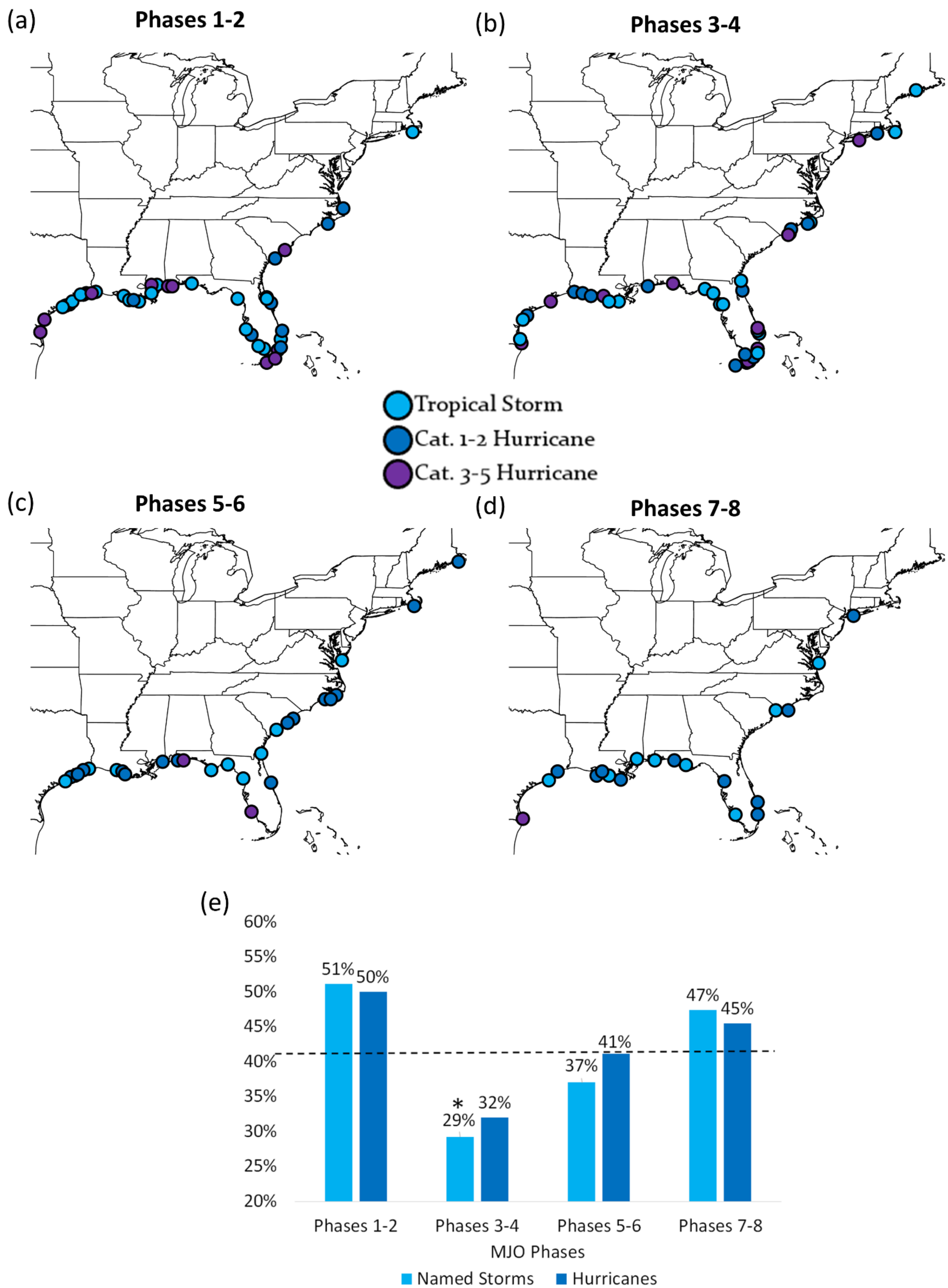
Figure 1. MJO modulation of basinwide Atlantic ACE and continental US landfalling hurricane activity. (a) Percentage of normalized Atlantic ACE generated in each MJO phase pair. (b) Percentage of normalized CONUS named storm, hurricane, and major hurricane landfalls generated in each MJO phase pair.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

4 Spatial modulation of CONUS landfalling hurricane activity by the MJO

We next examine the relationship between the MJO and TCs making CONUS landfall. Figure 2a–d displays landfalling hurricane locations during MJO phase pairs, highlighting the previously-noted increase in CONUS landfalls during MJO phases 1–4 relative to phases 7–8. For example, 23 major hurricanes made CONUS landfall in phases 1–4, while only 3 major hurricanes made CONUS landfall in phases 5–8.

On closer examination of Figure 2a–d, it also appears that the preferential location for where TCs make landfall shifts based on MJO phase. For the remainder of this manuscript, we define Gulf TC landfalls to be storms making landfall between Texas and Alabama, while all other CONUS TC landfalls are referred to as Florida and East Coast landfalls. Gulf TC landfalls appear generally favored relative to Florida and East Coast landfalls in phases 7–8 and 1–2, while Florida and East Coast landfalls are favored in phases 3–4 and 5–6. We now investigate this relationship in more detail.

Figure 2e displays the percentage of CONUS named storm and hurricanes making Gulf Coast landfall. Here we focus on ratios of named storms and hurricanes, as the sample size of major hurricanes is limited. Of 45 CONUS landfalling named storms in phases 1–2, 23 (51%) made Gulf landfall. In contrast, of 41 CONUS named storms in phases 3–4, only 12 (29%) made Gulf landfall, a significant reduction. We find that phases 3–4 and phases 5–6 show a consistent reduction in named storm and hurricane landfalls, and phases 1–2 and phases 7–8 show a consistent increase in the ratio of Gulf Coast to CONUS named storm and hurricane landfalls.


(a)
Phases 1-2
(b)
Phases 3-4
Tropical Storm
Cat. 1-2 Hurricane
Cat. 3-5 Hurricane
(c)
Phases 5-6
(d)
Phases 7-8
(e)
60%
55%
50%
45%
40%
35%
30%
25%
20%
51%
50%
*
29%
32%
37%
41%
47%
45%
Phases 1-2
Phases 3-4
Phases 5-6
Phases 7-8
MJO Phases
Named Storms
Hurricanes

194

Figure 2. Continental US landfalling TC locations by MJO phase. Tropical storm (light blue), category 1–2 hurricane (dark blue) and category 3–5 CONUS landfalling hurricane locations (purple) during (a) MJO phases 1–2, (b) MJO phases 3–4, (c) MJO phases 5–6, and (d) MJO phases 7–8. (e) Percentage of CONUS named storms and hurricanes making Gulf Coast landfall by MJO phase. Statistically-significant percentages are denoted with an asterisk. The black dashed line denotes the average rate of Gulf Coast to CONUS named storm and hurricane landfalls (41% for both quantities).

Hurricanes making Gulf Coast landfall tend to form farther west in the Atlantic basin than hurricanes making Florida and East Coast 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 (Fig. 3) highlight a westward shift in named storm formation for Gulf Coast landfalls relative to Florida and East Coast landfalls, corroborating Klotzbach et al. (2018).

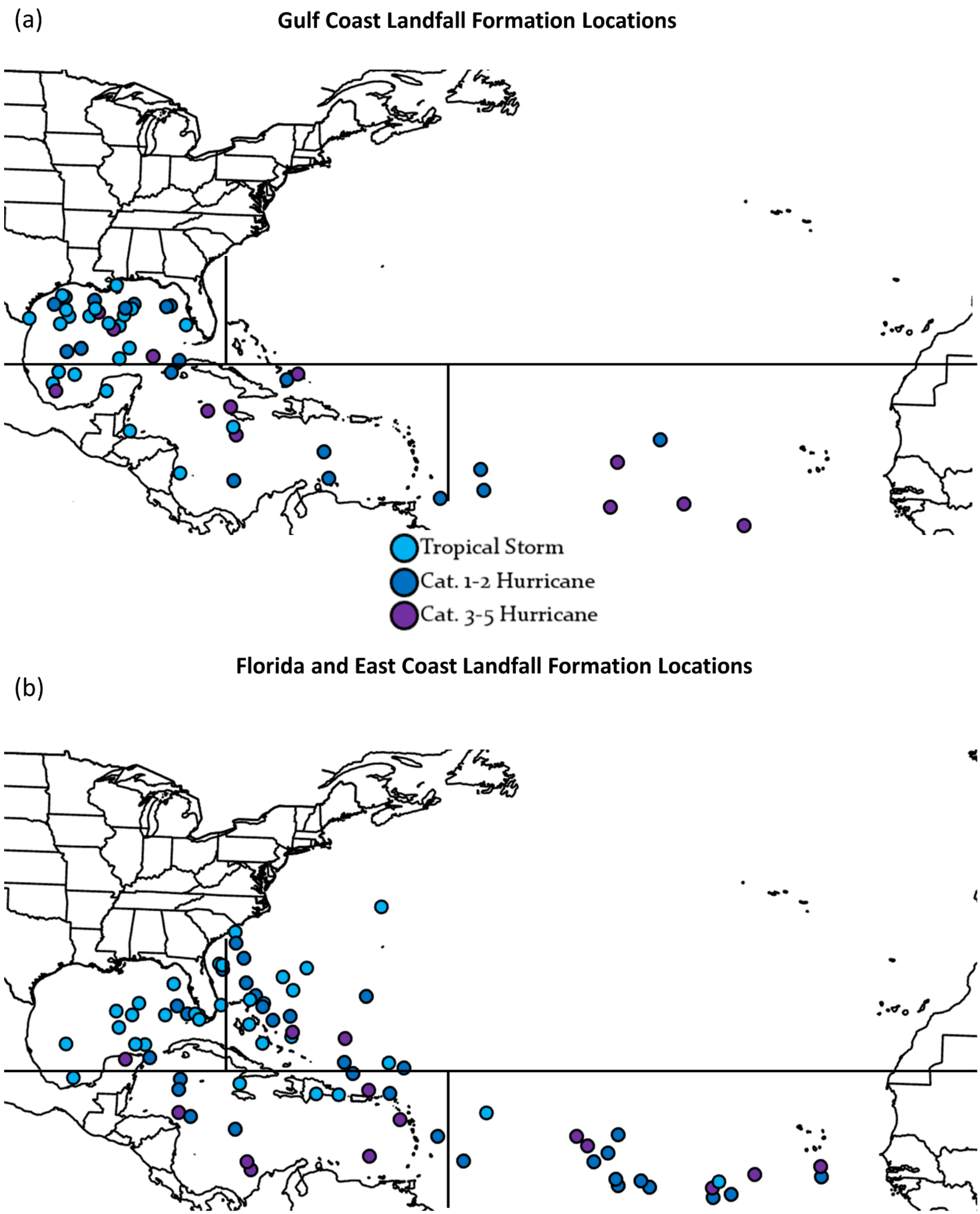

(a)
Gulf Coast Landfall Formation Locations
Tropical Storm
Cat. 1-2 Hurricane
Cat. 3-5 Hurricane
Florida and East Coast Landfall Formation Locations
(b)

Figure 3. Formation location of tropical storms (light blue), category 1–2 hurricanes (dark blue), and category 3–5 hurricanes (purple) that made landfall in (a) the Gulf of Mexico and (b) Florida and the East Coast. The black lines delineate the four formation regions discussed in the text.

We next separate the Atlantic basin into four formation regions (Figure 3): 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 Florida and East Coast named storms and hurricanes forming in each region (Figure 4a–b). The sample size for major hurricanes making landfall is small, especially when split into four formation regions, and consequently we choose to focus on named storms and all hurricanes (e.g., Category 1–5) in this analysis. As would be expected from visual inspection, 44% of Gulf hurricane landfalls and 59% of Gulf named storm landfalls form in the Gulf of Mexico, both of which are significant percentage increases from the full CONUS landfall named storm formation sample. Only 4% of Gulf named storm landfalls and 6% of Gulf hurricane landfalls form in the open Atlantic - a significant decrease from the full CONUS sample. In contrast, 33% and 29% of Florida and East Coast named storm and hurricane landfalls, respectively, form in the open Atlantic - a significant increase from the full CONUS sample. While 24% of Florida and East Coast named storm landfalls form in the tropical Atlantic, 38% of Florida and East Coast hurricane landfalls form in the same region, indicating that stronger storms making Florida and East Coast landfall tend to originate farther east in the basin.

Figure 4c–d display the percentage of all Atlantic named storms, regardless of if they made CONUS landfall, occurring in each formation region by MJO phase. We begin by examining the difference in named storm formation percentage between MJO phases 1–2 and phases 3–4, since this is the largest difference observed in the percentage of Gulf relative to Florida and East Coast landfalls. As noted in Figure 4a, 81% of all Gulf named storm landfalls form in either the Gulf or the Caribbean. In phases 1–2, 38% of named storms form in either the Caribbean or the Gulf, while only 27% of named storms form in these two regions in phases 3–4. The percentage of storms forming in the Caribbean or Gulf in phases 1–2 is a significant increase, while the percentage of storms forming in the Caribbean or Gulf in phases 3–4 is a significant decrease from the average eight-phase MJO ratio. This significant decrease in storms forming in the western Atlantic (e.g., Caribbean and Gulf) is likely one of the reasons why we observe a significant 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 Florida and East Coast landfalls relative to Gulf landfalls.

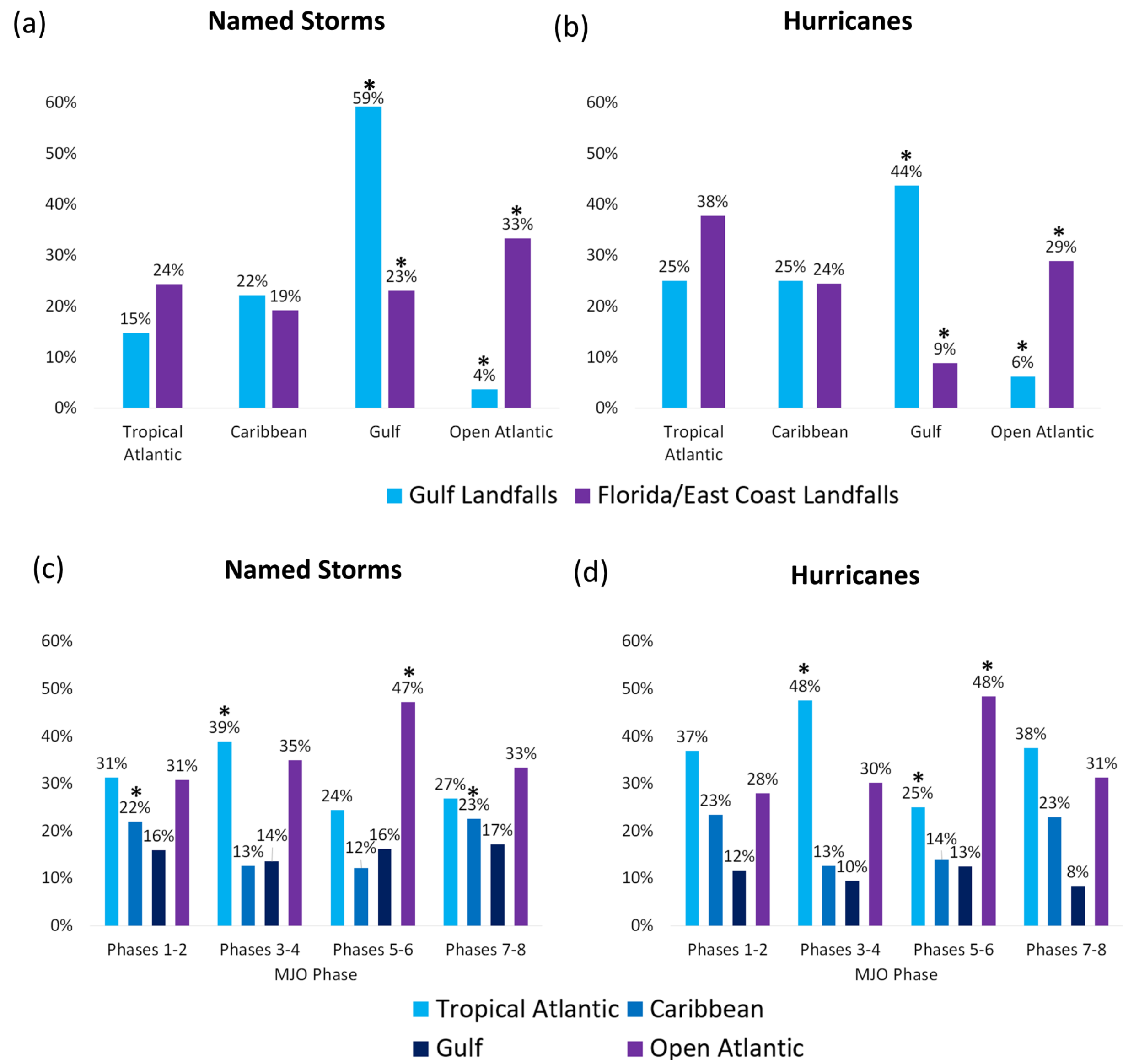


Figure 4. Percentage of continental US landfalling TCs categorized first by Atlantic formation region and then by MJO modulation of each region. (a) Percentage of named storm landfalls for the Gulf and Florida and the East Coast by formation region. (b) As in panel a but for hurricane landfalls. (c) Percentage of Atlantic named storms by formation region as modulated by the MJO. (d) As in panel c but for Atlantic hurricanes. Statistically-significant percentages are denoted with an asterisk.

5 MJO modulation of the large-scale atmospheric environment

The MJO appears to modulate where storms in the Atlantic tend to form, but another potential reason for differences in Gulf landfalls relative to Florida and East Coast landfalls is changes in the large-scale atmospheric environment. Here we investigate July–October 1905–2015 atmospheric composites of the following four fields from 20CRv3: 200-hPa zonal wind, 850-hPa zonal wind, sea level pressure, and 500-hPa geopotential height and vector wind (Figure 5).

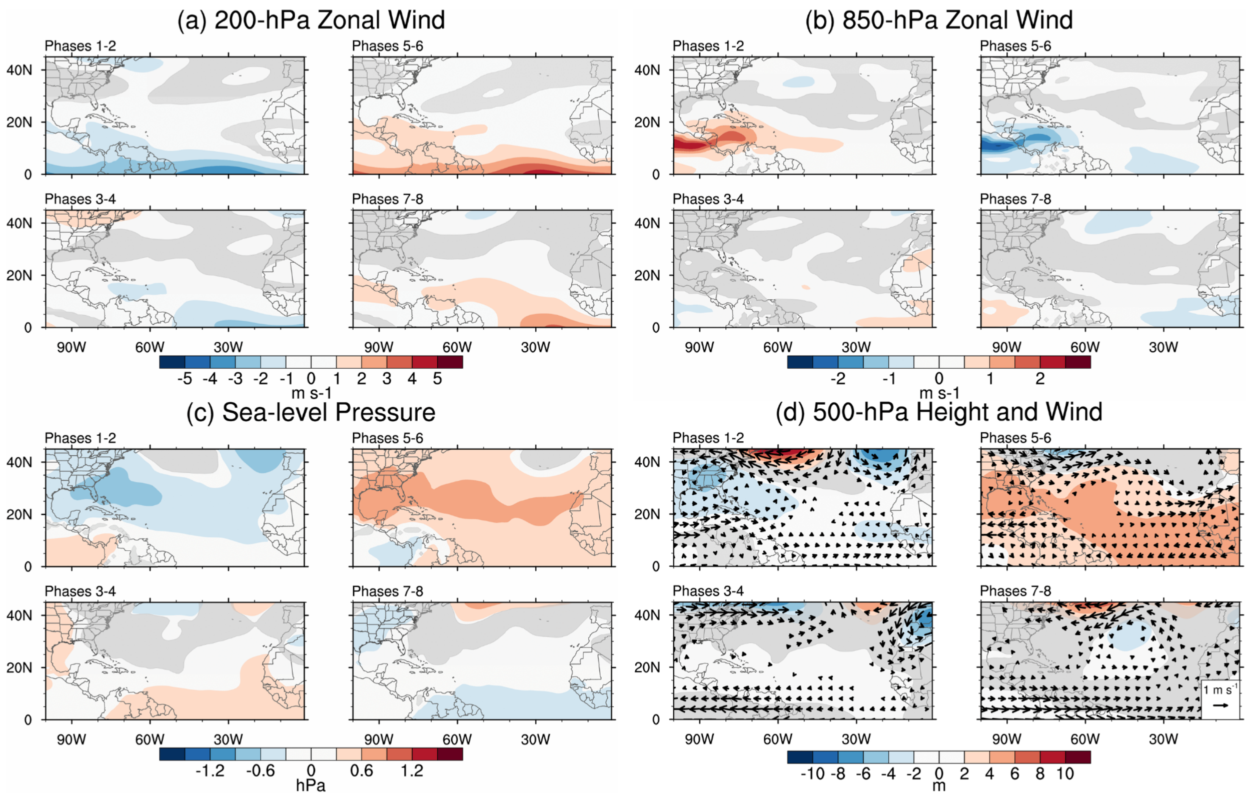


Figure 5. Large-scale atmospheric composites by MJO phase pair: (a) 200-hPa zonal wind, (b) 850-hPa zonal wind, (c) MSLP, and (d) 500-hPa geopotential height and wind vectors. Significant regions are shaded. Vectors are displayed when either the zonal or meridional component is significant.

As has been shown in prior research (Klotzbach, 2010; Ventrice et al., 2011; Klotzbach & Oliver, 2015b), 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 were found in the Caribbean, corroborating Klotzbach and Oliver (2015b). In addition, lower MSLP is observed across the tropical Atlantic and Caribbean in phases 1–2, with higher MSLP in phases 5–6.

The tropical Atlantic in general has lower 500-hPa heights in phases 1–2 and higher 500-hPa heights in phases 5–6. However, there do not appear to be any notable large-scale changes in the mid-latitude steering flow that would tend to favor Gulf vs. Florida and East Coast landfalls (or vice versa) in MJO phase pairing. Consequently, we find that the primary driver of MJO-driven variations in the ratio of Gulf Coast vs. Florida and East Coast landfalls is variations in the preferred formation regions for Atlantic TCs .

5 Summary and conclusions

This study examined the relationship between the MJO and CONUS landfalling hurricane activity. We find a significant increase in CONUS landfalling hurricane activity in phases 3–4 when the MJO is enhancing 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 is enhancing convection over the eastern part of the Maritime Continent and the western Pacific and in phases 7–8 when the MJO is enhancing 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 towards latter 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 passage of time may result in a shift of one (or more) MJO phases between when a TC forms and makes landfall.

We find a statistically significant decrease in Gulf Coast landfalls relative to Florida and East Coast landfalls in phases 3–4 with increases in Gulf Coast landfalls relative to Florida and East Coast landfalls in phases 7–8 and phases 1–2. We suggest that most of the difference in the ratio of Gulf Coast to Florida and East Coast landfalls is due to changes in where TCs form, with phases 1-2 favoring TC formation in the western Atlantic and phases 3–4 favoring TC formation in the tropical Atlantic and open Atlantic. These shifts in storm formation favor Gulf Coast and Florida and East Coast 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 to specifically examine the relationship between the MJO and landfalling TC activity. As the MJO has predictability several weeks in advance (e.g., Newman et al., 2003; Kim et al., 2018), our results suggest that TC landfall risk may have similar predictability. Our results could be used by forecasters to give coastal stakeholders advanced notice 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.

Acknowledgments

P. Klotzbach acknowledges support from the G. Unger Vetlesen Foundation. M. Bell was supported by ONR Grant N000142012069. C. Schreck was supported by NOAA through the Cooperative Institute for Satellite Earth System Studies under Cooperative Agreement NA19NES432000. E.C.J. Oliver was supported by NSERC Discovery Grant RGPIN-05255-2018. G. P. Compo was supported by the NOAA Cooperative Agreement with CIRES, NA17OAR4320101, and NOAA's Physical Sciences Laboratory.

Data Availability Statement

Atlantic basin hurricane data from 1905–2015 and CONUS landfalling TC data from 1970–1982 were extracted from the HURDAT2 dataset: https://www.aoml.noaa.gov/hrd/hurdat/hurdat2.html

Continental US landfalling hurricane data from 1905–1970 and 1983–2015 were taken from: https://www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html

Continental US landfalling named storm data from 1905–1970 and 1983–2015 were taken from: https://www.aoml.noaa.gov/hrd/hurdat/uststorms.html

All atmospheric and oceanic data 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, by NOAA's Physical Sciences Laboratory and Climate Program Office, and used resources of the DOE National Energy Research Scientific Computing Center 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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