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El Niño-Southern Oscillation, the Madden-Julian Oscillation and Atlantic Basin Tropical Cyclone Rapid Intensification

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1. Introduction

El Niño-Southern Oscillation (ENSO) is a large-scale mode of coupled atmospheric/oceanic variability that impacts weather and climate around the globe (Rasmusson and Carpenter 1982). ENSO has significant impacts on tropical cyclone (TC) activity worldwide (Camargo *et al.*, 2007), with its notable impacts on seasonal Atlantic basin TC activity as well as U.S. hurricane landfalls being noted in a large number of studies (*e.g.*, Klotzbach 2011 and references therein). The Madden-Julian Oscillation (MJO) is a large-scale mode of tropical variability that propagates around the globe on an approximately 30-60-day timescale (Madden and Julian 1972). As it does, it alters large-scale fields such as vertical wind shear, sea level pressure (SLP), mid-level moisture and vertical motion. Klotzbach (2010) showed that when the convectively active phase of the MJO was located over Africa or in the western Indian Ocean (Phases 1-2 of the Wheeler-Hendon (WH) index (Wheeler and Hendon 2004)), Atlantic TC activity was enhanced.

Given that climate conditions appear more favorable for Atlantic basin storm formation in particular phases of the MJO and ENSO than in others, this study examines the possibility that these impacts extend to RI events as well. Section 2 describes the data utilized, while Section 3 examines the impacts of ENSO on Atlantic basin RI. Section 4 examines how RI frequency changes with MJO phase, while the strength of the relationship between RI and the combined MJO/ENSO index is considered in Section 5. Section 6 concludes the manuscript and provides ideas for future work.

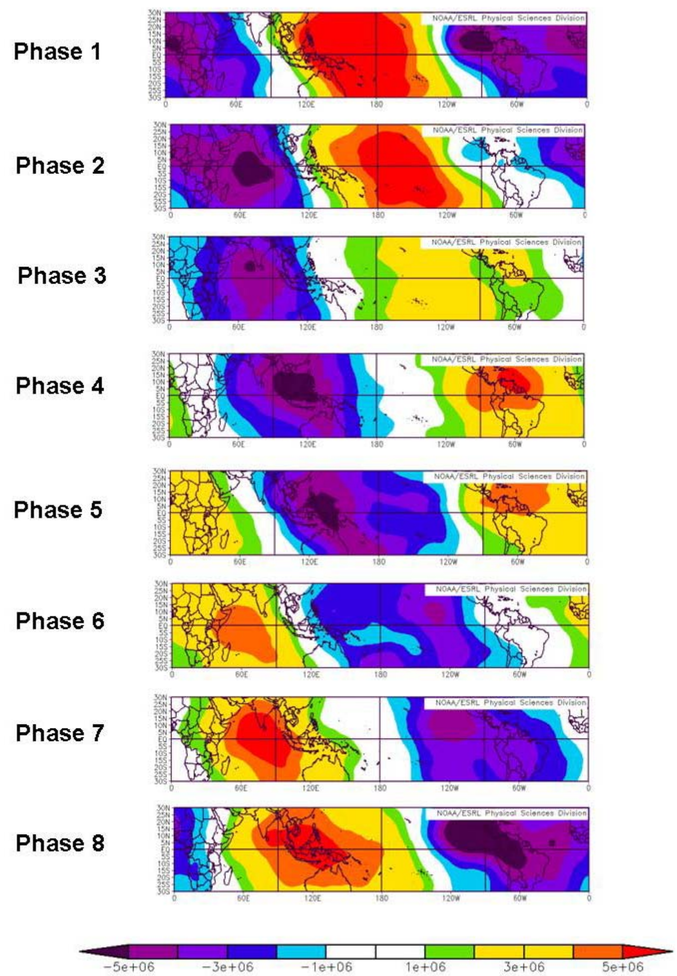

Fig. 1 200-mb velocity potential anomalies ($m^2 s^{-1}$) for the top 200 days for each MJO phase from July-October for each phase of the WH index. Cool colors indicate upper-level divergence while warm colors indicate upper-level convergence.

2. Data

The Multivariate ENSO Index (MEI) was utilized to classify ENSO events (Wolter and Timlin 1998). The MEI index is calculated using a bi-monthly average (*e.g.*, August-September). For the Atlantic hurricane season, the average of

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the August-September and September-October MEI values are utilized. The ten highest values of the index since 1974 are classified as El Niño, the ten lowest values are classified as La Niña while the sixteen years in the middle are classified as neutral. All years since 1974 (excluding 1978) are utilized in this analysis, since this is when the MJO index is available in real-time.

The index utilized to classify the MJO was developed by Wheeler and Hendon (2004). The WH index is available from 1974-present, with data missing from April-December 1978 when OLR was unavailable. For this study, the period from 1974-2010 (except 1978) was examined. Figure 1 displays 200-mb velocity potential anomalies for the 200 days where the MJO is of the strongest amplitude for each of the eight phases of the MJO as defined by the WH index. Negative velocity potentials (cool colors) denote areas of upper-level divergence where convection is enhanced, while positive velocity potentials (warm colors) indicate areas where convection is suppressed.

An additional index is one that analyzes a similar tropical convective signal to that analyzed by the WH index but with ENSO and the 120-day-mean retained. This index is utilized to approximate the combined signal of MJO and ENSO in this analysis and is referred to as the WH-Combined index throughout the remainder of this manuscript. All calculations for both MJO indices are done for systems where the index (RMM1 + RMM2) (Wheeler and Hendon 2004) is greater than one (approximately 60% of days during the hurricane season). This helps to separate out periods when the MJO is inactive.

TC statistics were calculated from the National Hurricane Center's Best Track file available online at http://www.nhc.noaa.gov/data/hurdat/tracks1851to2010_atl_reanal.txt. Rapid intensification (RI) events were defined when a system intensified by 25-, 30-, 35-, and 40 or more knots in a 24-hour period.

The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis I (Kistler *et al.* 2001) was utilized for all large-scale field calculations. All large-scale fields are calculated over the Main Development Region (MDR), which is defined to be 7.5-22.5°N, 75-20°W for this analysis, in keeping with the definition utilized by Klotzbach (2010).

3. ENSO's impacts on Atlantic basin RI

ENSO's impacts on Atlantic basin TCs have been related to a variety of physical fields, including changes in vertical wind shear, mid-level moisture, upper-tropospheric temperature and static stability (Tang and Neelin 2004; Klotzbach 2010). Given previous research, it is expected that Atlantic basin RI frequency might also be increased in La Niña years. Figure 2 displays the number of 24-hour RI events for various categories (from 25 to 40+ knots in 24 hours) for the MDR. The ratio differences between La Niña and El Niño reach approximately 6:1 when the MDR is considered.

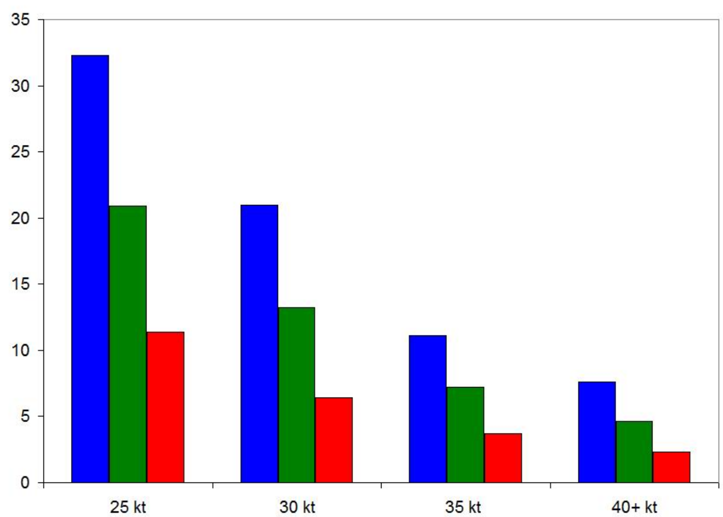

Fig. 2 Average numbers of events per-year for systems undergoing RI of 25-knot, 30-knot, 35-knot and 40+-knot thresholds for the entire Atlantic basin within a 24-hour period for years classified as La Niña (blue column), neutral (green column) and El Niño (red column). See text for ENSO classification scheme.

Another way to evaluate ENSO's impacts on RI is to examine the frequency of storms intensifying by various RI thresholds given a particular phase of ENSO. For example, 32% of systems forming in the MDR in a La Niña year undergo at least one 40+ knot RI at some point during their lifetime, while only 12% of systems forming in the MDR in an El Niño year undergo this level of RI.

Table 1 Number of 24-hour periods for systems undergoing RI of 25-knot, 30-knot, 35-knot and 40+-knot thresholds for systems forming in the MDR. Also provided are values normalized by the number of days that the MJO spends in each phase for July-October for systems forming in the MDR. These normalized values are multiplied by 100, so they can be interpreted as the number of 24-hour periods that one should expect given 100 days in a particular MJO phase. Ratios between Phases 1+2 and Phases 6+7 are provided for the normalized values.

MDR Systems								
	24 Hour Periods				Normalized Values			
MJO Phase	25 Kt	30 Kt	35 Kt	40+ Kt	25 Kt	30Kt	35 Kt	40+ Kt
1	98	61	36	27	22.0	13.7	8.1	6.1
2	89	58	37	27	22.4	14.6	9.3	6.8
3	15	6	3	2	6.9	2.8	1.4	0.9
4	37	23	11	7	14.5	9.0	4.3	2.7
5	31	22	11	8	6.8	4.8	2.4	1.8
6	21	12	6	2	6.8	3.9	1.9	0.6
7	3	1	1	0	1.5	0.5	0.5	0.0
8	13	10	5	2	5.8	4.5	2.2	0.9
Phases 1+2 / Phases 6+7					5.4	6.3	7.2	18.6

4. MJO's impacts on Atlantic basin RI

Since predicting TC RI remains one of the great challenges in hurricane forecasting (Sampson *et al.*, 2011), the knowledge of RI likelihood given what phase of the MJO a particular storm forms in is likely to be useful to TC forecasters. While several studies have examined the impacts of the MJO on Atlantic basin TC activity, to the author's knowledge, no study has explicitly studied RI. All calculations displayed in the following paragraphs are done for systems when the MJO is greater than or equal to one SD. When the WH index is less than one SD, the MJO is likely not playing a significant role in altering tropical convection.

Strong relationships are found between the MJO and systems forming in the MDR. Table 1 displays the number of 24-hour periods for each RI threshold for all TCs forming in the MDR. Also provided are normalized values, given that the MJO, as defined by Wheeler and Hendon (2004), spends more time in some phases than in others.

5. Combined MJO/ENSO impacts on Atlantic basin RI

In order to evaluate the MJO and ENSO in combination, the WH index with ENSO and the 120-day mean retained is now considered. As is the case with the WH index with ENSO and the 120-day-mean removed, the WH-Combined index is divided into eight phases spanning the globe. Since the ENSO phase is retained in the WH-Combined index, certain phases of the index are preferentially experienced during the hurricane season in El Niño versus La Niña years. Significantly

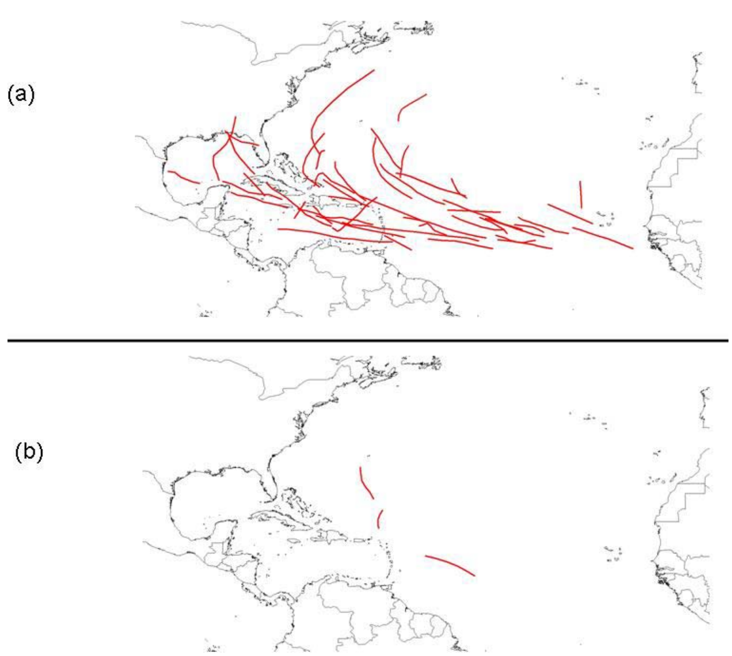

Fig. 3 Tracks of TCs undergoing an RI of 30 knots or greater in 24 hours during (a) Phases 2+3 defined by the WH-Combined index and (b) Phases 7+8 defined by the WH-Combined index. Normalized ratio differences between these phases is 38:1.

reduced levels of vertical wind shear are observed in Phases 2+3 of the WH-Combined index, while significantly increased levels of vertical wind shear are observed in Phases 7+8 of the WH-Combined index.

As would be expected given the dramatic changes in vertical shear, the largest differences are observed between Phases 2+3 and Phases 7+8. All differences in the mean between Phases 2+3 and Phases 7+8 are statistically significant at the 1% level for systems forming in the MDR. The difference in means are somewhat greater when the WH-Combined index is considered compared with the WH index by itself, indicating that considering both the MJO and ENSO in combination can provide extra signal compared with either the MJO or ENSO by itself. The difference between Phases 2+3 and Phases 7+8 is emphasized when displaying tracks for all TCs undergoing a 30-knot or greater RI during 24 hours (Figure 3).

6. Summary and future work

This paper showed the strong impact that both the MJO and ENSO have on RI episodes in the Atlantic basin. It began by examining ENSO's impacts on Atlantic basin RI and demonstrated that RI is much more frequent in La Niña events than in El Niño episodes with neutral ENSO events having RI frequency between cold and warm episodes. Given these relationships, RI episodes were then demonstrated to occur much more frequently in MJO Phases 1+2 than in MJO Phases 6+7, with other phases of the MJO showing relationships between these two extremes. When the MJO and ENSO were combined using the WH-Combined index, even stronger relationships were demonstrated.

The most conducive phases for RI in the Atlantic MDR occur when deep convective anomalies occur over the tropical Indian Ocean. Associated with these deep convective anomalies in the Indian Ocean are increased mid-level moisture and reduced vertical wind shear in the tropical Atlantic, both of which are critical factors for RI. When deep convective anomalies are concentrated over the central and eastern tropical Pacific, the Atlantic MDR tends to be drier and have enhanced vertical wind shear, which reduces the likelihood of RI.

One area of current research is determining whether incorporation of the daily MJO index would improve the skill of the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (DeMaria *et al.*, 2005) or the recently-developed revised rapid intensity index (Kaplan *et al.*, 2010). This statistical model typically provides the best real-time forecast guidance for the National Hurricane Center, and consequently, any improvements to the SHIPS model could help prevent loss of life and property. Additional avenues for research include examining other ways of combining the MJO and ENSO to maximize skill. The impact of the MJO and ENSO on RI in other global TC basins will also be investigated.

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