AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL063966

Key Points:
- Surface pressure derived MJO index used to look at long-term TC/MJO relationship
- Modulation of global TC activity by the MJO is stable back to the mid-1900s
- MJO and ENSO combined cause large modulations in TC activity for certain basins

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Citation:
Klotzbach, P. J., and E. C. J. Oliver (2015), Variations in global tropical cyclone activity and the Madden-Julian Oscillation since the midtwentieth century, *Geophys. Res. Lett.*, *42*, 4199–4207, doi:10.1002/2015GL063966.

Received 23 MAR 2015
Accepted 28 APR 2015
Accepted article online 30 APR 2015
Published online 26 MAY 2015

Variations in global tropical cyclone activity and the Madden-Julian Oscillation since the midtwentieth century

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Abstract The Madden-Julian oscillation (MJO) has been documented in previous studies to significantly impact tropical cyclone activity in all ocean basins. Most of these studies have utilized the Wheeler-Hendon index. This index is only available since 1974, the period over which remotely sensed outgoing longwave radiation data has been available. Our study utilizes a long reconstructed MJO index, based on surface pressures, which extends back to 1905. We document consistent modulation of tropical cyclone activity by the MJO in all basins over this time period. These modulations are shown to be remarkably stable over the entire analysis period. We also examine the combined impacts of El Niño-Southern Oscillation and the MJO on tropical cyclone activity in each basin over multidecadal time scales.

1. Introduction

The Madden-Julian oscillation (MJO) [*Madden and Julian*, 1971, 1972] is an equatorially propagating mode of deep convection that modulates vertical wind shear, midlevel moisture, and low-level vorticity, among other large-scale atmospheric fields, and propagates eastward around the globe along the equator on a time scale of approximately 30–70 days. Each of these atmospheric fields is significantly tied to intraseasonal fluctuations in tropical cyclone (TC) activity, as shown in *Klotzbach* [2014]. The impacts of the MJO on TC activity have been discussed extensively for each basin individually, as well as in summary articles for all TC basins in *Camargo et al*. [2009] and *Klotzbach* [2014].

Generally, studies on links between the MJO and TCs have utilized the *Wheeler and Hendon* [2004] index, hereafter the WH index, to assess the state of the MJO [e.g., *Camargo et al*., 2009; *Klotzbach*, 2014]. This index is based on the first two principal components of a multivariate empirical orthogonal function analysis of a combination of outgoing longwave radiation (OLR) and 200 mb and 850 mb zonal winds, after removing the annual mean and El Niño-Southern Oscillation (ENSO) signals to focus on time scales associated with the MJO. The WH index coverage is limited to post-1974 since daily OLR measurements over the tropics are not available prior to that time. While the WH index is a valuable tool for MJO monitoring, it is acknowledged that it cannot fully represent all MJO events. However, it is the most frequently used MJO diagnostic at present and will consequently be utilized here.

Recently, *Oliver and Thompson* [2012] have reconstructed MJO variability back to 1905 using a multiple linear regression model with surface pressure from the Twentieth Century Reanalysis [*Compo et al*., 2011] as predictors of the WH index. The Oliver and Thompson (OT) MJO index shows good agreement with the WH index over the period from 1979 to 2008 [*Oliver and Thompson*, 2012]. It was also shown to have consistent relationships with zonal winds and cloud cover in the tropics back to the early twentieth century. More recently, *Oliver* [2014] showed a consistent MJO relationship with long records of surface air temperatures over Alaska.

Klotzbach and Oliver [2015] showed that the Atlantic basin TC activity-MJO relationship has been stable back to 1905. Given the longer period of data analyzed, they were also able to investigate the combined impact of the MJO and El Niño-Southern Oscillation (ENSO) [e.g., *Rasmusson and Carpenter*, 1982] on Atlantic basin TCs. In the present study, we extend this work spatially to investigate the impacts of the MJO on TC activity globally. This study is the first to examine global TC-MJO relationships over such a long period of time.

Table 1. TC Basin, Time Period Investigated, Data Source Utilized, Longitudinal Boundary Definitions, and Number of TCs During the Pre-1979 and 1979–2012 Period[a]

Tropical Cyclone Basin	Time Period	Data Source	Longitudinal Boundaries (West/East)	Number of Pre-1979/1979–2012 TCs
North Atlantic	1905–2012	HURDAT2	Central America/Africa	682/421
Northeast Pacific	1949–2012	HURDAT2	International Date Line/West Coast of Central America	351/550
Northwest Pacific	1945–2012	JTWC	Asia/International Date Line	852/874
North Indian	1972–2012	JTWC	West Edge of Arabian Sea/East Edge of Bay of Bengal	28/159
South Indian	1960–2012	Neumann/JTWC	Africa/135°E	310/588
South Pacific	1960–2012	Neumann/JTWC	135°E/West Coast of South America	199/343

[a] Data sources are discussed in section 2.

This paper is organized as follows. Section 2 describes the data utilized in this study, while section 3 examines the stability of the MJO/TC relationship for all global TC basins. Section 4 looks at the combined MJO/ENSO relationship with TCs, while section 5 concludes the manuscript and provides a discussion of future work.

2. Data and Methods

TC data for the North Atlantic (NA) and Northeast Pacific (NEP) basins were taken from the HURricane DATabase 2 (HURDAT2) database maintained by the National Hurricane Center (NHC) [*Landsea and Franklin*, 2013]. For the remaining basins (the Northwest Pacific (NWP), the North Indian Ocean (NIO), the South Indian Ocean (SIO), and South Pacific (SP)), we used Joint Typhoon Warning Center (JTWC) data [*Chu et al.*, 2002]. JTWC data were utilized instead of the Regional Specialized Meteorological Center data due to consistency of 1 min wind averaging times for all basins. For the SP and SIO basins, JTWC has incomplete wind data prior to 1985, and consequently, a specialized data set developed by *Neumann* [1999] is utilized to extend the record back to 1960. Beginning with the 1985/1986 season, JTWC data were utilized for Southern Hemisphere (SH) TC activity. This combination of the Neumann and JTWC data sets was also utilized by *Webster et al.* [2005] and *Klotzbach* [2006]. Accumulated Cyclone Energy (ACE) [*Bell et al.*, 2000] was used as our primary TC intensity metric.

All data sets were obtained from the International Best Track Archive for Climate Stewardship archive [*Knapp et al.*, 2010]. Details of each basin's definition as well as the time period utilized and the number of TCs for the pre-1979 and 1979-2012 periods are provided in Table 1. There is obviously increased uncertainty with TC data as one goes back in time, but since MJO variability is focused on intraseasonal time scales as opposed to long-term climate trends, these increased uncertainties should be minimized. In particular, the bias toward fewer observed hurricanes in the early part of the record will be distributed evenly across all MJO phases. For SH TC activity, we refer to the year value as the end year of the season (e.g., the 1959/1960 SH TC season would be referred to as 1960 in our analysis).

We utilize both the WH index and OT index. For the WH index, we only use data since 1979. North Indian Ocean TC data with intensity information is only available since 1972, and several years' worth of data are needed for an independent evaluation of the stability of the MJO/TC relationship. The reason for using both indices despite the overlap since 1979 is that by comparing the MJO/TC relationship between the indices over 1979–2012 we demonstrate consistency between the indices. We then extend the analysis to examine the relationship between the MJO and TCs over the pre-1979 period using the OT index. The start date for the pre-1979 period is basin dependent since the beginning of TC data availability varies widely from basin to basin (Table 1).

In order to classify ENSO events, we utilize the Multivariate ENSO Index (MEI) which is described in *Wolter and Timlin* [1998]. This index is preferred to a canonical ENSO index such as the Nino 3.4, since the MEI better takes into account the full-scale atmospheric and oceanic response to ENSO. The MEI extends back to 1950, and so for TC basins where data are available prior to 1950, the Extended MEI is utilized [*Wolter and Timlin*, 2011]. When the seasonal MEI value exceeded 0.75, it was classified as an El Niño, and when the seasonal MEI value was less than −0.75, it was counted as a La Niña event, as was done in *Klotzbach and Oliver* [2015]. All other seasons are counted as neutral. *Wolter and Timlin* [2011] utilize a similar threshold by defining El Niño events when the twentieth percentile of all events is exceeded. The months for each TC basin's seasons were calculated as in *Klotzbach* [2014].

Deep layer vertical shear was calculated using the Twentieth Century Reanalysis [*Compo et al.*, 2011] as the difference between lower level (200 hPa) and upper level (850 hPa) zonal winds.

3. Global Modulation of TC Activity by the MJO

We begin our analysis by examining the amount of ACE generated in four two-phase MJO groupings (MJO Phases 1 + 2, Phases 3 + 4, Phases 5 + 6, and Phases 7 + 8). These groupings were utilized due to the findings in *Klotzbach* [2014] that TC activity is enhanced in the MJO phases associated with and immediately following the convective maximum in a specific basin, which causes an approximate one-phase shift from the maximum convective anomaly for a particular region (e.g., Phases 8 + 1 to Phases 1 + 2 for the NA). We use a normalized ACE, due to the fact that the MJO can preferentially spend more time in certain phases than in others. Normalized ACE is defined to be the amount of ACE generated by TCs forming in specific phases of the MJO divided by the number of days that the MJO spends in these phases during the respective TC season multiplied by 100. This metric was introduced in *Klotzbach* [2010] and was also utilized in *Klotzbach* [2014] and *Klotzbach and Oliver* [2015].

The MJO significantly modulates normalized ACE in all basins (Figure 1). Statistical significance at the 1% level is calculated assuming a binomial distribution and a null hypothesis that TC activity is uniformly distributed across all MJO phases, following *Hall et al.* [2001]. In general, there is consistency across all basins, both between the OT and WH index over the shared period (1979–2012) as well as between this period and the pre-1979 period. Generally, periods of enhanced TC activity (i.e., larger ACE anomalies) are associated with periods when the convectively active portion of the MJO passes over a specific basin. This occurs in MJO Phases 1–4 for the NA, 1 + 2 and 7 + 8 for the NEP, 5–8 for the NWP and SP, 1–4 for the NIO, and 3–6 for the SIO.

Tracks of major hurricanes (TCs with maximum 1 min sustained winds greater than 95 knots—corresponding to Category 3 or greater on the Saffir Simpson wind scale) grouped by MJO phase are consistent with the pattern of ACE modulation by the MJO (Figure 2). When the MJO is in its convectively suppressed phase, TC activity is generally reduced. This tends to occur in Phases 5 + 6 in the Western Hemisphere (WH) and 7 + 8 and 1 + 2 over the Indo-Pacific region. These tracks also demonstrate the general consistency of the MJO-TC relationship between the pre-1979 and 1979–2012 periods. Over the next few paragraphs, the relationships for each basin are discussed.

The long-term relationship between the MJO and TC activity in the NA basin (Figure 1a) was already investigated in *Klotzbach and Oliver* [2015]. MJO Phases 1 + 2 were characterized by significantly enhanced TC activity, regardless of MJO index or time period utilized, while MJO Phases 5 + 6 were generally characterized by suppressed TC activity. These MJO phase/TC relationships agreed well with prior studies over the more recent time period [*Klotzbach*, 2010; *Ventrice et al.*, 2011].

The relationships between the MJO and TC activity in the NEP also were generally consistent across MJO indices and time periods (Figure 1b). The only noticeable disagreement was that MJO Phases 1 + 2 were characterized by slightly above-average activity during the 1979–2012 period using either the OT or WH index, while those phases were characterized by significantly suppressed activity prior to 1978. Phases 3 + 4 had suppressed levels of TC activity, and Phases 7 + 8 had enhanced levels of TC activity over the entire period of record, regardless of MJO index, in agreement with what was shown in *Klotzbach* [2014]. It should be noted that there were issues with NEP TC data prior to 1988, when the responsibility for issuing TC advisories was transferred from Redwood City, California, to the NHC.

The MJO-TC relationship in the NWP was consistent over the entire analysis period (Figure 1c). Normalized ACE was significantly enhanced in MJO Phases 5 + 6 and 7 + 8 while it was significantly suppressed in MJO Phases 1 + 2 and Phases 3 + 4 for all indices and time periods, in agreement with findings over the more recent period discussed in *Camargo et al.* [2009] and *Klotzbach* [2014]. This result was reflected in the major hurricane tracks (Figure 2).

Both Indian Ocean basins exhibited a MJO-TC relationship that was fairly similar across time periods (NIO, Figure 1d; SIO, Figure 1e). In the NIO, Phases 1 + 2 were characterized by above-average TC activity, and Phases 7 + 8 were characterized by suppressed activity, consistent with *Klotzbach* [2014]. In the SIO, Phases 3 + 4 generated significantly enhanced TC activity, and Phases 7 + 8 were characterized by below average activity for all indices and time periods. The NIO basin had the shortest period of data for this study, with

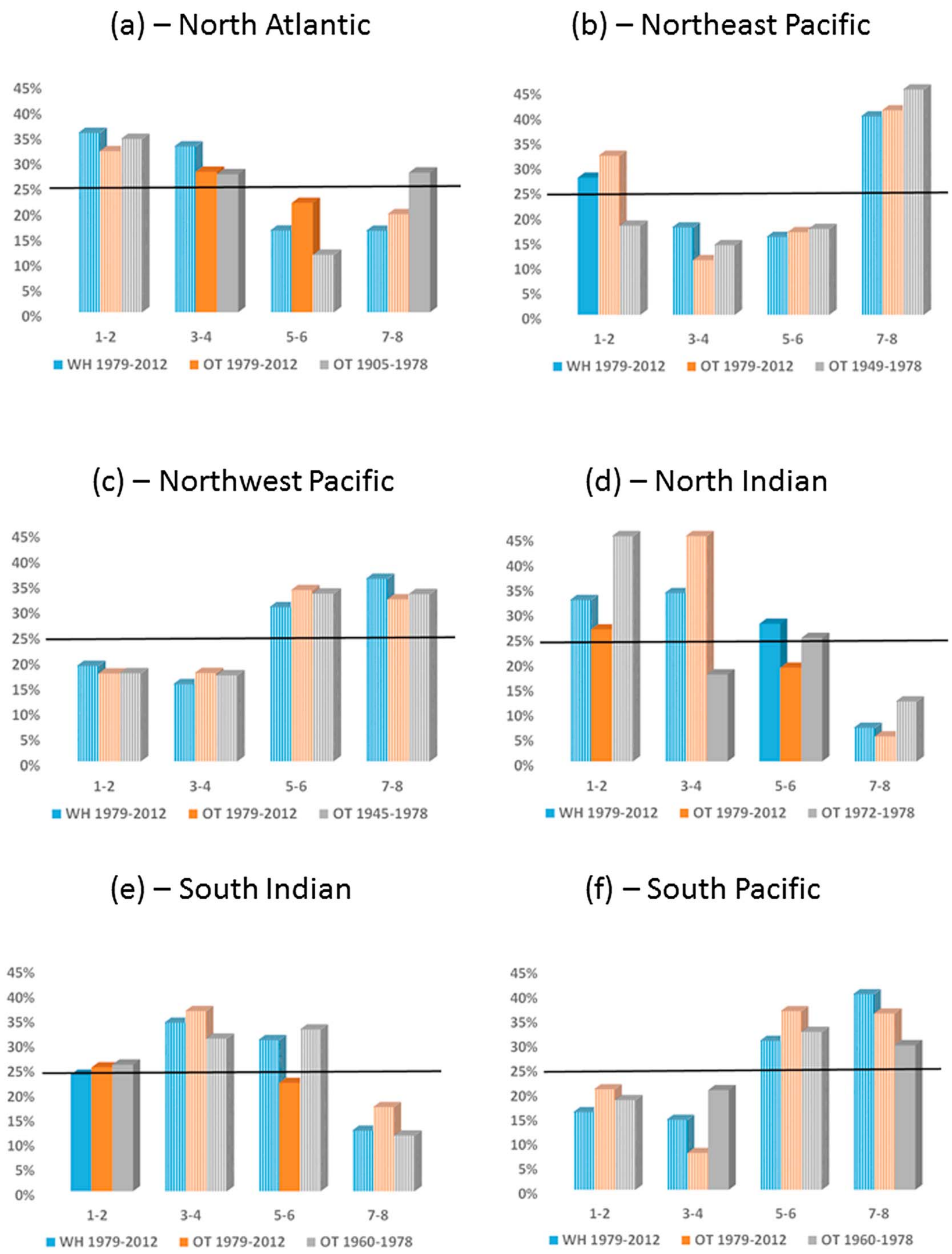

Figure 1. Modulation of TC activity in each basin by the MJO. Vertical bars show the percentage of normalized ACE generated in each two-phase grouping of the MJO for the (a) NA, (b) NEP, (c) NWP, (d) NIO, (e) SIO, and (f) SP using the WH index over the period from 1979-2012 (blue), the OT index from 1979-2012 (orange) and the OT index prior to 1979 (grey; see text for details). Striped bars indicate that the result is significantly different, at the 1% level, from the null hypothesis (as indicated by the black line) that 25% of all basin wide ACE is generated in each two-phase pairing of the MJO; solid bars are not significant at the 1% level.

most TCs for the basin containing no intensity information prior to 1972. In addition, intensities prior to the late 1980s were likely underestimated due to the lack of a directly overlooking satellite [*Knapp and Kossin*, 2007]. The SIO basin was also plagued by this same issue, which likely led to an underestimate of TC activity during the early part of the record. This underestimate is clearly seen by examining major

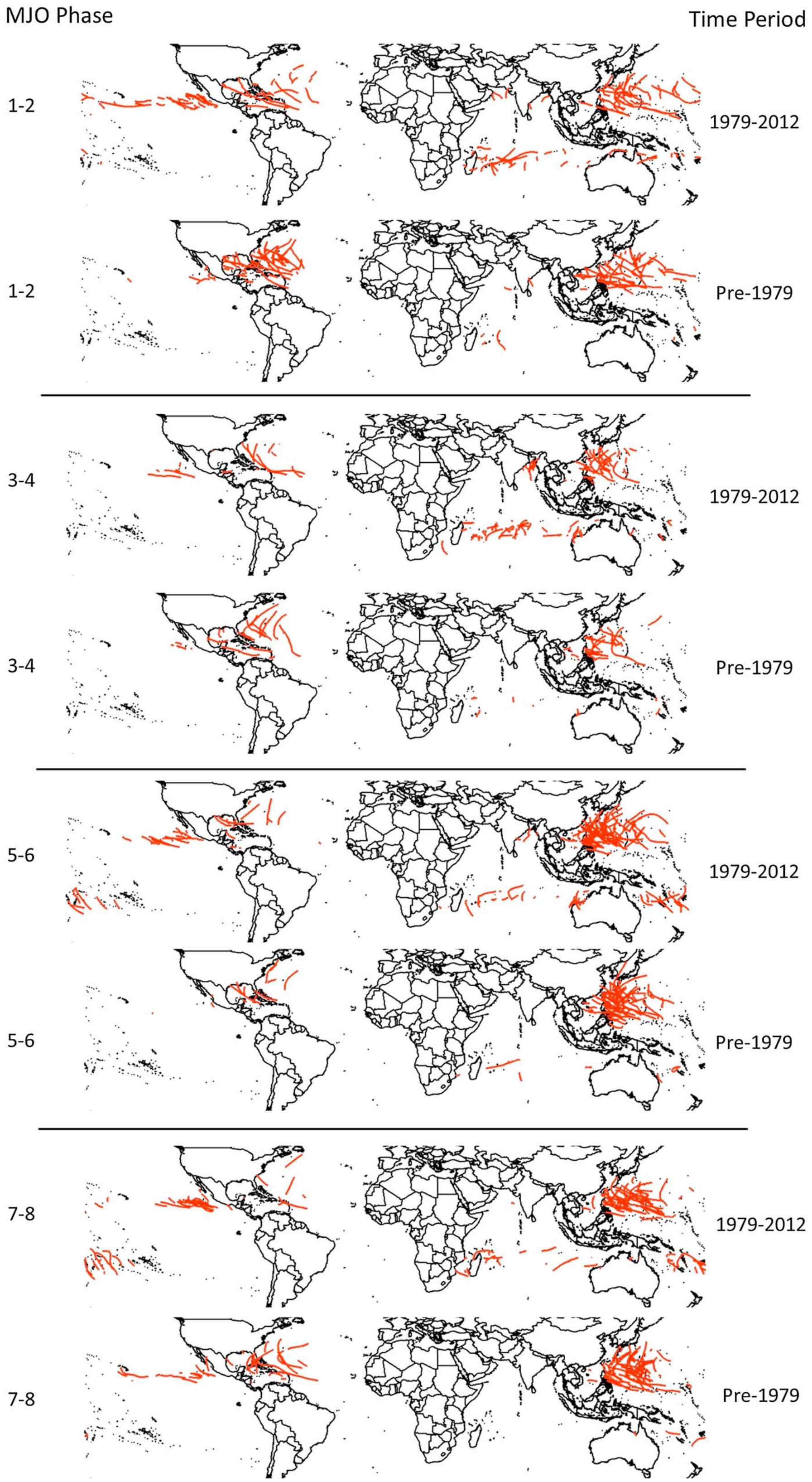

Figure 2. Global modulation of major hurricane tracks by the MJO. The tracks of all major hurricanes are shown during MJO Phases 1 + 2, 3 + 4, 5 + 6, and 7 + 8 over 1979-2012 and pre-1979 periods using the OT index. The pre-1979 period varies by basin depending on the start date of TC records (see text for details).

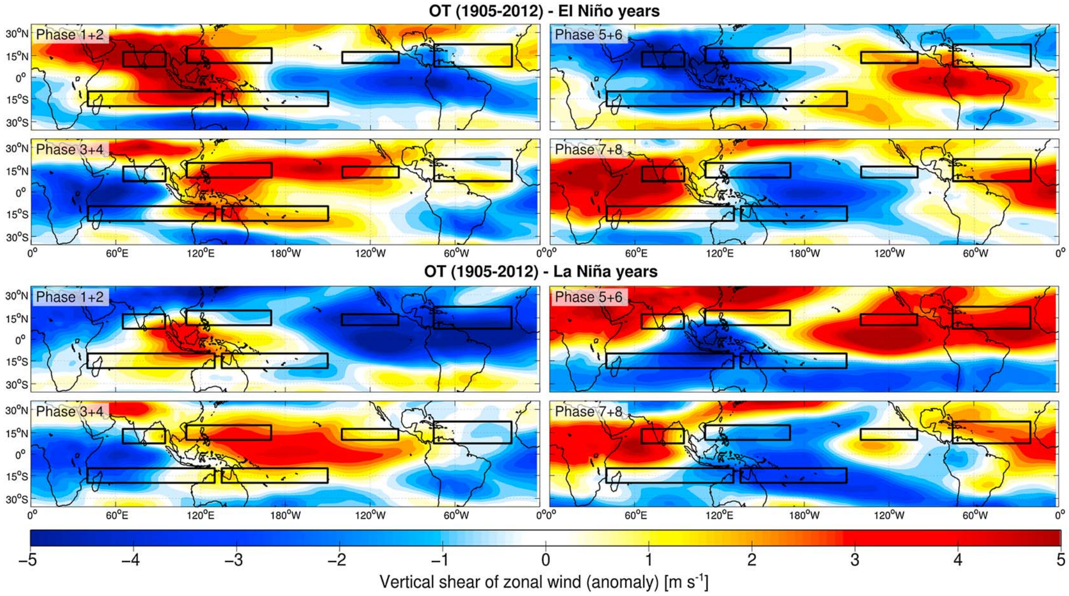

Figure 3. Modulation of vertical wind shear by the MJO. Colored contours show anomalous 200-850-mb wind shear for each two-phase MJO grouping during El Niño (top) and La Niña (bottom) events over 1905-2012. Black boxes indicate the approximate Main Development Region for each TC basin as defined in *Klotzbach* [2014].

hurricane tracks in Figure 2. Very few major hurricane tracks occur in the SIO in the pre-1979 period. However, since we are investigating the MJO/TC relationship, underestimations should apply equally to all phases. Despite these issues, the MJO-TC relationship remained fairly stable over time.

The SP also had stable relationships over the entire record: 1960–2012 (Figure 1f). Phases 1–4 showed suppressed TC activity over both the 1960–1978 and 1979–2012 periods (significant for Phases 1 + 2), while Phases 5–8 showed enhanced TC activity (significant for Phases 5 + 6). Again, as with the other basins, there was remarkable stability in the MJO-TC relationship over time in the SP.

4. Combined Modulation of TC Activity by the MJO and ENSO

El Niño has been documented in many studies to suppress NA TC activity, dating back to the seminal work of *Gray* [1984]. *Klotzbach and Oliver* [2015] discussed the combined impacts of both ENSO and the MJO on TC activity in the NA over the last ~100 years. One of the primary reasons why both ENSO and the MJO modulate TC activity around the globe is due to their impact on vertical wind shear fluctuations on interannual and intraseasonal time scales, respectively. The modulation of vertical wind shear by the MJO over the 1905–2012 period varied significantly by ENSO phase (Figure 3). Vertical wind shear anomalies were generally negative over the NA and positive over the Indo-Pacific region in MJO Phases 1 + 2. However, during El Niño, this pattern is enhanced over the NA and suppressed over the Indo-Pacific. During La Niña, the opposite occurs, with suppression over the NA and enhancement over the Indo-Pacific.

The degree to which the MJO modulates normalized ACE varies significantly according to the phase of ENSO (e.g., El Niño, neutral, and La Niña; Figure 4). In the NA, Phases 1 + 2 are the most active phases for El Niño, but despite the favorable intraseasonal conditions, the overall unfavorable interannual conditions still cause a significant decrease in activity from the climatological average (Figure 4a). Approximately 5 times as much normalized ACE occurs in Phases 1 + 2 in La Niña compared with Phases 3 + 4, Phases 5 + 6, or Phases 7 + 8 in El Niño. In other words, even TC-favorable MJO conditions are not sufficient to overcome TC-unfavorable ENSO conditions in the NA. Note that given the large number of years in the NA sample (1905–2012), even small deviations from climatology achieve statistical significance.

In general, the NEP experiences somewhat more TC activity in El Niño events (Figure 4b). Phases 7 + 8 have significantly enhanced TC activity in all phases of ENSO, while Phases 3 + 4 have significantly suppressed TC activity. In Phases 1 + 2, El Niño and neutral events have near-average activity, while activity is

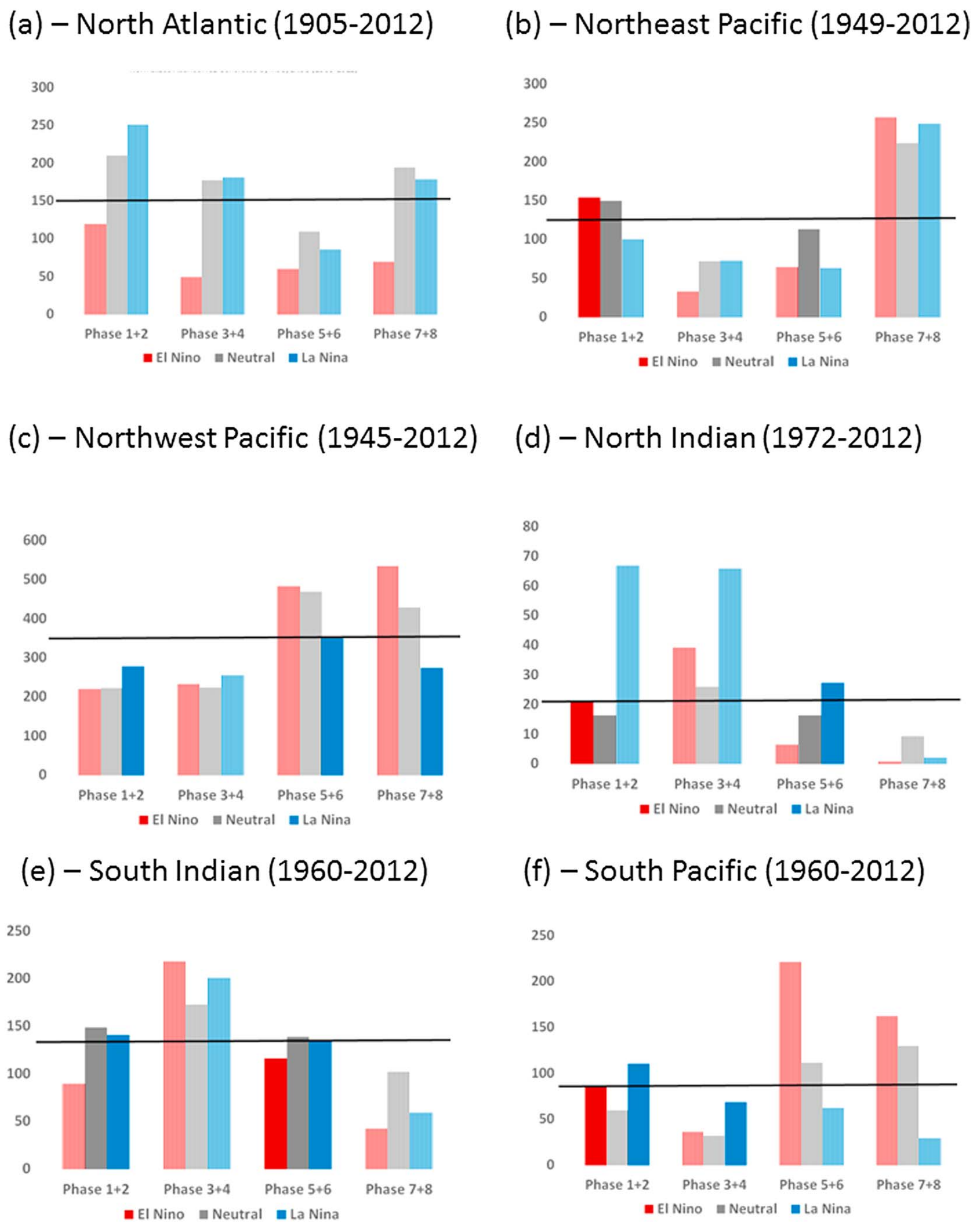

Figure 4. Modulation of TC activity in each basin by the combined influence of the MJO and ENSO. Vertical bars show normalized ACE generated in each two-phase grouping of the MJO for the (a) NA, (b) NEP, (c) NWP, (d) NIO, (e) SIO, and (f) SP basin during El Niño (red bars), neutral (grey bars) and La Niña (blue bars) seasons. Striped bars indicate that the result is significantly different, at the 1% level, from the null hypothesis (as indicated by the black line) of the climatological average normalized ACE for all ENSO phases; solid bars are not significant at the 1% level.

significantly suppressed in La Niña. This increase is generally observed more in the central Pacific than in the eastern Pacific as documented in *Klotzbach and Blake* [2013]. Consequently, when examining the NEP as a whole, increases in MJO-related TC activity from La Niña to El Niño are somewhat small.

In the NWP, increases in TC activity in El Niño appear to be confined to MJO Phases 5 + 6 and Phases 7 + 8 (Figure 4c). Both Phases 5 + 6 and Phases 7 + 8 have significantly enhanced TC activity from the climatological average in El Niño events, while TC activity shows no significant change from the long-term average in La Niña events in these MJO phase pairings. Phases 3 + 4 are characterized by suppressed TC activity regardless of ENSO phase. While storm numbers do not significantly change in the NWP from La Niña to El Niño, it has been documented that storms tend to form farther south and east in El Niño events [*Chia and Ropelewski*, 2002]. These systems tend to have longer lifetimes and consequently generate more ACE [*Camargo and Sobel*, 2005].

In the NIO, TC activity appears to be reduced somewhat during El Niño, with significant enhancement in La Niña (Figure 4d), consistent with *Ng and Chan* [2012] for the Bay of Bengal. Significantly enhanced TC activity occurs in Phases 1 + 2 and Phases 3 + 4 in La Niña. Phases 2 + 3 are when the MJO is enhancing convection and supporting increased vertical motion over the NIO [*Wheeler and Hendon*, 2004]. The increase of TC activity in either El Niño or neutral conditions was much less in these phases, although still significant in Phases 3 + 4. Phases 7 + 8 is associated with suppressed TC activity regardless of ENSO phase. However, given the limited period of study (1972–2012) and generally lower annual TC activity in the NI than in other basins, results should be interpreted with caution.

There do not appear to be any consistent significant impacts of ENSO on the MJO modulation of ACE in the SIO. MJO Phases 3 + 4 enhance activity in the SIO regardless of ENSO phase, while Phases 7 + 8 suppress activity. The only MJO phases that seem to show any ENSO modulation are Phases 1 + 2 where TC activity is significantly suppressed with El Niño while generating near-average levels of TC activity with both neutral and La Niña event. These results are consistent with *Jury* [1993] who found no strong ENSO relationship with SIO ACE. *Kuleshov et al*. [2008] found that tracks tend to shift westward with El Niño, but overall ACE levels do not change significantly.

As was found in the NWP, ACE levels tend to be enhanced in the SP with El Niño due to longer-tracked TCs. Phases 5 + 6 and Phases 7 + 8 are characterized by statistically significantly enhanced TC activity with El Niño, while TC activity is suppressed in these MJO phases with La Niña. ENSO's modulation of TC activity appears to be much less in MJO Phases 1 + 2 and Phases 3 + 4. This is consistent with previous work which has shown that fairly short-lived (and low ACE generating) TC activity near Australia is enhanced with La Niña [*Nicholls*, 1979], while longer-lived (and high ACE generating) TC activity forming farther to the north and east is enhanced with El Niño [*Ramsay et al*., 2012].

5. Conclusions and Future Work

This paper has examined the modulation of TCs by the MJO in all ocean basins over the past several decades using a long-duration MJO index. We find consistent MJO-TC relationships between the *Oliver and Thompson* [2012] MJO data set and the standard MJO data set developed by *Wheeler and Hendon* [2004] over the period from 1979 to 2012. Similar MJO-TC relationships in each TC basin are also documented over the historical pre-1979 period. The consistency of the relationships displayed here is remarkable, considering the increasing uncertainty in both MJO phase diagnosis as well as TC activity as one goes back in time. Therefore, we should expect these relationships to remain stable in the future. In general, the MJO-TC relationships described in *Klotzbach* [2014] using the *Wheeler and Hendon* [2004] MJO index over the post-1979 period are verified here over a longer period of record. The combined impacts of the MJO and ENSO are also investigated. The modulation of the MJO/TC relationship by ENSO appears in most basins to some degree, with the NA, SP, and NIO basins showing the largest differences.

The utility of the *Oliver and Thompson* [2012] MJO data set has been clearly documented for global TC activity. In the future, we plan to utilize this data set to investigate the modulation of TC landfalls by the MJO in various high-risk regions of the globe. The combined impact of the MJO and other interannual and longer time scale climate modes, such as the Atlantic Multidecadal Oscillation [*Goldenberg et al*., 2001] and the Pacific Decadal Oscillation [*Mantua et al*., 1997], on global TC activity will also be considered in future work.

Acknowledgments
The first author would like to acknowledge the G. Unger Vetlesen Foundation for financial support that helped fund this research. This paper makes a contribution to the objectives of the Australian Research Council Centre of Excellence for Climate System Science (ARCCSS). We would like to thank Hamish Ramsay and an anonymous reviewer for helpful comments that improved the manuscript. Data specific to this paper are available at http://tropical.atmos.colostate.edu.

The Editor thanks Hamish Ramsay and an anonymous reviewer for their assistance in evaluating this paper.

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