On the Madden–Julian Oscillation–Atlantic Hurricane Relationship

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ABSTRACT

The large-scale equatorial circulation known as the Madden–Julian oscillation (MJO) has been shown to impact tropical cyclone activity in several basins around the globe. In this paper, the author utilizes an MJO index created by Wheeler and Hendon to examine its impacts on tropical genesis and intensification in the Atlantic. Large differences in frequency and intensity of tropical cyclone activity are seen, both in the tropical Atlantic as well as in the northwest Caribbean and Gulf of Mexico depending on the MJO phase. Coherent changes in upper- and lower-level winds and relative humidity are likely responsible for these differences. Since the MJO shows potential predictability out to about two weeks, the relationships discussed in this paper may be useful for short-term predictions of the probability of tropical cyclone activity in the Atlantic as a complement to the already available longer-term seasonal predictions.

1. Introduction

The Madden–Julian oscillation (MJO) is a globally propagating mode of tropical atmospheric intraseasonal variability (Madden and Julian 1972, 1994). Associated with this convectively driven mode of variability are large-scale variations in upper- and lower-level winds, vertical motion, atmospheric moisture content, and sea surface temperatures (Fig. 1). This global wave tends to propagate eastward at approximately 5 m s^{-1}, circling the globe in approximately 40–50 days. Prior to the enhanced convection, anomalous easterly winds are observed at low levels with anomalous westerly winds observed at upper levels. Following the enhanced convection, anomalous westerly winds are observed at low levels with anomalous easterly winds observed at upper levels. Variability associated with the MJO is primarily concentrated in the 30–80-day time frame and shows potential predictability out to about two weeks, depending on the time of year and the location of enhanced convection (Mo 2001; Waliser et al. 2006; Jiang et al. 2008; Seo et al. 2009). The predictability of the MJO is typically greater in the Northern Hemisphere winter than it is in the Northern Hemisphere summer (Jiang et al. 2008).

It is well known that tropical cyclones (TCs) around the globe tend to cluster in time and space (Gray 1979). For example, during the very active 1995 Atlantic basin hurricane season that had a total of 19 named storms, 5 storms formed during the 7-day period between 22 and 28 August. Following this flurry of activity, only one TC formed between 29 August and 27 September during the climatologically most active period of the Atlantic TC season. Also, in 2008, during another active Atlantic hurricane season where 16 named storms formed, 4 storms formed between 25 August and 2 September followed by no tropical cyclone formations between 2 and 25 September.

Because of this observed clustering, the MJO has been considered a likely modulator of TC activity. Maloney and Hartmann (2000) documented that Gulf of Mexico and western Caribbean tropical cyclogenesis was 4 times more likely to occur when lower-tropospheric MJO wind anomalies in the eastern Pacific were westerly than when they were easterly. Mo (2000) demonstrated that TC activity in the Atlantic was most enhanced when the convectively enhanced phase of the tropical intraseasonal oscillation, of which the MJO was the dominant signal, was located over eastern Africa and the Indian Ocean and suppressed convection was located over the tropical Pacific. Maloney and Shaman (2008) show that TC activity in the east Atlantic tends to be suppressed about 5–10 days before a maximum in regional precipitation over the east Atlantic and West Africa, while

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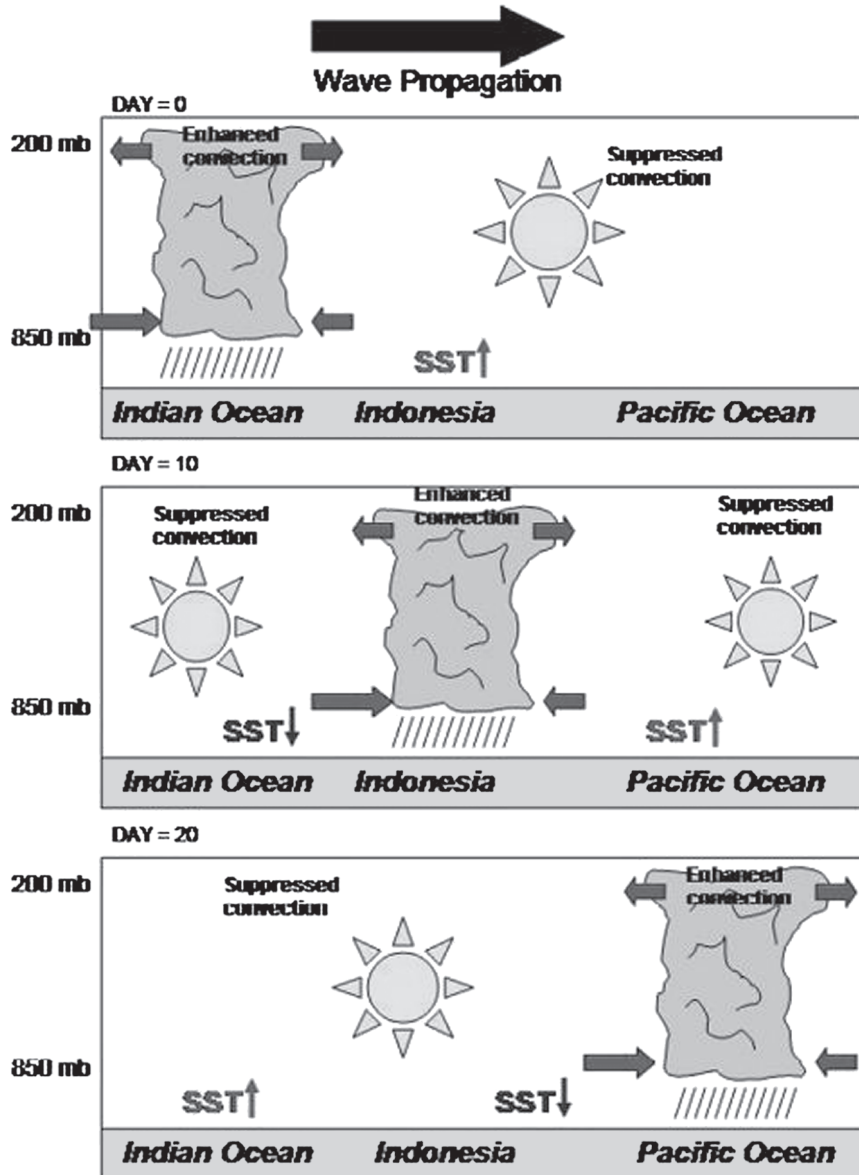E-mail: philk@atmos.colostate.edu

FIG. 1. Large-scale features associated with MJO convective anomalies. Note the anomalous westerly low-level flow and anomalous easterly upper-level flow that follows the enhanced convective signal. Figure adapted from Madden and Julian (1972).

TC activity is enhanced about 5–10 days after the maximum in regional precipitation. Barrett and Leslie (2009), using the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center's real-time MJO index, documented that storms were 4 times more likely to make landfall along the U.S. coastline when the MJO had a large amplitude and convection was enhanced at 120°W.

Researchers have also documented significant relationships between the MJO and TCs in other TC basins. Frank and Roundy (2006) suggested that, through alterations in levels of vertical wind shear, low-level vorticity, and changes in vertical motion, the MJO can enhance and suppress TC activity in various TC basins around the globe. Camargo et al. (2008) showed that the westerly phase of the MJO is typically associated with eastern Pacific TCs that track close to the Central American coast. Leroy and Wheeler (2008) have utilized the MJO as one of their predictors in a statistical forecast for TC formation in the Southern Hemisphere.

Seasonal forecasts have been issued for the Atlantic basin since 1984 (Gray 1984b). Several large-scale features
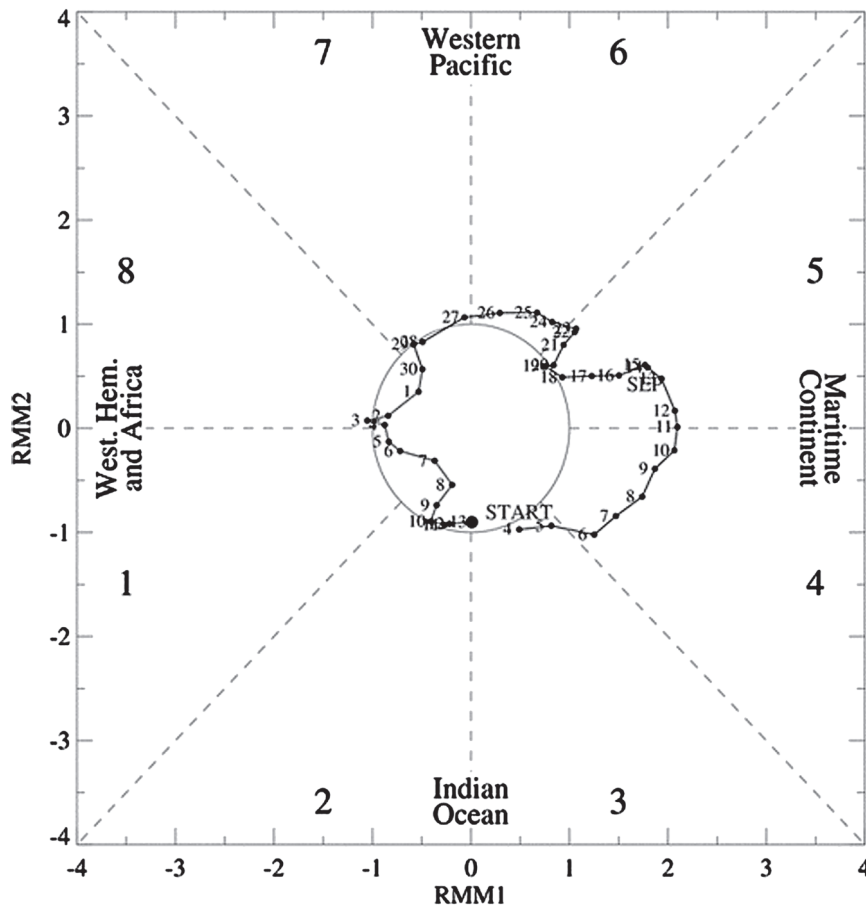
FIG. 2. Real-time values of the MJO index as calculated by Wheeler and Hendon (2004) over the period from 4 Sep 2008 to 13 Oct 2008. The phases are classified based on where convection is concentrated. For example, phases 2 and 3 are characterized by enhanced convection in the Indian Ocean. Figure adapted from Wheeler and Hendon (2004) with real-time data plotted from the Australian Government's Bureau of Meteorology Web site (http://www.bom.gov.au/).

have been documented that significantly modulate Atlantic basin tropical cyclone activity on seasonal time scales including El Niño–Southern Oscillation (ENSO) (Gray 1984a; Goldenberg and Shapiro 1996), Atlantic basin sea surface temperatures (Shapiro and Goldenberg 1998; Klotzbach and Gray 2008), and Atlantic sea level pressures (Knaff 1997). Also shown to be related to storm activity in the Atlantic are levels of vertical wind shear (Gray 1968, 1984a,b; Shapiro and Goldenberg 1998; Bell and Chelliah 2006) and West African rainfall (Landsea and Gray 1992). Anomalously cool ENSO conditions, warmer-than-normal tropical Atlantic SSTs, lower-than-normal tropical Atlantic sea level pressures, reduced levels of vertical wind shear, and anomalously wet conditions in the Sahel region of West Africa are associated with above-average Atlantic hurricane seasons. Seasonal hurricane forecasts issued operationally around 1 June and 1 August have shown skill above climatology (Owens and Landsea 2003; Klotzbach 2007; Klotzbach and Gray 2009). Short-term predictions (10–14 days) of TC genesis–intensification likelihood in the Atlantic are not currently available. With the recent development of a real-time MJO index (Wheeler and Hendon 2004), there is potential for real-time short-term prediction of TC activity in the Atlantic, assuming that significant relationships exist between the real-time MJO index and Atlantic basin storm activity. The purpose of this paper is to investigate relationships between Atlantic TC activity and the MJO as defined by Wheeler and Hendon (2004). Although other authors have examined various aspects of the relationship between Atlantic basin TCs and the MJO, to the knowledge of the author this is the first manuscript that extensively quantifies several aspects of Atlantic basin TCs along with large-scale changes in the tropical Atlantic. Section 2 discusses the data sources used in this manuscript, while section 3 examines large-scale atmospheric changes in the tropical Atlantic region associated with the MJO. Section 4 evaluates Atlantic TC

TABLE 1. The number of days in each MJO phase along with anomalous values of SST, SLP, 850-mb zonal wind (850-mb U), 200-mb zonal wind (200-mb U), 200–850-mb zonal wind shear, 700-mb relative humidity (700-mb RH), 300-mb omega (ω), and OLR by MJO phase for all days from June to November during the 1974–2007 period. Also provided are the anomalous values for all days where the MJO amplitude according to the Wheeler and Hendon definition is greater than 1. Anomalies are calculated over the MDR (7.5°–22.5°N, 20°–75°W). Anomalies that are statistically significant from the phase 1–8 average at the 90% level are underlined, at the 95% level are italicized, and at the 99% level are bold. Statistically significant difference between phase 1–2 anomalies and phase 6–7 anomalies are also calculated and are highlighted in the phase 1–2 row.

MJO phase	Number of days	SST anomaly (°C)	SLP anomaly (mb)	850-mb U anomaly (m s^{-1})	200-mb U anomaly (m s^{-1})	200–850-mb U anomaly (m s^{-1})	700-mb RH anomaly (%)	300-mb ω anomaly (mb day^{-1})	OLR anomaly (W m^{-2})
Phase 1	946	−0.01	*−0.32*	+0.24	−1.78	−2.03	+1.12	−1.70	−1.04
Phase 2	903	+0.02	−0.12	*+0.35*	−1.59	*−1.94*	+1.04	−1.00	*−1.53*
Phase 3	664	+0.03	+0.13	+0.19	−0.58	−0.77	−0.36	*+1.90*	+1.24
Phase 4	723	+0.07	+0.28	−0.02	+0.01	+0.02	−0.68	**+2.60**	**+2.29**
Phase 5	820	+0.07	+0.20	−0.28	+0.63	+0.91	−0.09	+0.60	+1.26
Phase 6	723	−0.06	+0.29	**−0.38**	+1.62	**+2.01**	−1.06	+1.00	+0.72
Phase 7	617	−0.09	+0.05	−0.28	+2.12	+2.41	−0.87	−0.70	−0.95
Phase 8	643	−0.02	*−0.42*	+0.08	+0.79	+0.71	+0.21	−2.00	−1.67
Phases 1–2	1849	0.00	**−0.22**	**+0.30**	**−1.69**	**−1.98**	**+1.08**	−1.30	−1.28
Phases 6–7	1340	−0.08	+0.18	−0.34	+1.85	+2.19	−0.97	−0.20	−0.05

MJO index > 1

MJO phase	Number of days	SST anomaly (°C)	SLP anomaly (mb)	850-mb U anomaly (m s^{-1})	200-mb U anomaly (m s^{-1})	200–850-mb U anomaly (m s^{-1})	700-mb RH anomaly (%)	300-mb ω anomaly (mb day^{-1})	OLR anomaly (W m^{-2})
Phase 1	573	−0.04	*−0.39*	*+0.39*	−1.93	−2.32	+1.39	−1.90	−1.79
Phase 2	516	+0.07	*−0.32*	**+0.58**	−2.17	−2.75	+1.56	−1.50	−2.17
Phase 3	333	−0.01	+0.22	+0.13	−0.41	−0.54	−0.62	*+2.20*	+1.63
Phase 4	369	+0.10	+0.32	−0.02	+0.50	+0.51	−0.70	**+3.20**	+2.32
Phase 5	568	+0.09	*+0.31*	−0.31	+0.51	+0.82	+0.21	+0.70	+1.77
Phase 6	473	−0.08	+0.33	**−0.50**	+1.86	+2.36	*−1.46*	+1.10	+0.96
Phase 7	311	−0.16	+0.12	*−0.53*	+2.00	+2.52	*−1.61*	−0.60	−0.26
Phase 8	349	−0.08	*−0.47*	+0.07	+1.12	+1.05	−0.24	−1.70	−1.81
Phases 1–2	1089	+0.01	**−0.36**	**+0.48**	**−2.05**	**−2.52**	**+1.47**	−1.70	*−1.97*
Phases 6–7	784	−0.11	+0.25	−0.51	+1.92	+2.42	−1.52	+0.50	+0.47

activity associated with the various phases of the MJO, while section 5 summarizes the results and highlights additional research needs.

2. Data

The daily phase of the MJO was determined from the Wheeler and Hendon (2004) analysis. They utilize a multivariate EOF analysis to isolate the signal of the MJO by combining upper- and lower-level winds with outgoing longwave radiation (OLR). Their index is constructed by first removing the annual mean and interannual variability associated with large-scale phenomena such as ENSO. The removal of ENSO is especially useful for looking at subseasonal variability in the Atlantic. The Wheeler and Hendon MJO index is used here from 1974 to 2007, except for 1978 when OLR data were unavailable. Figure 2 displays the schematic developed by Wheeler and Hendon (2004) with their calculated phases of the MJO over the period from 4 September through 13 October 2008 based on where the convection is enhanced. The distance from the center of the circle indicates the amplitude of the MJO, with individual Real-time Multivariate MJO series (RMMs) normalized to have a standard deviation of one (denoted by the circle on the figure). Typically, the MJO propagates from west to east, so one would expect to see the MJO move from phase 1 to phase 2 to phase 3, etc.

Large-scale fields of upper- and lower-level zonal winds, sea level pressure, relative humidity, and sea surface temperature are calculated from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kistler et al. 2001). Atlantic hurricane statistics are computed from the National Hurricane Center's Atlantic basin Hurricane Database (HURDAT) (Jarvinen et al. 1984). HURDAT provides 6-hourly information on storm location and intensity. In this analysis, subtropical cyclones are excluded. They are a very limited subset of storms in the HURDAT database, and the impact of a large-scale tropical mode such as the MJO would likely be limited for these types of cyclones, as subtropical cyclones tend to form in the midlatitudes.
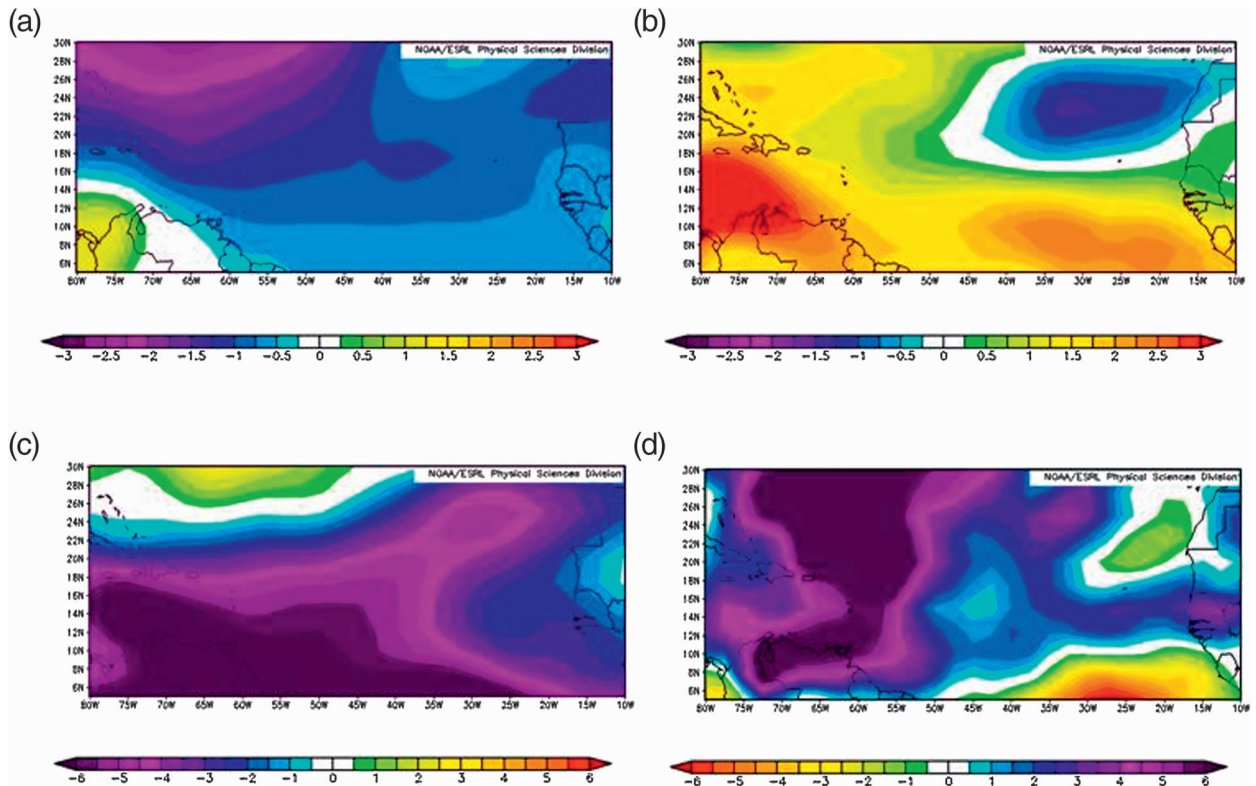
FIG. 3. The 200 days with the highest MJO amplitude in phase 1 (top 100 days) and phase 2 (top 100 days) minus the 200 days with the highest MJO amplitude in phase 6 (top 100 days) and phase 7 (top 100 days) for tropical Atlantic (a) sea level pressure, (b) 850-mb zonal wind, (c) 200-mb zonal wind, and (d) 700-mb relative humidity.

3. MJO impacts on the large-scale circulation in the tropical Atlantic

Table 1 (second column) displays the number of days that the MJO spent in each phase during the Atlantic hurricane season (1 June–30 November) from 1974 to 2007. The MJO spends approximately 50% more time in phases 1 and 2 than in phases 7 and 8, while phases 3–6 have frequencies of occurrence in between. According to Wheeler and Hendon (2004), during a single MJO cycle the approximate average time spent in each phase is about six days, although this varies greatly. Therefore, there are on the order of 100 MJO cycles represented in the data over the 1974–2007 period.

Atlantic basin tropical cyclones develop in the northern tropical Atlantic and subtropical Atlantic. The large majority of major hurricanes (maximum sustained winds greater than 95 kt) form in the Main Development Region (MDR) (Goldenberg et al. 2001). In this analysis, the MDR is defined to span from 7.5° to 22.5°N and 20° to 75°W. Over the 1974–2007 period, 81 major hurricanes formed in the Atlantic basin. Of these 81 major hurricanes, 58 (or 72%) were first classified as named storms (maximum sustained winds greater than 34 kt) in the

MDR. Major hurricanes are generally of most concern to individuals, because even though they only make up 20%–25% of all tropical cyclones that form in the Atlantic basin, when normalized by population, inflation, and wealth per capita, they cause approximately 80%–85% of the damage along the U.S. coastline (Pielke and Landsea 1998; Pielke et al. 2008).

Table 1 (columns 3–10) display anomalous values of MDR sea surface temperature, sea level pressure, 850-mb zonal wind, 200-mb zonal wind, 700-mb relative humidity, 300-mb omega, and OLR calculated for each phase of the MJO over the 1974–2007 period. Anomalies are calculated from the entire June–November 1974–2007 average. The maximum difference in vertical motion is approximately 4 mb day^{-1} while the maximum difference in OLR is approximately 3–4 W m^{-2}. These OLR differences are much less than the approximately 20–30 W m^{-2} differences that are observed over Indonesia and the Pacific (as seen on the Australian government's Bureau of Meteorology Web site: http://www. bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/RMM/ composites). Given the small OLR differences over the Atlantic, this paper focuses primarily on other metrics such as relative humidity and zonal wind to examine

impacts of the MJO on Atlantic TC activity. Statistically significant differences are highlighted using a two-tailed Student's t test, taking into account the autocorrelation of the time series using the methodology discussed in Santer et al. (2008).

As one can see from Table 1, considerable changes are evident for a number of fields, including sea level pressure anomalies, upper- and lower-level zonal wind anomalies, and relative humidity anomalies. In Table 1 as well as all remaining tables, statistics are calculated for all days from 1974 to 2007 as well as for the days where the MJO index amplitude exceeds 1.0 unit (approximately 70% of the time). The differences between phases 1 and 2 and phases 6 and 7 are also examined in all tables in the manuscript, since these phases have the most significant differences from each other for parameters considered important in modulating TC activity (such as zonal wind, sea level pressure, and relative humidity). Also, Mo (2000) highlighted that TC activity was much more likely in the Atlantic when the convectively enhanced portion of the MJO was over eastern Africa and the Indian Ocean than over the Pacific Ocean, and by the Wheeler and Hendon (2004) definition this is generally characterized by phases 1 and 2 and phases 6 and 7, respectively. Note that sea surface temperature anomalies are of low magnitude, and none of the eight phases of the MJO exhibit statistically significant differences from the phase 1–8 average.

The mean of phases 1 and 2 is statistically significant different at the 99% level from the mean of phases 6 and 7 for sea level pressure, zonal wind, and relative humidity. In similar research, Camargo et al. (2009) found that alterations in midlevel relative humidity were most important in altering the potential for tropical cyclogenesis by the MJO worldwide. In the Atlantic, the most dramatic differences appear to be between the 200–850-mb zonal wind shear and 700-mb relative humidity between phases 1 and 2 and phases 6 and 7. A difference of nearly 4 m s^{-1} or 8 kt in vertical shear over the MDR is experienced between these two phases, consistent with the analysis of Maloney and Shaman (2008). Since climatological wind shear in the tropical Atlantic is westerly—that is, upper-level winds blow out of the west while lower-level winds blow out of the east—easterly anomalies at upper levels and westerly anomalies at lower levels are associated with a reduction in vertical wind shear. These vertical shear anomaly differences appear quite physically significant, as August–October-averaged 200–850-mb vertical wind shear between very active and very inactive tropical cyclone seasons typically varies by similar amounts. August–October-averaged values of 700-mb relative humidity also vary by similar amounts. For example, since

TABLE 2. As in Table 1 but for normalized values of named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), major hurricanes (MH), major hurricane days (MHD), and ACE generated by all tropical cyclones forming in each phase of the MJO over the period from 1974 to 2007. Normalized values are calculated by dividing storm activity by the number of days spent in each phase and then multiplying by 100. This basically provides the level of TC activity that would be expected for 100 days given a particular MJO phase.

MJO phase	NS	NSD	H	HD	MH	MHD	ACE
Phase 1	6.4	35.9	3.7	17.9	1.8	*5.3*	76.2
Phase 2	7.5	43.0	5.0	18.4	2.1	4.6	76.7
Phase 3	6.3	30.8	3.0	14.7	1.4	2.8	56.0
Phase 4	5.1	25.5	3.5	12.3	1.0	2.8	49.4
Phase 5	5.1	22.6	2.9	9.5	1.2	2.1	40.0
Phase 6	5.3	24.4	3.2	7.8	<u>0.8</u>	**1.1**	35.7
Phase 7	<u>3.6</u>	<u>18.1</u>	*1.8*	7.2	<u>1.1</u>	2.0	<u>33.2</u>
Phase 8	6.2	27.0	3.3	10.4	0.9	2.6	46.8
Phases 1–2	7.0	*39.4*	*4.3*	**18.1**	*1.9*	4.9	**76.5**
Phases 6–7	4.5	21.5	2.5	7.5	1.0	1.5	34.6
Phase 1–2/phase 6–7	1.6	1.8	1.7	2.4	2.0	3.2	2.2
MJO index > 1							
Phase 1	6.3	37.6	4.0	19.5	1.7	*5.9*	84.3
Phase 2	8.5	<u>50.8</u>	<u>6.2</u>	19.2	<u>2.5</u>	3.8	81.2
Phase 3	6.6	30.4	2.7	13.9	1.5	1.9	50.5
Phase 4	6.5	33.7	5.1	17.9	1.6	3.3	65.0
Phase 5	5.3	23.2	3.0	10.0	1.2	2.3	42.3
Phase 6	4.7	22.1	2.5	*6.4*	<u>0.8</u>	**0.9**	*31.3*
Phase 7	<u>3.5</u>	*16.6*	1.9	6.4	<u>1.0</u>	**0.9**	28.3
Phase 8	5.4	23.3	2.3	<u>8.4</u>	0.9	3.1	42.4
Phases 1–2	*7.3*	**43.8**	5.1	**19.4**	**2.1**	4.9	**82.8**
Phases 6–7	4.2	20.0	2.3	6.4	0.9	0.9	30.1
Phases 1–2/phases 6–7	1.7	2.2	2.2	3.0	2.4	5.5	2.8

1974, the difference in MDR-averaged August–October vertical shear between the five most active seasons (as defined by accumulated cyclone energy; Bell et al. 2000) and the five least active seasons was approximately 4 m s^{-1}, and the difference in MDR-averaged August–October 700-mb relative humidity was approximately 1.5%.

Figure 3 displays NCEP–NCAR reanalysis fields in the tropical and subtropical Atlantic for sea level pressure (SLP), 850-mb U, 200-mb U, and 700-mb relative humidity for the difference between the 200 days with the highest MJO amplitude in phase 1 (top 100 days) and phase 2 (top 100 days) and the 200 days with the highest MJO amplitude in phase 6 (top 100 days) and phase 7 (top 100 days). As would be expected from Table 1, phases 1 and 2 are characterized by much lower pressures, reduced vertical wind shear, and enhanced midlevel humidity, all of which are associated with enhanced TC formation and intensification likelihood. Also note that the 850-mb U wind field implies anomalous cyclonic
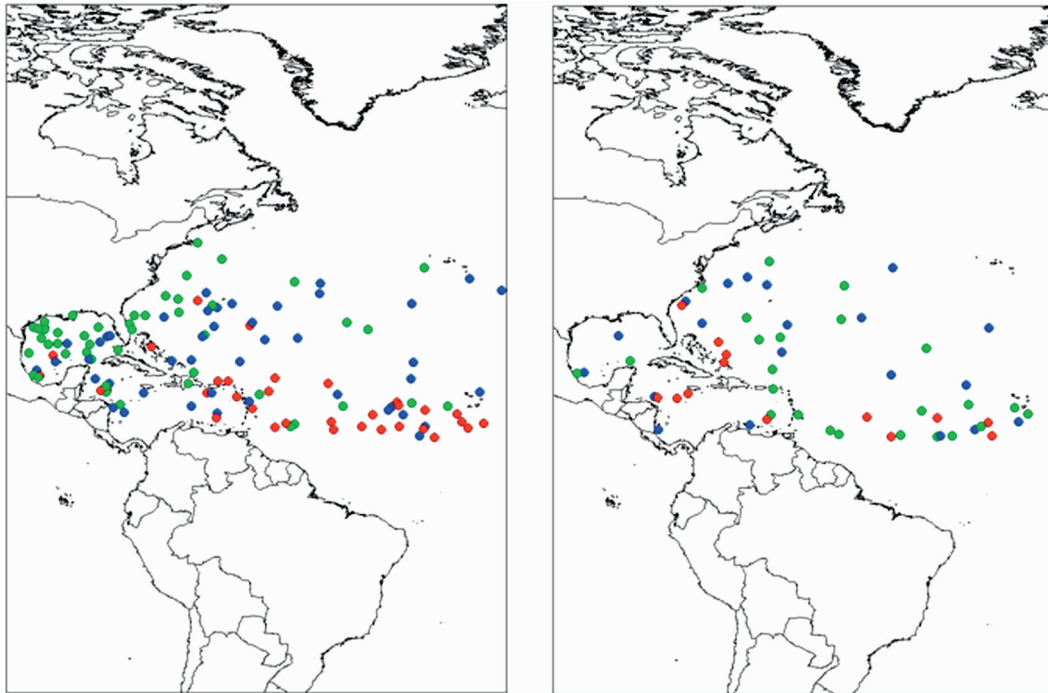
FIG. 4. Genesis locations for storms forming in (left) phases 1–2 and (right) phases 6–7 over the period from 1974 to 2007. Green dots indicate a storm that never reached hurricane strength (winds < 64 kt), blue dots indicate a storm that never reached major hurricane strength (winds < 96 kt), and red dots indicate a storm that reached major hurricane strength.

vorticity in the eastern tropical Atlantic. Anomalous horizontal cyclonic vorticity has been shown in several studies to be favorable for TC formation (Gray 1979; Klotzbach and Gray 2003).

Following the most pronounced convective anomalies, as evidenced by the lowest sea level pressure in phases 8 and 1, anomalous westerly anomalies at lower levels and anomalous easterly anomalies at upper levels are observed in phases 1–3, as would be expected from the analysis of Lin et al. (2005). The midlevels of the atmosphere are also moistened after the passage of the maximum MJO convective anomaly.

4. MJO impacts on Atlantic tropical cyclone activity

Based on the dramatic differences seen in large-scale fields between various phases of the MJO, one would expect to see significant differences in Atlantic tropical cyclone activity. Table 2 displays the numbers of named storms, named storm days, hurricanes, hurricane days, major hurricanes, major hurricane days, and accumulated cyclone energy (ACE) generated by all tropical cyclones that formed in the Atlantic basin in a particular MJO phase over the period from 1974 to 2007. All

numbers have been normalized by the number of days that each MJO phase occurred over the period from 1974 to 2007 and multiplied by 100. The difference in means between phases 1–2 and phases 6–7 are significant at the 95% level for all TC statistics except for named storms using a two-tailed Student's t test and assuming that each year represents 1 degree of freedom. All remaining statistical significance checks are done with the same test and assumptions. The greatest differences are observed between phases 1–2 and phases 6–7 for most TC parameters, and these differences will be focused on for the remainder of the analysis. For example, over twice as many hurricane days and over 3 times as many major hurricane days occurred with storms forming in phases 1–2 than with storms forming in phases 6–7. Figure 4 displays the locations of all storm formations in phases 1–2 in comparison with phases 6–7. Also shown is the maximum intensity category (e.g., named storm, hurricane, or major hurricane) reached by each storm. Note the general absence of major hurricane formations in the MDR in phases 6–7 along with the lack of formations in the Gulf of Mexico and the northwest Caribbean.

Perhaps most dramatic of all is the difference in major hurricane days. Figure 5 displays the tracks of tropical
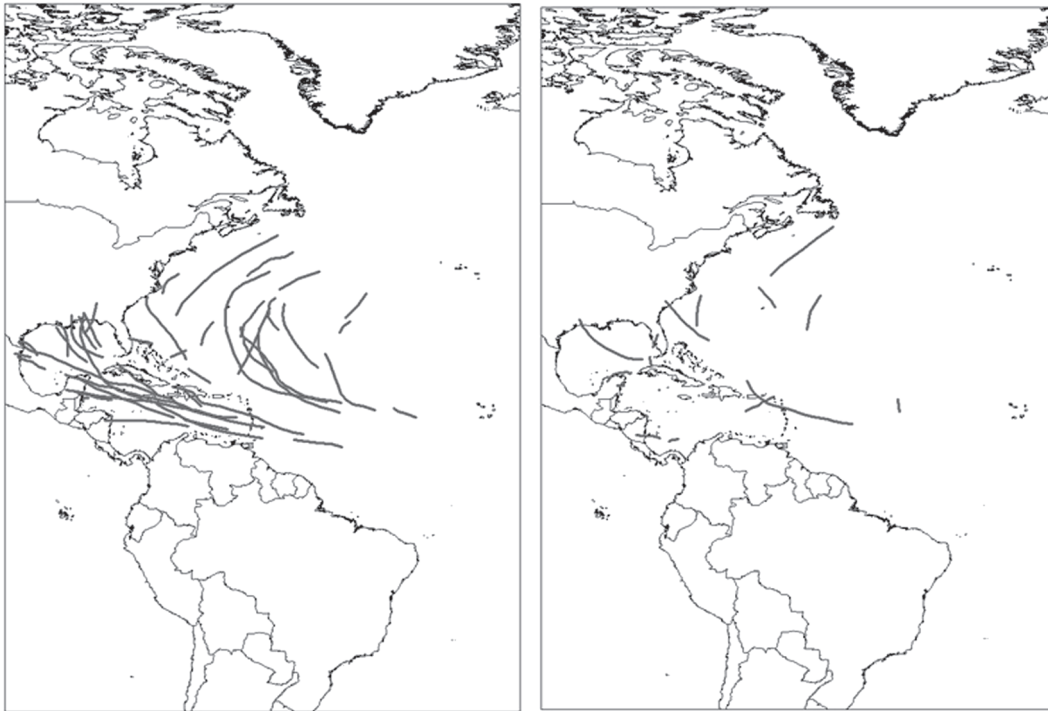
FIG. 5. Tracks of tropical cyclones at major hurricane strength in (left) phases 1–2 and (right) phases 6–7 over the period from 1974 to 2007. There were 91.5 major hurricane days in phases 1–2 compared with 20.5 major hurricane days in phases 6–7.

cyclones at major hurricane intensity for phases 1–2 (left column) and phases 6–7 (right column). Fewer tracks are evident in phases 6–7, and the major hurricanes that occur in phases 6–7 also tend to have shorter tracks as major hurricanes.

Table 3 displays the normalized values of cumulative tropical cyclone activity from storms developing in the MDR over the period from 1974 to 2007. Ratios between phases 1–2 and 6–7 are slightly greater than for the larger region, which is to be expected, since it has been documented that MDR conditions are significantly altered by the phase of the MJO. The difference in the number of storms forming in the MDR between the mean of phases 1–2 and the mean of phases 6–7 is significant at the 99% level for all TC statistics except for named storms and named storm days for all days, and for all TC statistics except for named storms where the MJO index amplitude is greater than one.

Note that ratios for named storms are generally not very large, indicating that weak tropical cyclones can form in any particular phase of the MJO. Intense storms, however, are much less likely in phases 6–7. Table 4 displays the ratio of named storms becoming hurricanes and named storms becoming major hurricanes in the MDR for each MJO phase: 85% (55%) of storms

forming in phases 1–2 reached hurricane (major hurricane) strength, while 45% (22%) of storms forming in phases 6–7 reached hurricane (major hurricane) strength. The differences in the percentages of storms reaching hurricane and major hurricane strength between phases 1–2 and phases 6–7 are significant at the 99% level for all MJO days and for days where the MJO index amplitude is greater than one. Given the much more hostile large-scale conditions across the MDR in MJO phases 6–7, these relationships are not surprising.

Maloney and Hartmann (2000) demonstrated strong relationships between MJO-related winds and TC formations in the Gulf of Mexico and northwest Caribbean. This study replicates these findings using the Wheeler and Hendon (2004) MJO index. In this analysis, a northwest Caribbean and Gulf of Mexico storm is classified as a tropical cyclone first being named north of 20°N and west of 80°W. Because of the close proximity of these storms to land, these storms rarely become major hurricanes. For all tropical cyclones in the Atlantic basin, 58% reached hurricane strength and 23% reached major hurricane strength over the period from 1974 to 2007. Only 40% of storms classified as northwest Caribbean and Gulf of Mexico storms reached hurricane strength, and only 6% reached major hurricane strength over the

TABLE 3. As in Table 1 but for all tropical cyclones forming in the MDR from 1974 to 2007.

MJO phase	NS	NSD	H	HD	MH	MHD	ACE
Phase 1	2.7	22.9	2.3	13.5	1.4	*4.9*	<u>57.5</u>
Phase 2	3.0	24.7	2.5	13.2	<u>1.8</u>	4.2	<u>53.0</u>
Phase 3	2.6	19.8	1.7	12.1	0.9	<u>2.1</u>	41.4
Phase 4	*1.7*	*12.1*	*1.1*	8.1	*0.7*	2.7	32.0
Phase 5	2.7	14.8	1.6	<u>6.3</u>	0.7	**1.3**	25.7
Phase 6	2.6	*13.1*	<u>1.2</u>	**3.9**	0.6	0.9	20.3
Phase 7	**1.6**	**9.4**	**0.6**	3.7	0.5	1.1	17.5
Phase 8	*1.9*	*12.2*	**1.1**	6.5	0.6	*1.9*	25.3
Phases 1–2	2.9	*23.8*	**2.4**	13.3	1.6	4.5	55.3
Phases 6–7	2.2	11.4	1.0	3.8	0.5	1.0	19.0
Phases 1–2/phases 6–7	1.3	2.1	2.5	3.5	3.0	4.4	2.9
MJO index > 1							
Phase 1	2.8	25.7	2.4	<u>16.2</u>	1.6	*5.7*	*68.6*
Phase 2	3.9	28.9	*3.3*	13.3	*2.1*	3.6	54.8
Phase 3	2.7	21.0	1.8	12.3	1.2	<u>1.3</u>	39.3
Phase 4	2.7	18.8	1.9	12.6	1.1	3.1	44.4
Phase 5	2.6	14.5	1.6	6.4	0.7	**1.2**	25.9
Phase 6	2.5	14.7	1.5	*4.9*	*0.6*	**0.7**	<u>22.2</u>
Phase 7	<u>1.6</u>	**7.1**	**0.6**	**2.7**	**0.3**	**0.2**	**11.3**
Phase 8	*1.4*	*9.1*	**0.6**	4.7	0.6	2.9	<u>22.1</u>
Phases 1–2	3.3	27.2	**2.8**	14.8	1.8	4.7	62.1
Phases 6–7	2.2	11.7	1.1	4.0	0.5	0.5	17.9
Phases 1–2/phases 6–7	1.5	2.3	2.5	3.7	3.6	9.2	3.5

TABLE 4. As in Table 1 but for the percentage of named storms forming in the MDR in a given phase that became hurricanes and the number of named storms forming in the MDR in a given phase that became major hurricanes for each phase of the MJO.

MJO phase	Percent of named storms becoming hurricanes	Percent of named storms becoming major hurricanes
Phase 1	*85*	50
Phase 2	*85*	*59*
Phase 3	65	35
Phase 4	67	42
Phase 5	59	27
Phase 6	*47*	*21*
Phase 7	**40**	30
Phase 8	58	33
Phases 1–2	**85**	**55**
Phases 6–7	45	22
MJO index > 1		
Phase 1	*88*	56
Phase 2	85	55
Phase 3	67	44
Phase 4	70	40
Phase 5	60	27
Phase 6	58	<u>25</u>
Phase 7	*40*	*20*
Phase 8	*40*	40
Phases 1–2	**86**	**57**
Phases 6–7	53	24

period from 1974 to 2007. Table 5 displays the normalized number of northwest Caribbean and Gulf of Mexico named storms, hurricanes, and major hurricanes forming in each phase of the MJO. Approximately 4–5 times the number of named storms form in phases 1 and 2 than in phases 6 and 7 when evaluating all days or when evaluating days where the MJO index amplitude exceeds one.

One of the most important reasons for investigating the MJO phase–Atlantic hurricane activity relationship is that it may provide information on U.S. landfall probabilities. Table 6 displays the normalized number of storms forming in each phase of the MJO that eventually made U.S. landfall as a named storm, hurricane, and major hurricane. Only the highest landfall intensity for each TC is considered in this analysis. As was seen with Atlantic storms in general, U.S. landfalls are considerably modulated based upon MJO phase. Differences between phases 1–2 and phases 6–7 are statistically significant at the 95% level for named storms, hurricanes, and major hurricanes for all days and for days where the MJO index amplitude exceeds one. Interestingly enough, the most significant ratios between phases are typically found for storms making landfall at tropical storm strength (maximum sustained winds less than 64 kt). This is likely due to the strong ratios that were observed in storm genesis in the Gulf of Mexico and

northwest Caribbean (Fig. 6). Tropical storms forming in the Gulf typically make landfall and often do so in the United States and therefore provide a large part of the landfall ratios. For example, in phases 1 and 2, there were 27 TCs that made landfall at tropical storm strength compared with only 3 TCs making landfall at tropical storm strength in phases 6 and 7—the difference is significant at the 99% level. All MJO phases were analyzed for potential differences in midlatitude flow patterns that could either prevent or enhance likelihood of storm recurvature (e.g., position of the Bermuda high), but no coherent changes were seen (not shown).

The last few paragraphs have clearly documented that the MJO alters both large-scale patterns across the tropical Atlantic and Atlantic TC activity. Tables 1–3 clearly demonstrate how the MJO modulates conditions across the MDR, and these altered conditions impact Atlantic TC activity substantially. The large-scale tropical Atlantic alterations and Atlantic TC activity agree quite well, with fewer storms forming in the heightened wind shear–lower humidity environment. The phase of the MJO plays an important role in dictating the likelihood for tropical cyclone activity in the MDR through alterations in large-scale parameters.

TABLE 5. As in Table 1 but for the normalized number of NS, H, and MH forming in each phase of the MJO in the northwest Caribbean and Gulf of Mexico over the period from 1974 to 2007. Statistical significance calculations are only provided for named storms and hurricanes, as only four tropical cyclones originating in the northwest Caribbean and Gulf of Mexico became major hurricanes over the 1974–2007 period.

MJO phase	NS	H	MH
Phase 1	1.4	*0.2*	0.0
Phase 2	<u>1.7</u>	0.7	0.1
Phase 3	<u>0.9</u>	**0.2**	0.2
Phase 4	1.1	<u>0.7</u>	0.1
Phase 5	0.9	<u>0.4</u>	0.1
Phase 6	**0.4**	<u>0.3</u>	0.0
Phase 7	**0.2**	<u>**0.0**</u>	0.0
Phase 8	1.6	*0.9*	0.0
Phases 1–2	**1.5**	*0.5*	0.1
Phases 6–7	0.3	0.1	0.0
MJO > 1			
Phase 1	1.6	0.3	0.0
Phase 2	<u>1.9</u>	*1.0*	0.2
Phase 3	<u>1.2</u>	**0.0**	0.0
Phase 4	1.1	*1.1*	0.3
Phase 5	0.7	0.4	0.0
Phase 6	*0.6*	0.4	0.0
Phase 7	**0.3**	**0.0**	0.0
Phase 8	1.7	0.9	0.0
Phases 1–2	**1.7**	<u>0.6</u>	0.1
Phases 6–7	0.4	<u>0.2</u>	0.0

TABLE 6. As in Table 1 but for the normalized number of systems making U.S. landfall as named storms, hurricanes, and major hurricanes for each phase of the MJO over the period from 1974 to 2007.

MJO phase	NS	H	MH
Phase 1	2.3	1.0	**0.7**
Phase 2	2.8	1.2	0.3
Phase 3	1.7	0.8	0.5
Phase 4	1.5	0.8	**0.1**
Phase 5	1.3	0.7	0.2
Phase 6	<u>1.1</u>	0.8	0.3
Phase 7	<u>**0.3**</u>	**0.2**	*0.2*
Phase 8	3.0	1.6	*0.2*
Phases 1–2	**2.5**	*1.1*	**0.5**
Phases 6–7	0.6	0.5	0.2
MJO > 1			
Phase 1	2.6	1.0	*0.7*
Phase 2	<u>3.5</u>	<u>1.7</u>	0.4
Phase 3	<u>1.2</u>	<u>**0.3**</u>	0.3
Phase 4	1.4	1.1	0.3
Phase 5	1.8	1.1	0.4
Phase 6	*1.3*	0.8	<u>0.2</u>
Phase 7	**0.0**	**0.0**	<u>**0.0**</u>
Phase 8	<u>3.4</u>	*2.0*	**0.0**
Phases 1–2	<u>**3.0**</u>	**1.4**	**0.5**
Phases 6–7	0.6	0.4	0.1

5. Summary and future work

This paper investigates the relationship between Wheeler and Hendon's (2004) MJO index, large-scale circulation features in the tropical Atlantic, and Atlantic basin TC activity. Clear signals are seen in large-scale circulation features in the tropical Atlantic, especially for levels of vertical wind shear and relative humidity values. Vertical wind shear averages approximately 4 m s^{-1} stronger and relative humidity averages about 2% lower in phases 6–7 than it does in phases 1–2. As would be expected given these considerable differences, TC activity in the tropical Atlantic is also significantly modified, especially in the MDR. For example, more than 3 times the number of major hurricanes and major hurricane days occur in the MDR from TCs forming in phases 1 and 2 than by TCs forming in phases 6 and 7. As was originally shown by Maloney and Hartmann (2000), strong relationships also exist for the Gulf of Mexico and northwest Caribbean. Five times as many named storms formed north of 20°N and west of 80°W in phases 1 and 2 than in phases 6 and 7.

The clear implication of this study is the potential for tropical genesis and intensification forecasts for the Atlantic basin that are based on the phase of the MJO. Studies have shown that the MJO exhibits a moderate level of predictability out to about 15 days (Mo 2001; Waliser et al. 2006; Jiang et al. 2008; Seo et al. 2009). Current and predicted information for the MJO could provide an additional layer of forecasts between the short-term genesis/intensity forecasts issued by the National Hurricane Center and seasonal forecasts issued by Colorado State University, the National Oceanic and Atmospheric Administration, and many other groups. The predictability of Wheeler and Hendon's MJO index during the Northern Hemisphere summer–fall months, and the relationship between these predicted values and Atlantic TC activity, will be investigated in future work. Also, additional research into the impact that the MJO has on easterly wave structure and intensity (e.g., Maloney and Shaman 2008; Thorncroft et al. 2008) and how it relates to Atlantic TC genesis will be considered.
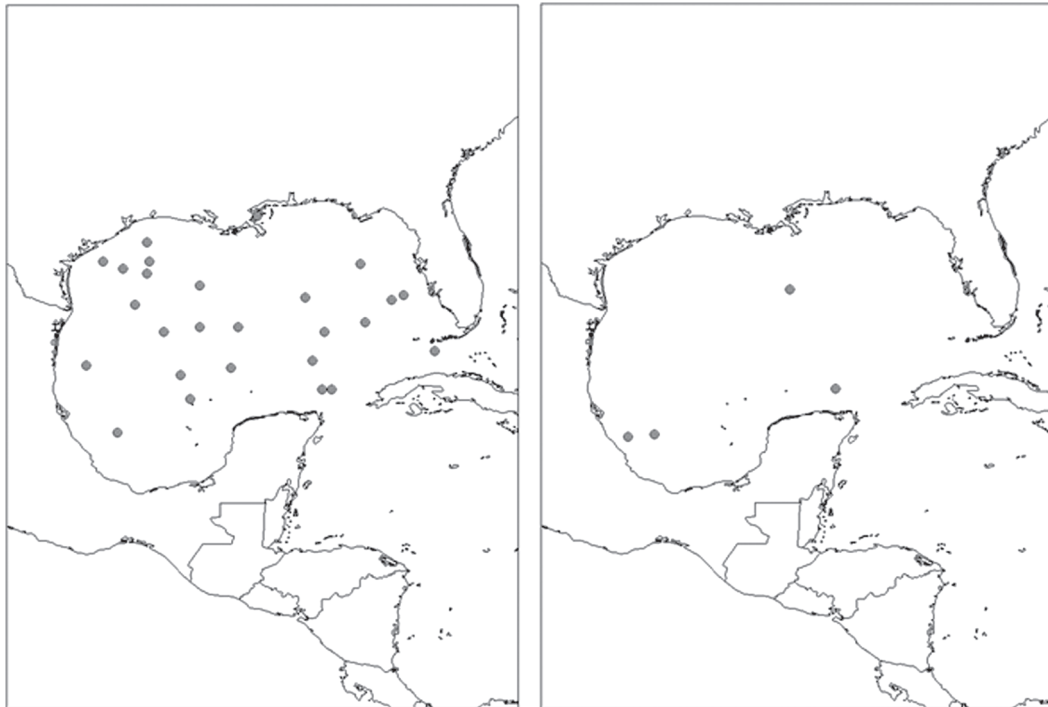
Fig. 6. Genesis locations for storms forming in (left) phases 1–2 and (right) phases 6–7 over the period from 1974 to 2007 in the Gulf of Mexico and northwest Caribbean (north of 20°N and west of 80°W).

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