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CARIBBEAN PRECIPITATION AND THE MADDEN-JULIAN OSCILLATION

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1. INTRODUCTION

The Caribbean is one of many regions of the world where it is vital to understand precipitation patterns, variability and extremes. The low-lying coastal regions of Caribbean islands are densely populated with development pressure increasing. The region is also vulnerable to many natural hazards that are related to and exacerbated by precipitation, such as hurricanes, earthquakes, mudslides and drought. There is also evidence that precipitation patterns can influence the spread of Dengue fever in the region (Jury, 2008). Planning, policy and management of these events are extremely dependent on knowledge of the precipitation of the region. These social and economic reasons provide considerable motivation for increasing and expanding current knowledge of precipitation in the Caribbean.

Precipitation in the Caribbean varies spatially and has a bimodal annual cycle with an initial maximum in May, a minimum around July-August, and a second maximum in September-October (e.g. Jury et al., 2007). Precipitation in this region has variability on a variety of timescales. Interannually, precipitation is influenced by the El Niño-Southern Oscillation and the North Atlantic Oscillation (NAO) (Chen and Taylor, 2002; Giannini et al., 2001). The first rainfall season tends to be wetter the year after an El Niño and drier in a La Niña year (Chen and Taylor, 2002) and the second rainfall season tends to be drier in El Niño years and wetter in La Niña years (Giannini et al., 2000; Taylor et al., 2002). A positive NAO phase implies a stronger than normal North Atlantic high and amplifies the drying during an El Niño (Giannini et al., 2001). The region is also affected on shorter timescales (days to weeks) by the propagation of easterly waves, which can mature into tropical storms and hurricanes.

A period of variability that has not been studied in the Caribbean is the intraseasonal range of 30 to 90 days. A connection between the dominant mode of intraseasonal variability in the Pacific, the Madden-Julian Oscillation (Madden and Julian, 1971), and Gulf of Mexico hurricane numbers was identified by Maloney and Hartmann (2000). In addition, Barlow and Salstein (2006) showed a relationship between the MJO and summertime precipitation in Mexico and Central America.

It is the aim of this paper to explicitly investigate the nature of precipitation changes associated with the MJO, including extreme events. Knowledge of a precipitation connection in the Caribbean with the MJO may lead to enhanced forecasting skill due to the predictability of an MJO event being approximately 2 weeks once an event has been initiated. It is hypothesized that low-level circulation changes due to the MJO affect precipitation amounts and patterns in the Caribbean region.

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2. DATA AND METHODOLOGY

This study uses 12 years (1997-2008) of daily Global Precipitation Climatology Project, 1° gridded data to investigate precipitation patterns. Near-surface daily (925 hPa) wind data required to investigate circulation changes were acquired from the European Center for Medium Range Weather Forecasting (ECMWF) reanalysis interim (ERA-Interim) dataset at 1.5° resolution. ERA-Interim has been shown to be a significant improvement over previous reanalysis products, especially in the hydrological cycle (Simmons et al., 2007).

To characterize the impact of the MJO on the region, anomalies in wind and precipitation were calculated as differences from the annual cycle. This allows for meaningful comparisons between seasons and prevents the wet season from overwhelming important variability in the dry season

To relate Caribbean precipitation to the MJO, the MJO index developed by Wheeler and Hendon (2004) was used in this study. This index contains daily values of both amplitude (greater than 1 is considered a strong MJO event) and phase. Precipitation and circulation anomalies were composited according to phase of the MJO for all strong MJO events.

3. RESULTS

Intraseasonal variability in the Caribbean-wide (55º-90º W; 10º-25º N) averaged precipitation anomaly time series was identified using wavelet analysis (Torrence and Compo, 1998) and is shown in Fig. 1. Periods of significant power at 30-90 days are seen throughout the 12-year period.

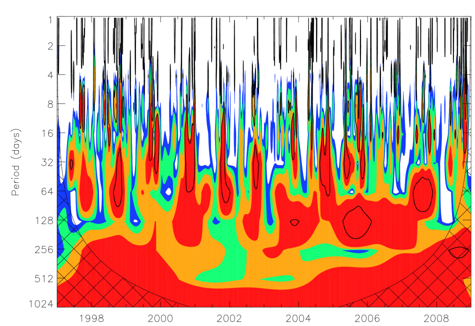

Figure 1: *Wavelet analysis of Caribbean area averaged precipitation anomaly time series. Shaded contours show power with intervals of 2, 4, 8, 16 [mm day^{-1}]^2 shaded as blue, green, orange and red respectively. Black contour shows areas of significant power at the 90 % contour level and cross hatching indicates the cone of influence due to the finite length of the time series.*

The intraseasonal variability may be due to local intraseasonal variations and/or the remote influence of the MJO. The influence of the MJO on this intraseasonal precipitation variability will be addressed in forthcoming sections.

3.1 *Precipitation*

To investigate the connection between the intraseasonal precipitation variability (Fig. 1) and the MJO, as well as the spatial patterns of this connection, the compositing technique described in Section 2 was used on annual precipitation anomalies and is shown in Fig. 2. Precipitation anomalies are composited by the MJO in groups of two phases; phase 1 and 2 (MJO convection located in Africa and the western Indian Ocean), phases 3 and 4 (MJO convection in the eastern Indian Ocean and Maritime continent), phases 5 and 6 (MJO convection in the Western Pacific) and phases 7 and 8 (MJO convection in the western hemisphere).

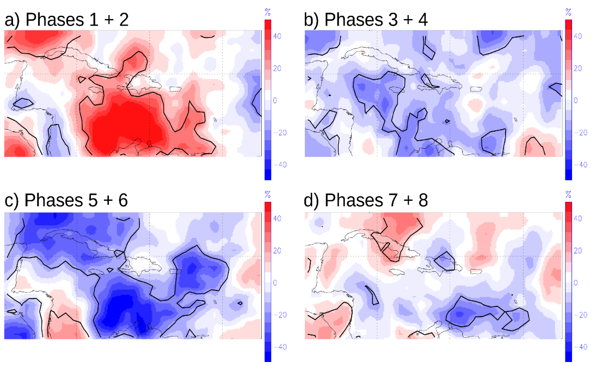

Figure 2: *Precipitation anomalies from the annual cycle (as percent change from annual average mean precipitation) composited by phase of the MJO, a) phases 1 and 2, b) phases 3 and 4, c) phases 5 and 6, and d) phases 7 and 8. Thick black lines show 90 % significance as calculated by a simple t-test.*

Much of the Caribbean receives above normal precipitation during phases 1 and 2 (Fig. 2a) with precipitation anomalies reaching up to 50 % above normal. The exception is the region off the coast of southern Central America where conditions are drier than normal. The reverse pattern is seen in phases 5 and 6 (Fig. 2c), with precipitation anomalies 40 % below normal. Whilst the general pattern is reversed between phases 1 and 2 and phases 5 and 6 there are slight differences, including over Cuba. These smaller scale features may be a result of localized differences in wind directions around the islands. The interstitial phases (Figs. 2b and d) show smaller and less coherent precipitation anomalies (although still significant in some locations) and may be acting as transition phases, hence focus will be on phases 1 and 2 and phases 5 and 6 from this point forward.

The same analysis shown here was also performed on precipitation data divided by season (not shown), to determine whether the MJO impact occurs throughout the entire seasonal cycle. It was found that the MJO influences Caribbean precipitation in all seasons, with significant precipitation anomalies of similar percentage magnitudes and patterns seen across all phases and seasons.

To evaluate the causes of the precipitation changes, low-level (925 hPa) wind anomalies and their divergence for different phases are shown in Fig. 3. Significant differences in the wind direction anomalies exist between the two groups of phases, with westerly anomalies in phases 1 and 2 acting to slow down the prevailing easterly trade winds and anomalous easterlies in phases 5 and 6 increasing the strength of the trade winds. The maximum wind speed anomalies are focused in the region of the Caribbean Low-Level Jet (CLLJ) in the southern Caribbean Sea and into Central America. This wind anomaly maximum acts to strengthen (weaken) the jet in phases 5 and 6 (1 and 2), respectively.

Changes in the jet strength consequently affect the low-level divergence in the region (Fig. 3). The pattern of divergence and convergence well matches the precipitation anomalies in Figs. 2a and c, especially in the southern Caribbean where precipitation anomalies are largest. Low-level convergence (divergence) is seen in the region of positive (negative) precipitation anomalies. The low-level divergence anomalies appear in the two phases prior to the precipitation anomalies (not shown) and maximize in the phases with maximum precipitation anomalies. This suggests that the cause of the precipitation anomalies is changes in low-level divergence associated with changes in the CLLJ.

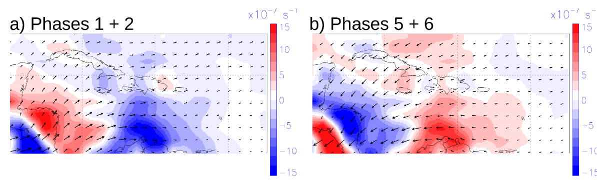

Figure 3: *Low-level (925 hPa) divergence anomalies (shading) and winds (vectors) for a) phases 1 and 2, maximum wind vector 2.9 m s^{-1} and, b) phases 5 and 6, maximum wind vector 2.8 m s^{-1}.*

3.2 *Caribbean Low-Level Jet*

The locations of the precipitation and low-level wind and divergence anomalies suggest that the CLLJ is being modulated by the MJO, which then leads to the observed changes in precipitation. Previous literature has not shown intraseasonal variability of the CLLJ or a relationship with the MJO. To illustrate seasonal changes in the CLLJ, wind anomalies were composited by season and phases of the MJO and a selection of these images corresponding to seasons with a climatologically weaker CLLJ (SON) and stronger CLLJ (DJF) are shown in Fig. 4.

As seen in Fig. 4, wind speed anomalies in the region of the CLLJ are approximately consistent across seasons and phases (1-3 m s^{-1}). This consistency in wind speed anomalies will affect the CLLJ differently in each season due to the semi-annual cycle of the CLLJ (e.g. Muňoz et al. 2008). It is necessary to determine the influence of the MJO on the CLLJ in each season, as it appears to have a large impact on precipitation in the region.

To investigate the influence of the MJO on the CLLJ, an index of the CLLJ was defined based on Wang (2007). The CLLJ index is defined by taking the negative of the mean 925 hPa wind anomalies in the region of 12.75ºN-17.25ºN and 69.25ºW-80.5ºW (i.e., the thick box in Fig. 4c). Since the CLLJ is easterly, taking the negative of the wind anomalies makes the index positive (negative) when the CLLJ is stronger (weaker) than average.

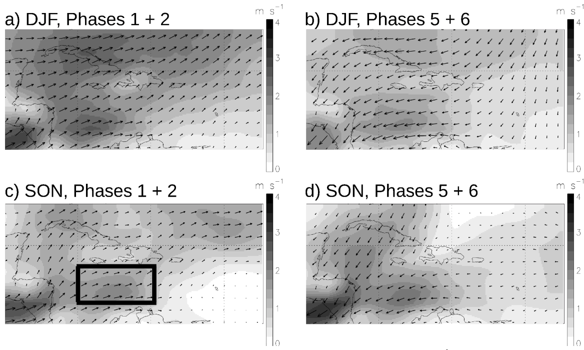

Figure 4: *Seasonal wind speed (shading, m s^{-1}) and direction (vectors) anomalies composited by phase of the MJO, a) and b) DJF, c) and d) SON. Phases 1 and 2 on left (a and c) and phases 5 and 6 on left (b and d). Box in (c) indicates region for calculating CLLJ index.*

Means of the CLLJ index by season and phase are shown in Table 1. Jet index means have a larger magnitude for phases with large precipitation changes (e.g. -1.50 for phases 1 and 2 in the annual mean) compared to those with small changes (e.g. -0.46 for phases 7 and 8 in the annual mean). This differences are apparent both annually and seasonally, again showing the importance of the CLLJ in the MJO-precipitation connection in the region. For the seasons and phases shown in Fig. 4, jet indices are large and positive for phases 1 and 2 and large and negative for phases 5 and 6, for both DJF and SON. The jet index means for phases 1 and 2 and phases 5 and 6 are significantly different from each other at the 99.9 % confidence level. These statistics provide evidence that the MJO is modulating the CLLJ.

	Phases 1+2	Phases 3+4	Phases 5+6	Phases 7+8
Annual	-1.5	0.73	1.46	-0.46
DJF	-1.73	0.63	1.36	-0.9
MAM	-1.31	0.97	1.45	-1.15
JJA	-1.52	0.92	1.62	0.76
SON	-1.47	0.54	1.49	-0.27

Table 1: *Mean of the CLLJ index composited by phases and season.*

Cross-spectral analysis (not shown) on the Caribbean area-averaged time series of precipitation anomalies and the CLLJ index showed significant (at the 99 % level) coherence squared at periods between 41 and 61 days. This high coherence between the two time series in the intraseasonal period indicates that both the precipitation and CLLJ are varying in phase in the 41-61 day time period.

3.3 *Extreme Events*

Large changes in precipitation associated with the MJO as indicated in Section 3.1, suggest that extreme wet precipitation events may be affected by phase of the MJO. It should be noted that the precipitation dataset is daily averages over 1º grid-boxes, so it may not be capturing very localized (in both space and time) extreme events.

The most relevant extreme precipitation events to society are those that occur over land. To investigate extreme events over the larger Caribbean islands, the 100 wettest days (corresponding approximately to the 97.5 percentile) across all seasons and all years at four locations (Central Cuba, Hispaniola, Puerto Rico and the central Caribbean Sea) were categorized by the MJO phase at the time of the wet event (Fig. 5). Only days where the MJO was strong were included. Figure 5 clearly shows that the wettest days occur when the MJO is in phases 1 and 2 for all four locations. Cuba has the largest number of wettest days in phases 1 and 2, but this peak is not well separated from phases 7 and 8. However, the distribution is similar to the other locations if a southeasterly Cuban grid point is chosen. Strong MJO events affect the large-scale patterns of convergence and divergence in the region, which contributes to extreme rainfall events in the region. Weak MJO events account for approximately 30 of the 100 events at each location, comparable with the number of events in phase 1 and 2.

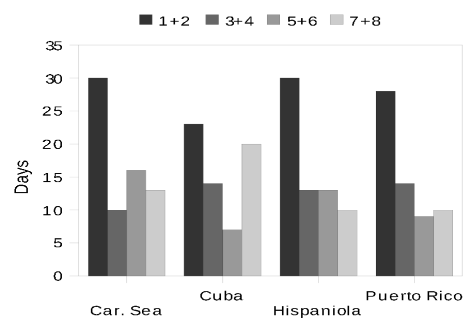

Figure 5: *Number of days in each phase of the MJO for 100 highest rain rate days at four Caribbean locations. Only days with strong MJO events are included.*

It is important to be aware of what season the 100 wettest days occur in for each location. Approximately 50 of the wettest days at each island location occur in SON, with a range of 8 to 12 occurring in the driest season (DJF). Clearly tropical cyclones contribute to extreme events in the region, but this analysis shows that they are not the only contributor and extreme events throughout all seasons are modulated by the MJO phase. This modulation of extreme precipitation events by the MJO may play an essential role for prediction of extreme events due to the predictability of MJO phase, which in turn could improve planning and preparation for such events.

4. SUMMARY

Based on 12 years of daily satellite precipitation data and reanalysis winds, intraseasonal (30-90 day) variability in Caribbean precipitation has been linked to phases of the MJO. Precipitation anomalies of up to 50 % above (below) the annual mean are observed in phases 1 and 2 (5 and 6) of the MJO. These precipitation anomalies are observed across all seasons. The changes in Caribbean precipitation associated with the MJO are shown to be related to changes in the low-level (925 hPa) winds. When precipitation anomalies are above (below) average in phases 1 and 2 (5 and 6) wind anomalies act to decrease (increase) the strength of the prevailing easterly trade winds.

The changes in the low-level winds are most apparent in the region of the Caribbean low-level jet (CLLJ) and divergence anomalies associated with the entrance and exit region of the CLLJ precede the precipitation anomalies. The CLLJ itself is also shown to be subject to intraseasonal variability, and its magnitude varies with phase of the MJO. Again, intraseasonal variability in the CLLJ associated with the MJO is observed in all seasons and shows a significant coherence with intraseasonal variability in the precipitation.

Extreme rainfall events over islands in the Caribbean show a strong relationship with MJO phase, with extreme events being most common in phases 1 and 2 of an MJO event. This relationship between the MJO and extreme events has important implications for predictability of precipitation extremes in the Caribbean.

This strong connection between the MJO and the regional climate of the Caribbean stresses the need to understand global-regional connections before we can adequately simulate precipitation variability in numerical models (which typically have difficulties in accurately capturing the MJO and precipitation variability).

5. ACKNOWLEDGMENTS

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