EFFECTIVENESS OF A NEW METHOD (SOFTWARE) TO EVALUATE THE IMPACTS OF THE MADDEN-JULIAN OSCILLATION ON RAINFALL IN CENTRAL AND SOUTH AMERICA

EFICACIA DE UN NUEVO MÉTODO (SOFTWARE) PARA EVALUAR LOS IMPACTOS DE LA OSCILACIÓN DE MADDEN-JULIAN DE LAS PRECIPITACIONES EN AMÉRICA CENTRAL Y DEL SUR

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Abstract:

Knowledge of the rainfall distribution over a region is a prerequisite to any attempt at efficient water resources management and, in the face of a changing global climate, reveals regions vulnerable to more frequent extreme events. This knowledge will help to determine the climate adaptation measures that are needed for a particular community with regard to more intense extreme events. With this in mind, a free tool referred to as ICI-RAFT was developed at the International Center for Integrated Water Resources Management (ICIWaRM) to estimate the frequency/intensity of a rainfall event of a particular duration using ground-based rainfall observations. ICI-RAFT accomplishes this through Regional Frequency Analysis using the method of L-Moments. In order to judge the effectiveness of ICI-RAFT, three case studies were performed in selected regions within Argentina, Nicaragua, and Venezuela. Each study uses rainfall data provided in each region and attempts to identify a global climate index capable of predicting if rainfall will be greater than or less than average several months in advance for a particular season using lag times between 1 and 6 months. It was found that total rainfall for selected seasons correlated best with the Madden-Julian Oscillation (MJO) in each region, particularly with MJO activity over central Africa and the western Indian Ocean, and that the MJO could be used as a predictor of rainfall 3 to 4 months in advance. Critical values of the MJO were estimated for each region; MJO index values greater than or less than these critical values caused greater than or less than average total rainfall and vice versa for the season being analyzed. Substantial differences of up to 40 percent were observed when looking at the intensities associated with a specific rainfall frequency and the value of the MJO index compared to its critical value for a region. Linear regressions were also performed in order to better quantify these relationships; R^2 values for all three regions were greater than 0.50.
Keywords: frequency analysis, Madden-Julian Oscillation, rainfall distribution, extreme events, climate change.

Resumen:

Conocimiento de la distribución de lluvia sobre un área es un requisito para cualquier intento de la gestión eficiente de recursos hídricos y, en el frente del clima cambiante, muestra las regiones más vulnerables a un aumento de los eventos extremos. Este conocimiento va a ayudar a determinar las medidas contra el cambio climático que se necesitan para una comunidad en particular con respecto a los eventos extremos más intensos. Con esta en mente, una herramienta libre se conoce como ICI-RAFT fue desarrollada en el Centro Internacional de Gestión Integrada de Recursos Hídricos (ICIWaRM) para estimar la frecuencia/intensidad de un evento de lluvia de una duración determinada utilizando observaciones aéreas de lluvias. ICI-RAFT logra esto a través de Análisis Regional de Frecuencias mediante el método de L-Momentos. Para juzgar la eficacia de ICI-RAFT, tres estudios de caso se realizaron en regiones seleccionadas en Argentina, Nicaragua y Venezuela. Cada estudio utiliza datos de las precipitaciones previstas en cada región y trata de identificar un índice de clima global capaz de predecir si la lluvia será mayor o menor que la media con varios meses de antelación para una estación en particular utilizando los tiempos de retardo entre 1 y 6 meses. Se encontró que la precipitación total para las estaciones seleccionadas se correlacionaron mejor con la Oscilación de Madden-Julian (MJO) en cada región, en particular con la actividad de la MJO sobre el centro de África y el Océano Indico occidental, y que la MJO podrían utilizarse como predictor de lluvia tres a cuatro meses de antelación. Los valores críticos de la MJO se estimaron para cada región; valores de MJO índice mayores que o menor que estos valores críticos causados mayor que o menor que la precipitación total promedio y viceversa para la temporada que se analiza. Se observaron diferencias sustanciales de alrededor de 40 por ciento cuando se mira en las intensidades asociadas con una frecuencia de precipitaciones específica y el valor del índice de la MJO en comparación con su valor crítico para una región. Regresiones lineales también se realizaron con el fin de cuantificar mejor estas relaciones; valores de R^2 para las tres regiones fueron mayores que 0,50.
Palabras importantes: análisis de frecuencias, Oscilación Madden-Julian, distribución de las precipitaciones, fenómenos extremos, cambio climático.

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INTRODUCTION

The hydrologic cycle begins and ends with precipitation; therefore, knowledge of the amount and distribution of rainfall over an area is a prerequisite for any attempt at efficient water resources management. In addition, in the face of a changing global climate, knowledge of the distribution of rainfall reveals regions that are most vulnerable to an increase in extreme events, such as floods and droughts. This knowledge will help to determine the climate adaptation measures that are needed for a particular community with regard to more intense extreme events. Researchers also seek to develop robust, defensible, low-error methods for frequency analysis so that users, such as decision makers tasked with addressing recurring physical events, can make estimates that are more certain, transparent, and consistent. The goal is to help answer questions such as:

1. Will the next growing season have above or below average rainfall?
2. Should available water storage be increased prior to the next rainy season?
3. What is the frequency of the maximum drought and flood intensities that have been observed in my region?

With these questions in mind and based on the method of Regional Frequency Analysis (RFA) and L-moments (Hosking & Wallis, 1997), a tool was developed to estimate the frequency/intensity of a rainfall event of a particular duration using ground-based rainfall observations. Some of the code used to develop this tool was taken from the FORTRAN code provided by Hosking & Wallis and rewritten in Visual Basic 2010. This tool was developed at the International Center for Integrated Water Resources Management (ICIWaRM) and is referred to as the ICIWaRM Regional Analysis of Frequency Tool (ICI-RAFT) (Giovannettone & Wright, 2012).

ICI-RAFT is the result of work performed in order to support the overall mission of ICIWaRM to aid developing countries in water resource management with a focus on climate change adaptation and extreme events. In order to follow the mission of ICIWaRM as a Category II UNESCO center and in the spirit of UNESCO, ICI-RAFT is free; the only costs involve expenses associated with the additional programs that are required to fully utilize ICI-RAFT, such as Microsoft Excel and ESRI ArcGIS or other GIS software.

The method of L-moments is preferred over using regular moments because L-moment statistics are more robust for accommodating extreme values and characterizing a greater number of frequency distributions. In addition, L-moments are less susceptible to bias in their estimation. RFA has the advantage over site frequency analysis in that it helps alleviate the issue of insufficient data at a site. Insufficient data does not allow the user to make accurate estimates of rainfall intensity; this is a concern in arid and semi-arid regions where gauge sites are sparse and where existing rain gauges measurements contain numerous periods of missing data. RFA is used with the assumption that if the frequencies of rainfall events are similar at several nearby locations within a "region", a statistical analysis of all observations at all sites within the "region" will result in a more accurate frequency distribution at each location in comparison to the analysis of individual site data.

METHODOLOGY

ICI-RAFT was designed to be user-friendly, while not compromising its ability to perform the work it was designed to accomplish. The most difficult step of any analysis using ICI-RAFT is the preparation of the input file; the specific input format is discussed in the ICI-RAFT Users' Manual. After the input file is loaded, a data screening window can be accessed that allows the user to specify the desired period for analysis, which consists of the beginning month, duration in months, and a lag, if any, that the user would like to introduce between the precipitation data and the global index values. The ability to compare the input data to any of several global climate indices using various lag times saves a substantial amount of time compared to attempting to perform such an analysis manually. The remainder of the program uses the values entered here when computing event frequencies and intensities and when displaying the various graphs and other features that are available.

In order to study the effectiveness of ICI-RAFT, three case studies were selected for the analysis. The studies take place in selected regions within Argentina, Nicaragua, and Venezuela. Rainfall data were provided at locations throughout each country; total rainfall for specific periods were computed and analyzed with respect to several global climate indices (see Table 1) using lag times ranging from 1 to 6 months. Each analysis attempts to identify a global climate index capable of predicting above or below average rainfall several months in advance, qualitatively and using an equation that is developed. One such index is the Madden-Julian Oscillation, which is considered the largest element of intra-seasonal (30 – 90 days) variability in the tropical atmosphere and, unlike other indices, is characterized by the eastward propagation of large areas of convective anomalies near the equator, propagating from the Indian Ocean east into the Pacific Ocean. The anomalies are monitored globally using ten different indices located on lines of longitude near the equator, with seven in the eastern hemisphere and three in the western hemisphere. The longitudes each index represents are: (1) 80°E, (2) 100°E, (3) 120°E, (4) 140°E, (5) 160°E, (6) 120°W, (7) 40°W, (8) 10°W, (9) 20°E, and (10) 70°E. It was found that the MJO is linked to summer rainfall in Southeast China (Zhang et al., 2009) and southern Africa (Pohl et al., 2007) and to rainfall patterns in Australia (Wheeler et al., 2009). The final section will summarize the findings of each case study into a simple set of conclusions.

Table 1: Global climate indices and range of values for each since 1948.

Abbreviation	Full Name	Range	Citation(s)
AAO	Antarctic Oscillation	-3.01 to 2.69	Thompson & Wallace (2000)
AO	Arctic Oscillation	-4.27 to 3.50	Lorenz (1951)
EA	East Atlantic Index	-3.33 to 2.68	Barnston & Livezey (1987)
EA/WR	Eastern Atlantic/Western Russia Index	-4.17 to 3.68	Barnston & Livezey (1987)
EP/NP	East Pacific/North Pacific Index	-2.96 to 3.88	Bell & Janowiak (1995)
MJO	Madden-Julian Oscillation	-2.02 to 2.01	Madden & Julian (1971)
NAO	North Atlantic Oscillation	-3.14 to 3.06	Walker & Bliss (1932); Barnston & Livezey (1987)
NOI	Northern Oscillation Index	-12.20 to 8.68	Schwing et al. (2002)
NP	North Pacific Index	996.44 to 1020.99	Walker & Bliss (1932); Barnston & Livezey (1987); Trenberth & Hurrell (1994)
ONI	Oceanic Niño Index	-2.10 to 2.50	NOAA (2009)
PDO	Pacific Decadal Oscillation	-3.60 to 3.51	Mantua et al. (1997)
PNA	Pacific/North American Index	-3.65 to 2.87	Wallace & Gutzler (1981)
POL	Polar/Eurasia Index	-3.44 to 3.53	Wallace & Gutzler (1981); Barnston & Livezey (1987)
SCA	Scandinavian Index	-2.44 to 3.15	Barnston & Livezey (1987)
SOI	Southern Oscillation Index	-3.60 to 2.90	Walker & Bliss (1932); Bjerknes (1969)
WP	West Pacific Index	-3.45 to 3.39	Wallace & Gutzler (1981)

RESULTS

Case Study #1: Argentina

Rainfall data were provided for twenty climate stations located in a region in west-central Argentina. A correlation is attempted between each station's total rainfall over a range of months and different global climate indices averagedta over an equal range of months, while considering temporal lags of 0 to 6 months between both ranges. It was found that the index showing the highest correlation with precipitation was the Madden-Julian Oscillation, in particular the components associated with regions in central Africa (MJO9) and the western Indian Ocean (MJO10). The highest correlation was found to occur between October and January using a lag of 4 or 5 months between the MJO index values and the precipitation events. Locations showing the highest correlations are Las Acequias (33º 16' S, 63º 59' W) (LCQ), Marcos Juarez (32° 41' S, 62° 06'W) (MJR), Ucacha (33° 03' S, 63° 30' W) (UCH), and Las Vertientes (33° 17' S, 64° 35' W) (LVR); results are shown in Fig. 1.

Figure 1 demonstrates that it is possible to make a somewhat accurate estimate of the total rainfall during the period of October – January four to five months prior. This result shows a strong signal between the MJO and the total precipitation at these stations that should be investigated in greater detail in future studies. An explanation of the mechanism responsible for this correlations is beyond the scope of this paper; however, the connection between the MJO in the western Indian Ocean and summertime rainfall in west-central Argentina is described in more detail in Agosta and Compagnucci (2012).

Even though it is difficult to predict the amount of rainfall that will occur during a particular season or period at a specific site, it is possible to predict three or four months prior with some accuracy if a particular region will have a higher chance to receive greater than average or less than average rainfall during that period. This concept is shown in Figure 2a for the rain gauge located at station UCH. The dark squares represent annual October – January rainfall during years when the June – September average MJO9 value was < 0.05, whereas the lighter squares represent years when the June – September average MJO9 value was > 0.05. According to the historical data, the station UCH can expect with some confidence that total rainfall from October –January will be average or greater-than-average if the average MJO9 four months prior is > 0.05, and vice versa.

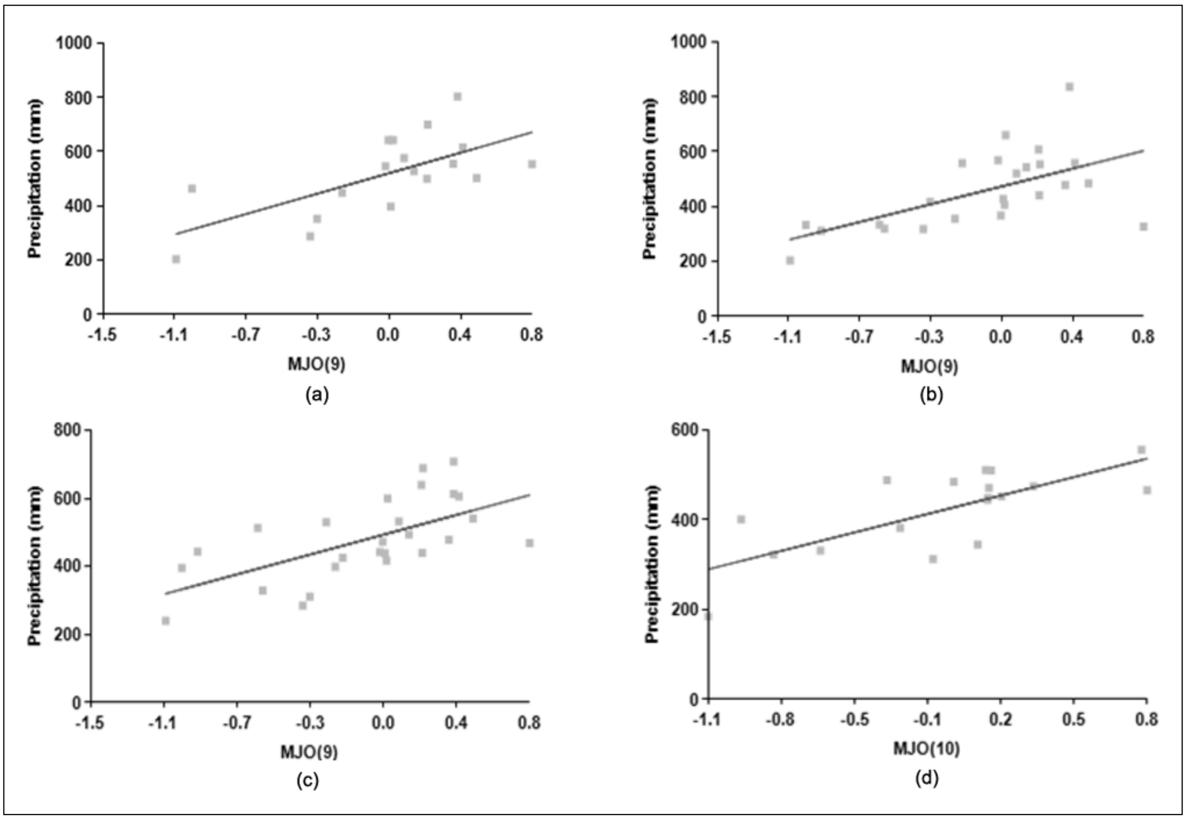

Figure 1: Linear regressions between total October – January rainfall in (a) LCQ, (b) MJR, (c) UCH, y (d) LVR, (squares) and values of the Madden-Julian Oscillation located at longitudes (a, b, c) 20° E and (d) 70° E, using a lag of (a, b, c) 4 and (d) 5 months. R2 values are (a) 0.44, (b) 0.36, (c) 0.39, and (d) 0.54.

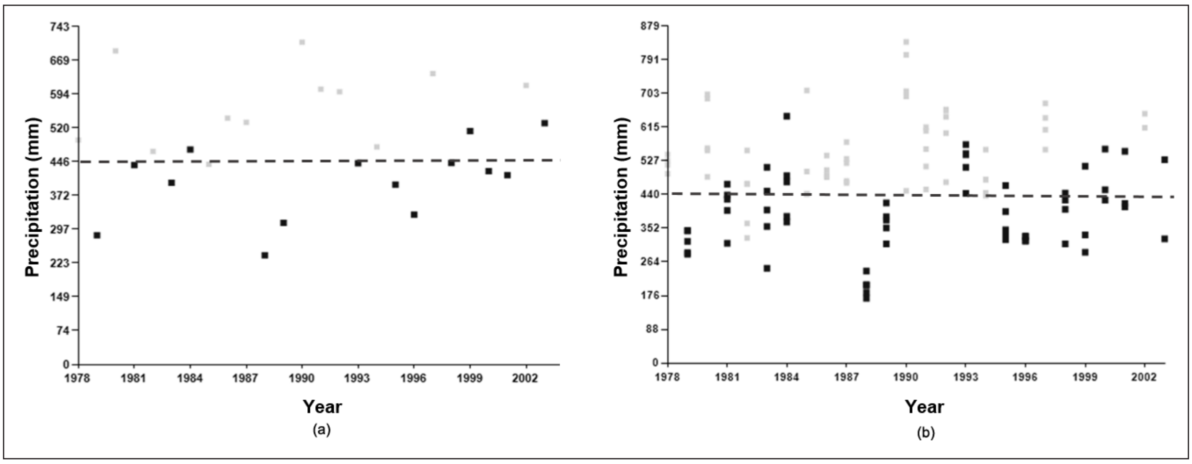

Figure 2: Annual rainfall totals are shown as black squares for the period October – January if the average MJO9 for June – September of the same year was < 0.05 (a) at station UCH and (b) within a region that includes sites MJR, LCQ, UCH, IVR, and LVR. Dashed lines represent average rainfall (a) at UCH (~448 mm) and (b) for the corresponding region (~446 mm) for each period.

In order to study the impact of the MJO9 on total annual rainfall during the period of October - January in more detail, a frequency analysis was performed using data collected at the UCH station. The analysis consisted of three conditions related to the mean value of the MJO9 during the 4-month period of June – September: 1) considering all rainfall data; 2) using rainfall data from those years when the MJO9 was < 0.05; 3) using rainfall data from those years when the MJO9 was > 0.05. The results are shown in Table 2. Some drastic differences can be observed between these results. For example, the 20-year exceedance event using all years is 665 mm; when the average June – September MJO9 > 0.05, this rainfall amount was exceeded every 5 years; when the average MJO9 during the same period was < 0.05, the possibility that UCH would receive greater than 665 mm of rainfall between October and January is almost zero. In fact, according to the current analysis, it is estimated that this rainfall amount has a recurrence period substantially greater than 1,000 years.

Table 2: Exceedance rainfall amounts at station UCH during the period October – January for various frequencies, considering three conditions in relation to the mean MJO9 during June – September. The frequency distribution used was the Generalized Extreme Value (GEV); the conditions of the MJO9 are: 1) all years without considering the value of the MJO9; 2) those years when the MJO9 was > 0.05; 3) those years when the MJO9 < 0.05.

Frequency	All Years (mm)	MJO (9) > 0.05 (mm)	MJO (9) < 0.05 (mm)
0.001	789	857	557
0.002	776	841	555
0.005	754	817	550
0.010	734	794	546
0.020	708	769	539
0.050	665	728	524
0.100	623	691	507
0.200	569	646	481
0.500	462	563	414
0.800	356	487	331
0.900	303	450	283
0.950	260	422	241
0.980	214	391	192
0.990	183	371	159
0.995	156	354	128
0.998	124	334	89
0.999	102	320	62

In a similar manner, non-exceedance probabilities can be analyzed. The 20-year non-exceedance event using all years is 260 mm, but when considering only those years when the average value of the MJO9 during June – September was < 0.05 (the third column of Table 2), the same rainfall total is not received about once in every 15 years. When looking at years when the average MJO9 was > 0.05, however, the possibility that UCH receives less than 260 mm between October and January is negligible. According to the current analysis, it is improbable that UCH would receive less than 350 mm during this period when the average MJO9 is > 0.05.

Five stations out of the twenty stations analyzed in this study showed similar behavior as was described above: MJR, LCQ, UCH, LVR, and IVR. In order to perform a regional analysis for a region that includes these sites, the rainfall totals from each site were combined into one data set. In an attempt to find a method to predict the amount of rainfall that can be expected in a region defined by these sites, all of the October – January rainfall events for each site were plotted, differentiating those events during which the average June - September MJO9 index was > or < 0.05 (Fig. 2b). As can be seen in Fig. 2b, when the average June - September MJO9 index is < -0.05, it can be expected that precipitation within the region between October and January will be below average, whereas when the average June - September MJO9 index is > -0.05, mean rainfall throughout the region can be expected to be greater than average. Afterwards, an attempt was made to develop an equation that can predict the average precipitation to be expected by computing the average rainfall of all sites for each year and plotting this average against the corresponding MJO9 value (Fig. 3). The following trend line was fit to the data:

$$R = 205.93 \times M9 + 491.55, \quad (1)$$

where R is the total rainfall for the period being analyzed (October – January) and M9 is the average value of the MJO9 index during the corresponding period of June – September. R^2 for the trend line is 0.66. Three MJO9 values were not included in the above analysis in order to estimate the error caused by Eq. (1). Values of the MJO9 were chosen near 0.20, -0.20, and -0.60; the exact values and the resulting predictions are shown in Table 3. The highest error in Table 3 is 14% with an average error of approximately 7%.

Table 3: Predictions of rainfall versus observations for three average June – September values of the MJO9 index for a region in central Argentina. Predictions were made using Eq. (1).

MJO9 Value	Observed (mm)	Predicted (mm)	Error (mm)
-0.61	379	366	-13
-0.21	392	448	56
0.23	523	540	17

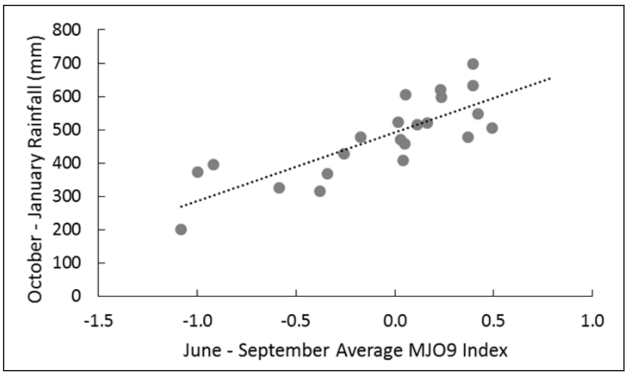

Figure 3: Circles represent the mean total rainfall calculated for the period October – January using stations MJR, LCQ, UCH, IVR, and LVR, for several average 4-month (June - September) values of the MJO9 index. The black line represents a linear trend line based on the data.

Case Study #2: Nicaragua

Rainfall data from several climate stations in Nicaragua were used. As in the previous analysis in Argentina, this analysis correlated various global climate indices with each station's total rainfall using lag times ranging from 0 to 6 months. It was again found that the index that had the greatest correlation to rainfall is the MJO, particularly components associated with the following regions: Western Pacific Ocean (MJO5), Africa (MJO9), and the Western Indian Ocean (MJO10). The highest correlation was produced during the 3-month period of August – October using a lag of three months between MJO values and the rainfall events. The highest correlation between rainfall and the MJO was found at Condega; the results are shown in Fig. 4.

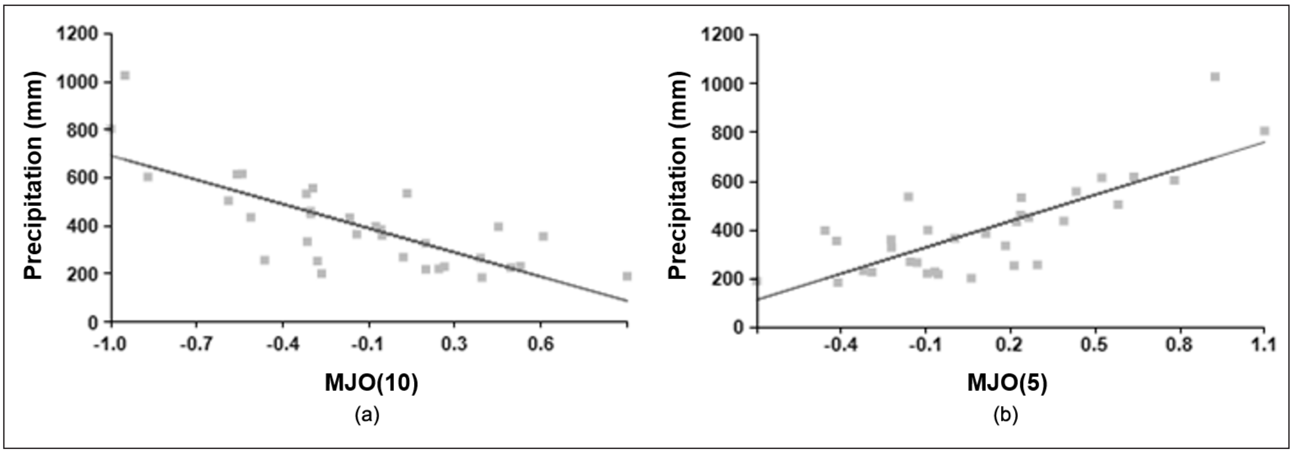

Figure 4: Linear regressions between total August – October rainfall in Condega, Nicaragua, (orange squares) and values of the Madden-Julian Oscillation located at longitudes (a) 70° E and (b) 150° E, using a lag of three months. R2 values are 0.57 and 0.62, respectively.

Figure 4 demonstrates that it is possible to make a somewhat accurate estimate of the total rainfall that is going to occur during the 3-month period of August – October in Condega three months prior. This result shows a strong signal between the MJO and the 3-month precipitation total at Condega that should be investigated in greater detail in future studies.

As mentioned earlier, even though it is difficult to predict the amount of rainfall that will occur during a particular season or period at a specific site, it is possible to predict three months prior with some accuracy if a particular region will have a higher chance to receive greater than average or less than average rainfall during that period. Figure 5a demonstrates this concept for the rain gauge located at Condega. The dark squares represent annual August – October rainfall during years when the May – July average MJO5 value was > 0.205, whereas the lighter squares represent years when the May – June average MJO5 value was < 0.205. According to the historical data, the city of Condega can expect with some confidence that total rainfall from August – October will be average or greater-than-average if the average MJO5 three months prior is < 0.205, and vice versa.

In order to study the impact of the MJO5 on total annual rainfall during August – October in more detail, a frequency analysis was performed on rainfall data collected at Condega. Three conditions related to the mean value of the MJO5 during the 3-month period of May – July were considered: 1) using all rainfall data; 2) using rainfall data from those years when the MJO5 was > 0.205; 3) using rainfall data from those years when the MJO5 was < 0.205. The results are shown in Table 4. Some drastic differences can be observed. For example, the 20-year exceedance event considering all years is 742 mm; when the average May –July MJO5 > 0.205, this rainfall amount was exceeded every 5 – 10 years; when the average MJO5 during the same period was < 0.205, the possibility that Condega would receive greater than 742 mm of rainfall between August and October is almost zero; it is estimated that this rainfall amount has a recurrence period of 1,000 years.

Table 4: Exceedance rainfall amounts in Condega during the period August - October for various frequencies, considering three conditions in relation to the mean MJO5 during May – July. The frequency distribution used was the Pearson Type III; the conditions of the MJO5 are: 1) all years without considering the value of the MJO5; 2) those years when the MJO5 was > 0.205; 3) those years when the MJO5 < 0.205.

Frequency	All Years (mm)	MJO(5) > 0.205 (mm)	MJO(5) < 0.205 (mm)
0.001	1267	1543	741
0.002	1179	1440	697
0.005	1059	1300	638
0.010	967	1193	592
0.020	872	1085	544
0.050	742	937	479
0.100	639	821	427
0.200	528	700	370
0.500	357	520	282
0.800	235	402	218
0.900	189	361	193
0.950	159	335	176
0.980	132	315	161
0.990	118	306	153
0.995	107	299	146
0.998	97	293	140
0.999	92	290	136

In a similar manner, non-exceedance probabilities are analyzed. The 20-year non-exceedance event using all years is 160 mm, but when considering only those years when the average August - October MJO5 was < 0.205 (third column of Table 4), the same rainfall total is not received about once in every 50 years. When looking at years when the average MJO5 was > 0.205, however, the possibility that Condega would receive less than 160 mm of rainfall between August – October is negligible. In fact, according to the current analysis, it is improbable that Condega would receive less than 300 mm during this period when the average MJO5 is > 0.205.

Several stations out of those analyzed in this study showed similar behavior as was described above and were selected for a regional analysis: Condega, Quilali, Santa Rosa de Ventia, Hacienda Palmira, San Fernando, Ocotal, Montañuela, Los Planes, San Francisco, Mina La Reina, Sebaco, Los Robles, Dario, La Labranza, and Tierra Azul. In an attempt to find a way to predict the amount of rainfall that can be expected in a region defined by these sites, all of the August – October rainfall events for each site were plotted, differentiating those events during which the average May – July MJO9 index was > or < -0.10 (Fig. 5b). When the average May – July MJO9 is < -0.10, precipitation within the region between August and October will be likely be greater than average, whereas when the average May – July MJO9 > -0.10, mean rainfall throughout the region can be expected to be below-average. Afterwards, an attempt was made to develop an equation that can predict the average precipitation to be expected, the average rainfall of all sites for each year was computed and plotted against the corresponding MJO9 value (Fig.

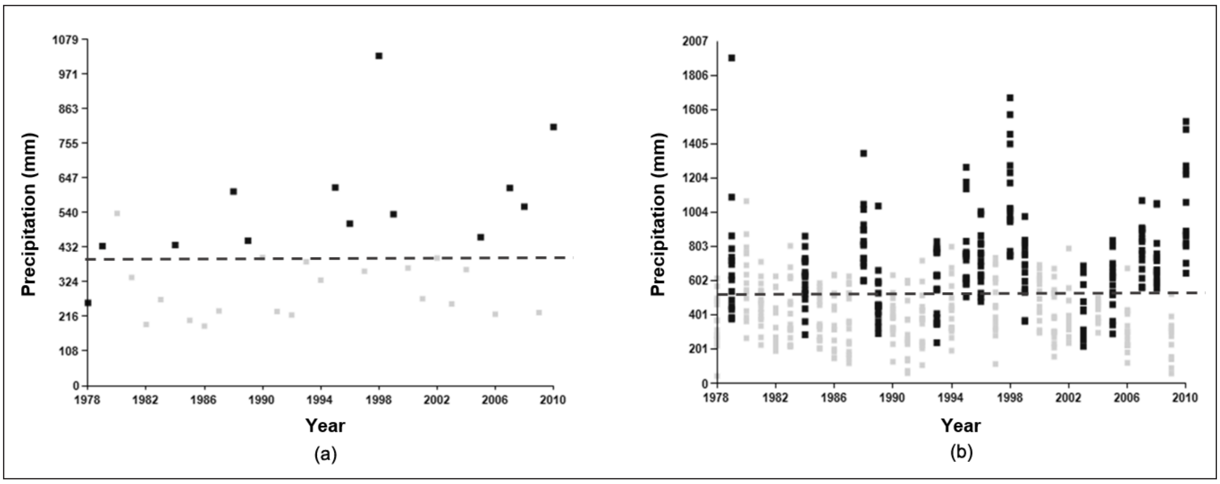

Figure 5: Annual rainfall totals are shown as black squares for the period August – October if (a) the average MJO5 for May – July of the same year was > 0.205 at station Condega and (b) if the average MJO9 for May – July of the same year was < -0.10 within a region that includes sites Condega, Quilali, Santa Rosa de Ventia, Hacienda Palmira, San Fernando, Ocotal, Montañuela, Los Planes, San Francisco, Mina La Reina, Sebaco, Los Robles, Dario, La Labranza, and Tierra Azul. Dashed lines represent average rainfall (a) at Condega (~391 mm) and (b) for the corresponding region (~529 mm) for each period.

6). A trend line using the following equation was fit to the data:

$$R = -442.24 \times M9 + 496.27, \quad (2)$$

where R is the total rainfall for the period being analyzed (August – October) and M9 is the average value of the MJO9 index during the corresponding period of May - July. The R^2 value of the trend line is 0.68. Three MJO9 values were not included in the above analysis in order to estimate the error of the predictions made by Eq. (2). Values of the MJO9 were chosen near 0.20, -0.20, and -0.60; the exact values and the resulting predictions are shown in Table 5. The highest error in Table 5 is 18% with an average error of approximately 8%.

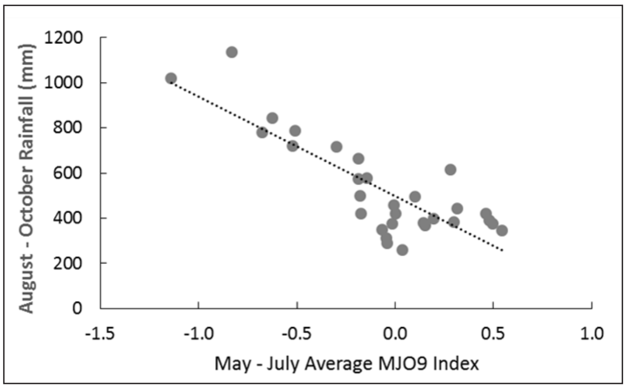

Figure 6: Circles represent the mean total rainfall calculated for the period August – October using the following sites: Condega, Quilali, Santa Rosa de Ventia, Hacienda Palmira, San Fernando, Ocotal, Montañuela, Los Planes, San Francisco, Mina La Reina, Sebaco, Los Robles, Dario, La Labranza, and Tierra Azul, for several average 3-month (May - July) values of the MJO9 index. The black line represents a linear trend line based on the data.

Table 5: Predictions of rainfall versus observations for three average May – July values of the MJO9 index for a region in Nicaragua. Predictions were made using Eq. (2).

MJO9 Value	Observed (mm)	Predicted (mm)	Error (mm)
-0.62	731	770	39
-0.22	599	592	-7
0.23	479	393	-86

Case Study #3: Venezuela

Rainfall data were provided for a myriad of stations located throughout the country of Venezuela. As with the previous two case studies, a correlation is attempted between different global climate indices and each station's total rainfall over a range of months while considering temporal lags between 1 and 6 months. It was again found that the index showing the highest correlation with precipitation was the MJO, in particular the component located over the western Indian Ocean as shown in Fig. 7 for four stations (Station #'s 0031, 0088, 1000, and 1002 in northwest Venezuela). The highest correlation was found to occur between June and August using a lag of 1 month between the MJO index values and the precipitation events.

Figure 8a indicates that it is possible to estimate with some accuracy whether a particular site will receive greater than or less than average precipitation during the three-month period of June to August for a particular site (in this case Station 1002) with one month of lead time. The dark squares represent June – August rainfall events during years when the May – July average MJO10 value was < -0.12, whereas the lighter squares represent years when the May – July average MJO10 value was > -0.12. According to the historical data, Station 1002 can expect with some confidence that accumulated rainfall between June and August will be average or greater-than-average if the average MJO10 during May – July is > -0.12, and vice versa.

In order to study the impact of the MJO10 on total precipitation in more detail during the period of June - August, frequency analyses were performed on the rainfall data collected at Station 1002. As was done earlier, analyses were conducted under three conditions related to the mean value of the MJO10 during May - July: using all rainfall data irrespective of the value of the MJO10; 2) using rainfall data from those years when the average MJO10 was > -0.12; and 3) using rainfall data from those years when the average MJO10 was < -0.12. The results of the frequency analyses are presented in Table 6. Some drastic differences can be observed when comparing these results. For example, the 20-year exceedance event using all years is 420 mm, but when the average May – July MJO10 is > -0.12, the probability of exceeding this amount of rainfall is near zero. In fact, the analysis shows that rainfall amounts greater than 230 mm are improbable under these conditions.

In a similar manner, non-exceedance probabilities can be analyzed. The 20-year non-exceedance event using all years is equal to 45 mm, and when looking at only those years when the May – July MJO10 was > -0.12, total rainfall less than 45 mm will occur approximately every 10 years. When looking at years when the average MJO10 was < -0.12, however, the chances of Station 1002 receiving less than 45 mm of rainfall between June – August are negligible. In fact, according to the current analysis, it is improbable that Station 1002 would receive < 100 mm during this period when the average May – July MJO10 is < -0.12.

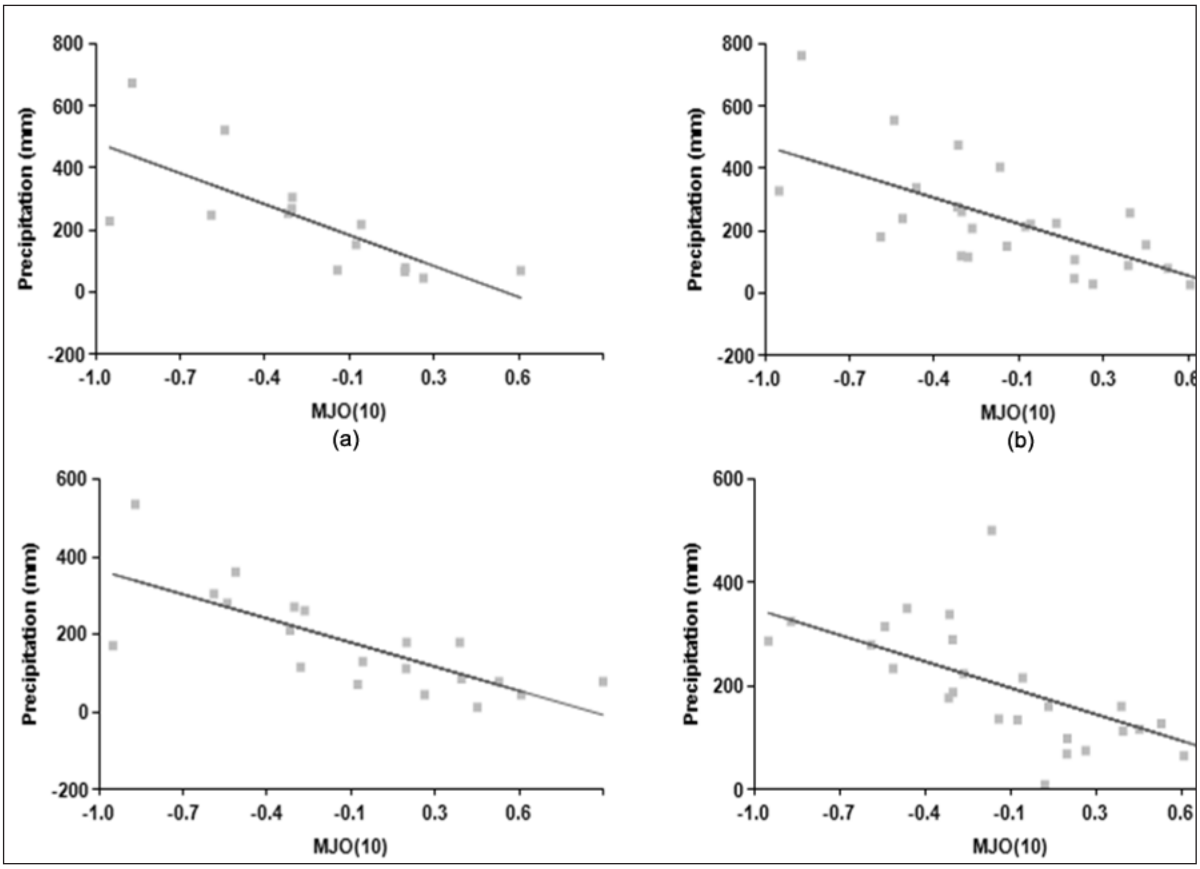

Figure 7: Linear regressions between precipitation at Station #'s (a) 0031, (b) 0088, (c) 1000, and (d) 1002, and values of the Madden-Julian Oscillation located at longitude 100 degrees E (MJO10). Data represents total rainfall during the period June – August, one month out of phase with relation to the corresponding MJO10 values. R2 values are (a) 0.55, (b) 0.46, (c) 0.56, and (d) 0.40.

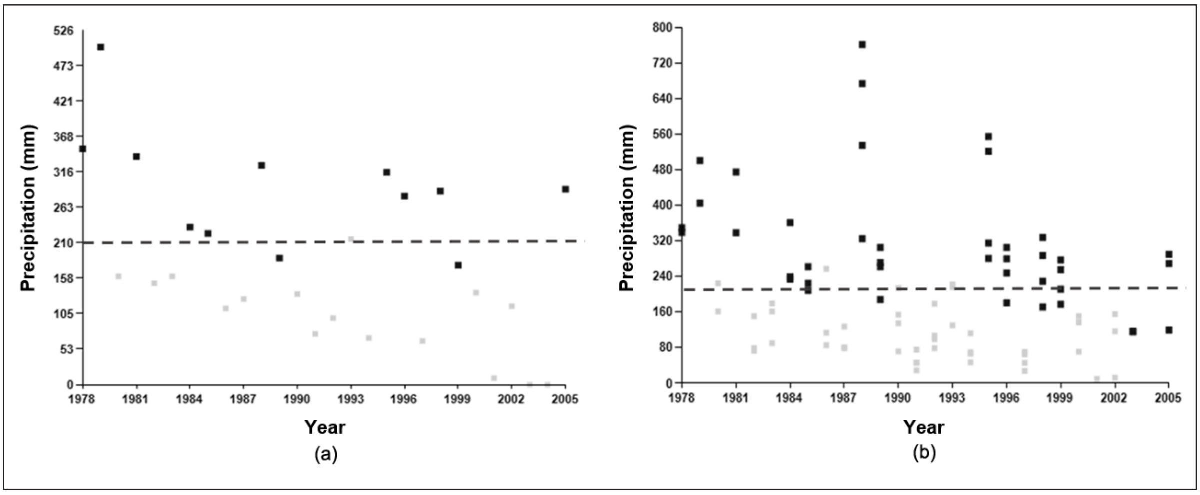

Figure 8: Annual rainfall totals are shown as black squares for the period June – August if the average MJO10 for May – July of the same year was < 0.12 (a) at Station 1002 and (b) within a region that includes Station #'s 0031, 0088, 1000, and 1002. Dashed lines represent average rainfall (a) at Station 1002 (~211 mm) and (b) for the corresponding region (~214 mm) for each period.

Table 6: Exceedance rainfall amounts at Station 1002 during the period June – August for various frequencies considering three conditions in relation to the average MJO10 during the period May – July. The frequency distribution used was the Generalized Extreme Value (GEV); the conditions of the MJO10 are: 1) all years regardless of the state of the MJO10; 2) those years when the MJO10 > -0.12; 3) and those years when the MJO10 < -0.12.

Frequency	All Years (mm)	MJO(10) > -0.12 (mm)	MJO(10) < -0.12 (mm)
0.001	661	229	676
0.002	625	227	640
0.005	574	222	591
0.010	531	216	552
0.020	486	209	511
0.050	419	196	455
0.100	364	183	409
0.200	302	163	359
0.500	198	120	281
0.800	113	72	219
0.900	74	47	192
0.950	45	26	171
0.980	15	2	150
0.990	0	0	137
0.995	0	0	126
0.998	0	0	113
0.999	0	0	105

In order to perform a regional analysis for a region that includes all of the sites shown in Fig. 7, the rainfall totals from each site were combined into one data set, from which a regional frequency analysis could be performed. In an attempt to find a way to predict the amount of rainfall that can be expected in a region defined by these sites, all of the June – August rainfall events for each site were plotted, differentiating those events during which the average May – July MJO10 index was > or < -0.12 (Fig. 8b). When the average May – July MJO10 index is < -0.12, it can be expected that precipitation within the region between June and August will be greater than average, whereas when the average May – July MJO10 index is > -0.12, mean rainfall throughout the region can be expected to be below-average. An attempt was made to develop an equation that can predict the average precipitation to be expected by computing the average rainfall of all sites for each year and plotting this average against the corresponding MJO10 value (Fig. 9). Eq. (3) describes the resulting trend line:

$$R = -221.34 \times M10 + 201.77, \quad (3)$$

where R is the total rainfall for the period being analyzed (June – August) and M10 is the average value of the MJO10 index during the corresponding period of May - July. R^2 for the trend line is 0.52. Three MJO10 values were not included in the above analysis in order to estimate the error of predictions made by Eq. (3). Values of the MJO10 were chosen near 0.20, -0.20, and -0.60; the results are shown in Table 7. Magnitudes of error ranged from 24 – 105 mm, but the percentage of error was much larger in this case due to the fact that observed precipitation was less and a potential outlier was randomly chosen for the error analysis.

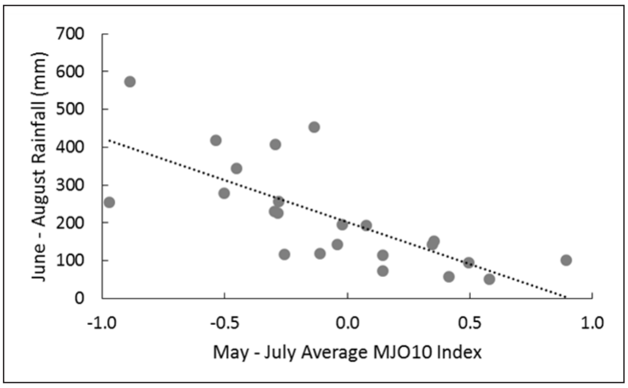

Figure 9: Circles represent the mean total rainfall calculated for the period June – August using rainfall data from Station #'s 0031, 0088, 1000, and 1002, for several average value of the MJO10 index during the period of May – July. The black line represents a linear trend line based on the data.

Table 7: Predictions of rainfall versus observations for three average May – July values of the MJO10 index for a region in northwestern Venezuela. Predictions were made using Eq. (3).

MJO10 Value	Observed (mm)	Predicted (mm)	Error (mm)
-0.59	253	331	78
-0.24	231	255	24
0.21	49	154	105

CONCLUSIONS

The International Center for Integrated Water Resources Management (ICIWaRM) Regional Analysis of Frequency Tool (ICI-RAFT) was used to perform several types of rainfall analyses at three locations in Central and South America. The stations are UCH (Argentina), Condega (Nicaragua), and Station #1002 (Venezuela). Additional analyses were performed over regions including these three sites to determine a quantitative relationship between seasonal rainfall in any of these regions and one of several global climate indices.

Frequency analyses using rainfall data at each station helped to estimate a critical value of either the MJO5, MJO9 or the MJO10 for various lag times. These critical values provide an educated guess whether a particular season will experience greater than or less than normal precipitation. Results, together with the specific range of months studied and the lag time used, are summarized in Table 8. The final column of Table 8 reveals whether higher or lower values of the MJO lead to increased activity at each location. Table 9 illustrates these results further by providing estimates of the 20-year event for each station using all data, using only those years when the appropriate MJO index is less than the critical value in Table 8, and using only those years when the appropriate MJO index is greater than the critical value in Table 8. The differences in the results are substantial; for example, using the information in Tables 8 and 9, the 20-year exceedance rainfall event at Station 1002 in Northwest Venezuela between June and August is 39% (42%) less (greater) when the average MJO10 between May and July is greater (less) than -0.12. Tables 8 and 9 suggest that the MJO has a similar effect on rainfall at Condega in Nicaragua (where enhanced MJO activity near Australia or suppressed activity near Africa enhances rainfall) but has an opposite effect on rainfall in central Argentina (UCH) (where increased MJO activity near Africa enhances rainfall amounts). This shift in influence should be studied in more detail.

Table 8: The critical values of the MJO are given for each location during the season indicated and using the specified lag time between MJO and rainfall. The signs in the final column indicate MJO index values that tend to lead to greater rainfall.

Location	Season	Index	Lag (months)	Critical MJO
Station UCH, Argentina	Oct - Jan	MJO9	4	> 0.05
Station 1002, Venezuela	Jun - Aug	MJO10	1	< -0.12
Condega, Nicaragua	Aug - Oct	MJO5	3	< 0.205

Linear equations were also developed for regions that include the stations mentioned above and that relate the value of the MJO9 or MJO10 indices to rainfall. The final results of these analyses are shown in Table 10 for the seasons indicated in Table 8. The equations show strong correlations with the MJO with R^2 values of 0.65, 0.68, and 0.53, for Argentina, Nicaragua, and Venezuela, respectively.

Table 9: Magnitude of the 20-year event (mm) in each location using all data, only data from years when the appropriate MJO index was less than a critical value (Table 9), and only data from years when the appropriate MJO index was greater than a critical value (Table 9).

Location	All Years	< Crit. MJO	> Crit. MJO
Station UCH (mm)	462	414	563
Station 1002 (mm)	198	281	120
Condega (mm)	357	282	520

The analysis and results above demonstrate the effectiveness of using ICI-RAFT to quickly and efficiently determine rainfall intensities for events of various durations and frequencies for any season of the year. Lag times between rainfall events and global climate index averages can be easily incorporated in order to determine if rainfall is correlated to one of several indices included in the software. This feature can be especially useful when trying to predict whether the upcoming season will be wetter or drier than average.

Table 10: The slope (m), independent variable (x), x-intercept (b), and R^2, are given for the linear trends observed in terms of rainfall and hurricane activity in the locations listed.

Location	m	x	b	R^2
Argentina	205.93	M9	491.55	0.65
Venezuela	-221.34	M10	201.77	0.53
Nicaragua	-442.24	M9	496.27	0.68

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