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THE INFLUENCE OF CLIMATE VARIABILITY ON RISK ASSESSMENT OF TROPICAL CYCLOGENESIS IN THE GULF OF MEXICO

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ABSTRACT. Climate change and climate variability risk assessments are usually focus on tropical cyclones due to the potential hazard for human society, especially in urban coastal areas such as those along the Gulf of México. The frequency of this natural phenomenon depends on the confluence of different dynamic (wind divergence and relative vorticity) and thermodynamic (atmospheric water content and sea surface temperature) factors. Large scale atmospheric oscillations modulate these factors and influence tropical cyclone (TC) formation and development, producing important social and economic impacts. This work explores the Maden-Julian Oscillation (MJO) and El Niño-South ern Oscillation (ENSO) relationship in regard to the Gulf of México tropical cyclogenesis, using time series and synoptic case study analyses, in order to contribute to future risk assessments in these coastal zones. Results indicate MJO and ENSO frequencies are present in wind divergence and relative vorticity, atmospheric water vapor content, and sea surface temperature. Concurring cold phase ENSO and convective phase MJO conditions benefit TC formation, while warm phase ENSO conditions inhibit TC formation and affect the MJO cycle. Synoptic case study analyses show wind divergence and atmospheric water content anomalies dominate TC behavior.

Influencia de la variabilidad climática en la evaluación del riesgo de ciclogénesis tropical en el Golfo de México

RESUMEN. Las evaluaciones de riesgos del cambio climático y la variabilidad climática generalmente se centran en ciclones tropicales debido al peligro potencial para la sociedad humana, especialmente en áreas costeras urbanas como las que se encuentran a lo largo del Golfo de México. La frecuencia de este fenómeno natural depende de la confluencia de diferentes factores dinámicos (divergencia del viento y vorticidad relativa) y termodinámicos (contenido de agua atmosférica y temperatura de la superficie del mar). Las oscilaciones atmosféricas a gran escala modulan estos factores e influyen en la formación y el desarrollo de ciclones tropicales (TC), produciendo importantes impactos sociales y económicos. Este trabajo explora la relación entre la Oscilación Maden-Julian (MJO) y El Niño-Oscilación del Sur (ENSO) con respecto a la ciclogénesis tropical del Golfo de México, utilizando series temporales y análisis de estudios de casos sinópticos, con el fin de contribuir a futuras evaluaciones de riesgos en estas zonas costeras. Los resultados indican que las frecuencias de OMJ y ENSO están presentes en la divergencia del viento y la vorticidad relativa, el contenido de vapor de agua atmosférico y la temperatura de la superficie del mar. Las condiciones concurrentes de ENOS de fase fría y OMJ de fase convectiva benefician la formación de TC, mientras que las condiciones de ENOS de fase cálida inhiben la formación de TC y afectan el ciclo de OMJ. Los análisis sinópticos de los estudios de caso muestran que la divergencia del viento y las anomalías en el contenido de agua atmosférica dominan el comportamiento de los TC.

Key words: Tropical cyclogenesis, natural hazard, risk assessment, Madden-Julian Oscillation, El Niño-Southern Oscillation, Gulf of México.

Palabras clave: Ciclogénesis tropical, peligro natural, evaluación de riesgos, Oscilación Madden-Julian, El Niño-Oscilación del Sur, Golfo de México.

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1. Introduction

Tropical cyclogenesis involves several ambient factors acting at multiple time-space scales. Previous studies evidence the importance of the environmental dynamic and thermodynamic state: low-level wind vorticity, low and high-level wind divergence, atmospheric water content, sea surface temperature; for tropical cyclone formation and development (Emanuel, 1986). Large scale atmospheric and oceanic phenomena, such as the Madden-Julian Oscillation (MJO) and El Niño-Southern Oscillation (ENSO), also play an important role in tropical cyclogenesis, modulating these dynamic and thermodynamic factors and tropical weather patterns.

MJO's first reports date from the early 1970s (Madden and Julian, 1971) evidencing a 30-60 day period atmospheric pressure oscillation at Cantón Island, propagating East from the Indian Ocean. MJO represents the tropical weather, dominant variability mode at intra-seasonal time scales; having high impact influences on weather patterns around the world, such as monsoon circulations, tornadoes, cold waves, flooding, forest fires, tropospheric zonal wind anomalies (Kiladis, 2005; Lafleur *et al.,* 2015). Positive and negative wind divergence regions defined from the 200 hPa wind potential, and outgoing long-wave radiation, indicating high and low cloud coverage regions are used as main indexes to monitor MJO.

MJO's influence on North Atlantic and North Pacific TC activity has been documented by Barret and Leslie (2009). MJO modulation of the tropical cyclogenesis on the northeast Pacific and Gulf of México during August and September 1995 was studied by Aiyyer and Molinari (2008); Rao *et al.* (2017) also studied this modulation in the Indian Ocean.

ENSO represents a coupled large-scale ocean-atmosphere phenomena originating in the Equatorial Pacific Ocean, impacting global climate variability. During its warm phase (El Niño) East Pacific Sea surface temperature (SST) increase above normal along the coast of America north and south from the Equator, and trade winds weaken; during its cold phase (La Niña) East Pacific SST decrease below normal north and south from the Equator, and trade winds strengthen (Capel, 1999). ENSO is considered as the most singular and significant teleconnection event (Magaña, 1997) worldwide. Has been shown that ENSO and TC interactions in the North Atlantic and North Pacific basins are strong at every TC formation and development stage (Reyes and Troncoso, 1993; Xu and Huang, 2015).

Tropical cyclogenesis changes position in the North Pacific, eastern, and western, during both cold and warm ENSO stages, shifting to the northwest (Irwin and Davis, 1999). El Niño events are associated with a cyclogenesis decrease west of 160°E; a corresponding cyclogenesis increase from 160°E to the dateline; a tendency for cyclogenesis to increase near the Equator (Pan, 1981; Chan, 1985; Lander, 1994); an increment of TC activity for the northeastern Pacific towards México, due to higher SST, without an increase in cyclogenesis (Bell, 2006); and higher TC intensity and duration, with no changes in TC formation frequency. La Niña events have, in general, opposite effects (Gray and Sheaffer, 1991; Whitney and Hobgood, 1997).

During warm-phase ENSO events, TCs in the North Atlantic are less frequent, less intense, and short-lived, due to the increase vertical wind shear produced by the westerly winds at 200 hPa height (Gray, 1984; Knaff, 1997; Goldenberg and Shapiro, 1996; Landsea *et al.,* 1999).

Since the discovery of these large-scale oscillations, many results have pointed out their impact on tropical cyclogenesis. Nevertheless, there still questions to answer regarding their own interactions and the resulting effects on tropical cyclogenesis, as MJO's main footprint lies in dynamic, while ENSO's main footprint lies in thermodynamic aspects of atmospheric physics. Furthermore, most studies focus on large oceanic basins like the North Atlantic and North Pacific oceans, not in regional basins such as the Gulf of México. A basin with distinct physiographic, atmospheric, and oceanic conditions, having densely populated human settlements along its coasts, and continuous high-impact economic activities taking place at its coastal and marine environments.

Tropical cyclones represent one of the major natural hazards on human life and infrastructure in the Gulf of México region, due to high-intensity winds, storm surges, large volume rainfall, and flooding. Risk assessment for proper urban development and emergency response highly depends on accurate TC prognostic models incorporating, as possible, all ambient factors involved. This work aims to further our understanding of how MJO and ENSO oscillations relate to tropical cyclogenesis in the Gulf of México. We use correlation and Fourier analyses to study these oscillations inter-relationships and their signature on dynamic and thermodynamic variables; classify tropical cyclogenesis occurrence in relation to possible MJO and ENSO state combinations, and review the synoptic ambient conditions present for two TC sample cases associated to the combination of MJO and ENSO states related to higher cyclogenesis.

2. Materials and Methods

To monitor MJO convection activity location and intensity we use the RMM (Real-time Multivariate index described by Wheeler and Halton, 2004), published by the Australian Government's Bureau of Meteorology (www.bom.gov.au/climate/mjo). RMM index definition uses the two leading modes resulting from an empirical orthogonal function analysis (EOF). The EOF covariance matrix is constructed with intra-seasonal anomalies time series in the tropical region of outgoing long wave radiation, 850hPa zonal wind, and 250hPa zonal wind; normalized respectively by their standard deviation. RMM index values [<0, 0, >0] indicate no-convective activity, inactivity, and convective activity respectively. MJO convection intensity is defined, according to RMM index magnitude range as (Lafleur et al., 2015): inactive [0 - 1], active [1 – 1.5], highly active [1.5 – 2.5], and strongly active [> 2.5].

ENSO description and analysis is done with the Oceanic El Niño Index (ONI); used by United States National Oceanic and Atmospheric Administration (NOAA) as the standard to identify warm (El Niño) and cold (La Niña) events in the tropical Pacific (http://ggweather.com/enso/oni.htm). ONI values are calculated as the 3 months running mean of ERSST.v5 SST anomalies in El Niño 3.4 region (5°N-5°S, 120°-170°W), based on 30-year base-periods updated every 5 years. A threshold of ± 0.5°C for the ONI values define warm (+) and cold (-) periods. Events (El Niño/La Niña) are defined by 5 consecutive months of ONI values above the threshold; classified as weak, moderated, strong, and very strong for ONI values in the respective absolute ranges: 0.5 to 0.9, 1.0 to 1.4, 1.5 to 1.9, ≥ 2.0.

TC data corresponds to NOAA IbTraCs v03r10 database (https://www.ncdc.noaa.gov/ibtracs) which gathers tropical cyclone best track, distribution, frequency, and intensity worldwide from all US Regional Specialized Meteorological Centers and other international centers and individuals. In this work, TC genesis is counted at the time an organism is named, i.e. when it reaches Tropical Storm status.

Atmospheric parameter time series used are from NOAA's NCEP/NCAR reanalysis database (Kalnay et al., 1996); while SST time series are from NOAA High-resolution Blended Analysis of Daily SST and ICE with a 0.25° latitude/longitude resolution.

ENSO and MJO state will be noted further as: -ENSO (no presence); ENSO- (cold pahse); ENSO+ (warm phase); -MJO (no presence); MJO- (no convective); MJO+ (convective).

The following data analysis was carried out for the time period 1981 to 2019: time series power spectra of SST, 700hPa relative humidity, 200hPa divergence, and 850hPa vorticity where calculated to identify their frequency distribution and variability at MJO and ENSO frequencies; daily tropical cyclogenesis was classified according to 9 different ENSO and MJO state combinations (1 = ENSO+, -MJO; 2 = ENSO+, MJO-; 3 = ENSO+, MJO+; 4 = ENSO-, -MJO; 5 = ENSO-, MJO-; 6 = ENSO-, MJO+; 7 = -ENSO, -MJO; 8 = -ENSO, MJO-; 9 = -ENSO, MJO+).

The power spectrum is a mathematical representation illustrating how the power of a signal is distributed across different frequencies, providing a description of the relative contribution of each frequency to the energy content of that signal. To conduct the research, the initial numerical series was decomposed into a series of frequencies in order to identify those with the highest energy, as these would optimally represent the oscillations present in the time series. Subsequently, these dominant frequencies were compared to the oscillation periods associated with the climatic phenomena ENSO and MJO.

The software utilized to compute the power spectrum is MATrix LABoratory (MATLAB), a widely recognized tool for signal processing and data analysis. MATLAB provides various functions and tools specifically designed to calculate power spectra of signals, both in the time domain and in the frequency domain.

Covariance function was used to determine ENSO, MJO, and tropical cyclogenesis daily time series relationships; and synoptic conditions anomalies where calculated for two TC case, developed under the ENSO and MJO state combination with higher cyclogenesis presence. The covariance function is not directly related to wavelet coherence or cross-wavelet analysis. While these concepts may be related in time series analysis, the covariance function is a more general measure of the relationship between two random variables, whereas wavelet coherence and cross-wavelet analysis are specific techniques used in signal and time series analysis.

3. Results

3.1 Power Spectra

Tropical cyclones, like any natural phenomena, have a multi-factor character were different-scale variables converge. Predicting tropical cyclogenesis, by analyzing and weighting its different influence factors behavior, is an undergoing challenge for the scientific community. Large-scale weather oscillations as MJO and ENSO, whose impact around the globe on several environmental variables are well known, represent influence factors still open for discussion in some TC formation regions such as the GOM.

To explore MJO and ENSO influence on tropical cyclogenesis, normalized power spectra were calculated for: daily TC formation, MJO, ONI, SST, 700 hPa relative humidity, 200 hPa wind divergence, and 850 hPa wind vorticity time series. TC formation time series includes only those organisms with name, formed within the GOM; SST and 700 hPa relative humidity time series correspond to averages over the entire GOM region; for 200 hPa divergence and 850 hPa vorticity the

GOM was divided in four regions (I - northwest, II - southwest, III - northeast, and IV - southeast; Fig. 1), constructing time series for each region's spatial average.

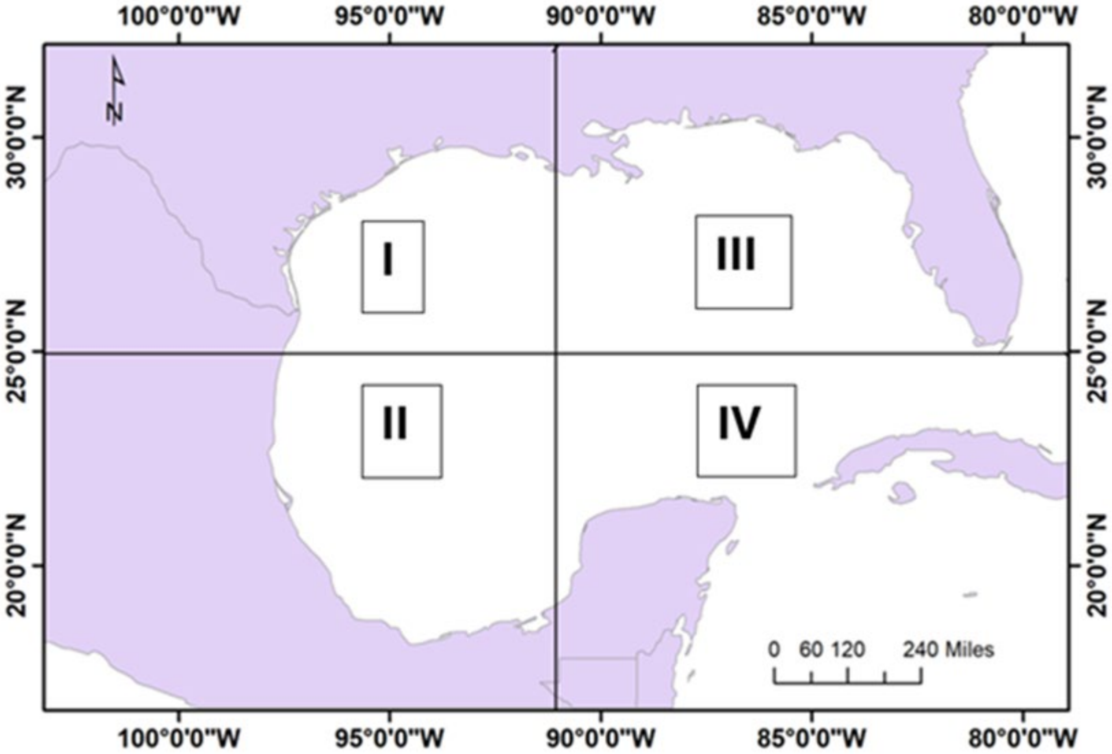

Figure 1. Study Area.

In Figure 2, the spectra of low frequency are shown Low (< 1 cycle/year) and high (> 1 cycle/year) frequency spectra for the time series. Shaded areas represent 95% confidence intervals; for reference, spectral peaks are marked with vertical color lines throughout the plots for, TC formation (red), MJO (green), and ONI (blue); TC formation spectral peaks corresponding period values are shown on top the plots.

700 hPa relative humidity and SST spectra show significant variability at 5.6 and 4.2-year periods respectively indicating ENSO modulation; an expected result, considering SST is the principal oceanic index to trace ENSO activity. MJO modulation is also evident in 700 hPa relative humidity, represented by 60 to 40 days period variability; but it is not so clear for SST, showing 70.5 and 62.8 day periods, out of the Madden and Julian (1971) period range.

200 hPa wind divergence shows the MJO signal presence in all four GOM regions as expected since it reflects vertical convection, and it is used to monitor MJO activity. GOM regions I, II, and III present 200 hPa wind divergence variability within the period range 66 to 34 days in which, periods 62, 52, 41, and 34 days are present in all three regions. GOM region IV only has significant 200 hPa wind divergence variability at periods of 63 and 38 days. Variability within the MJO period range is less intense on region II, possibly influenced for the continental high relief on the southwest GOM coast. At low frequencies, 200 hPa wind divergence in GOM regions I and II show significant variability at 6.5 years period while the significant period within the ENSO range in region IV is at 4.5 years. These results reflect the ENSO atmospheric component modifying circulations like Walker's and the trade wind strength, with a consequent high troposphere response.

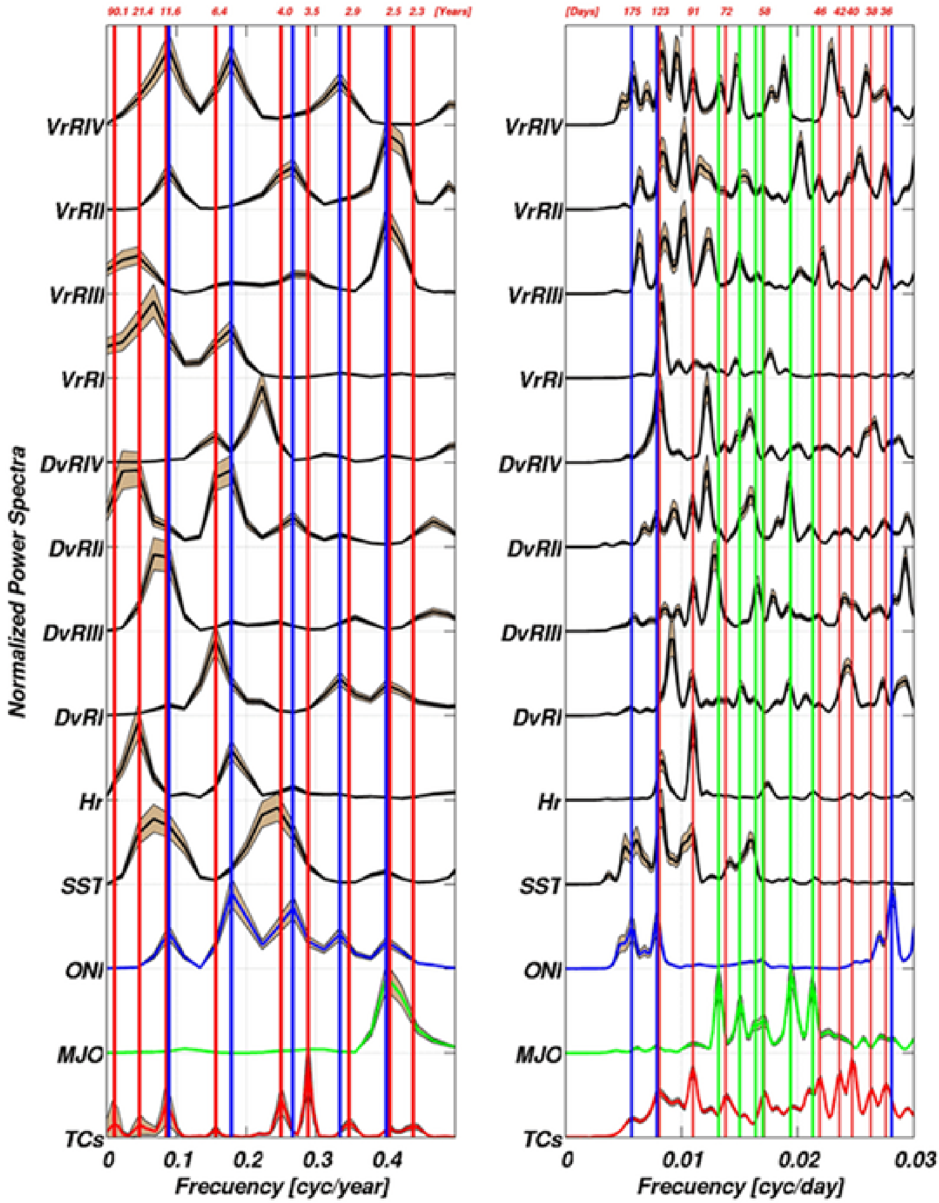

Figure 2. Frequency spectra of vorticity (VrR), divergence (DvR), relative humidity (Hr), sea surface temperature (SST), ONI, MJO and tropical cyclones (TCs) time series.

3.2 Phase Configurations

TC formation individual events are associated in this section according to ENSO and MJO phase configurations at formation time (configurations defined in Section 2 and listed in Table 1). There were 72 TC formation events within the GOM for the period 1981 to 2019.

Table 1. Phase Configurations at TC formation time. -ENSO (no presence); ENSO- (cold phase); ENSO+ (warm phase); -MJO (no presence); MJO- (no convective); MJO+ (convective).

Phase Configurations		
1 ENSO+, -MJO	4 ENSO-, -MJO	7 -ENSO, -MJO
2 ENSO+, MJO-	5 ENSO-, MJO-	8 -ENSO, MJO-
3 ENSO+, MJO+	6 ENSO-, MJO+	9 -ENSO, MJO+

Phase configuration relative frequency, during TC formation, is shown in Figure 3a. Configuration 7 represents 42% of total cases being the most frequent. This is expected since this is the most common circumstance during the TC season (ENSO is only present about once every five years and the MJO convective phase is seldom present during TC season).

Leaving out configurations 7 to 9, representing ENSO absence, the highest relative frequency, 59%, corresponds to Configuration 4 (Fig. 3b), i.e. cold phase ENSO, and no MJO presence. An extra 16% corresponds to cold phase ENSO and MJO presence: 11% with (Case 6), and 5% without active convection (Case 5). Only 12% correspond to ENOS configuration, lower than the other two states of ENSO (-ENSO and ENSO-) that were presented before.

To further evaluate these results the number of days corresponding to each configuration, for the period 1981-2019, are presented in Figure 4. ENSO absence accounts 5663 days; of which 5003 days are also MJO free. Cold and warm ENSO phases are present 3680 and 3806 days respectively. There is a noteworthy difference of more than 1000 fewer days with MJO presence with configurations having ENSO cold than with ENSO warm phase, indicating a negative influence on MJO behavior.

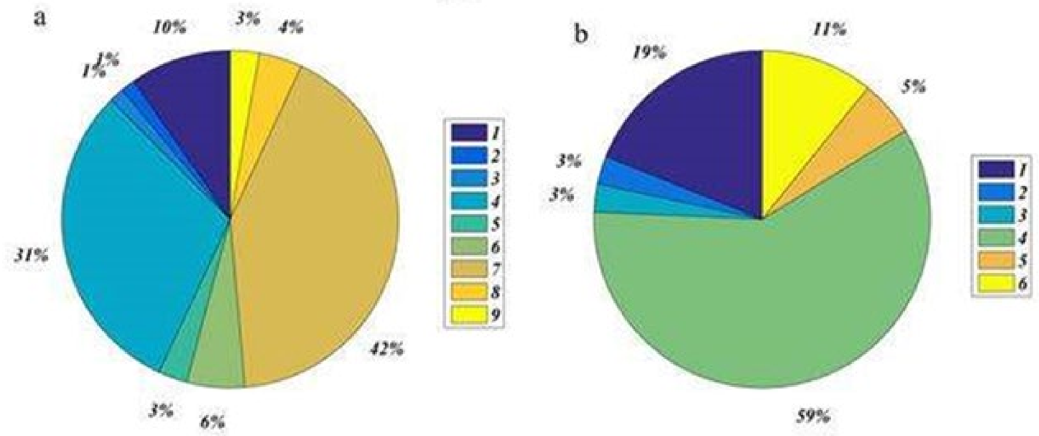

Figure 3. Phase Configuration Relative frequency. a) values taking all configurations into account; b) values taking only configurations 1 to 6 into account.

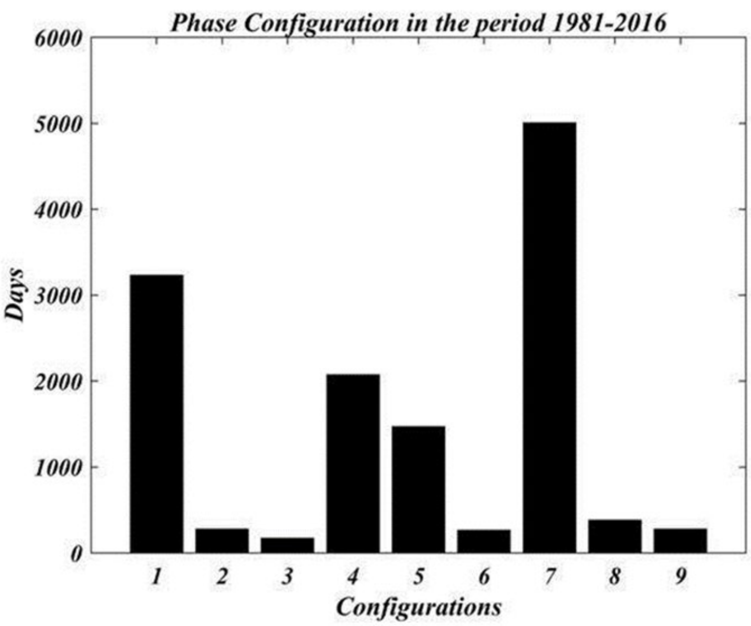

Figure 4. Number of days corresponding to each Phase Configuration for the time period 1981-2016.

Percentages of TC formation for each configuration (Fig. 5) indicate Configuration 6 (ENSO-, MJO+) is the most frequent, followed by Configuration 4 (ENSO, -MJO). Configuration 7 (-ENSO, -MJO), is no longer the dominant one as was for absolute frequency; it falls to the fifth position in relative frequency, behind configurations 8 and 9.

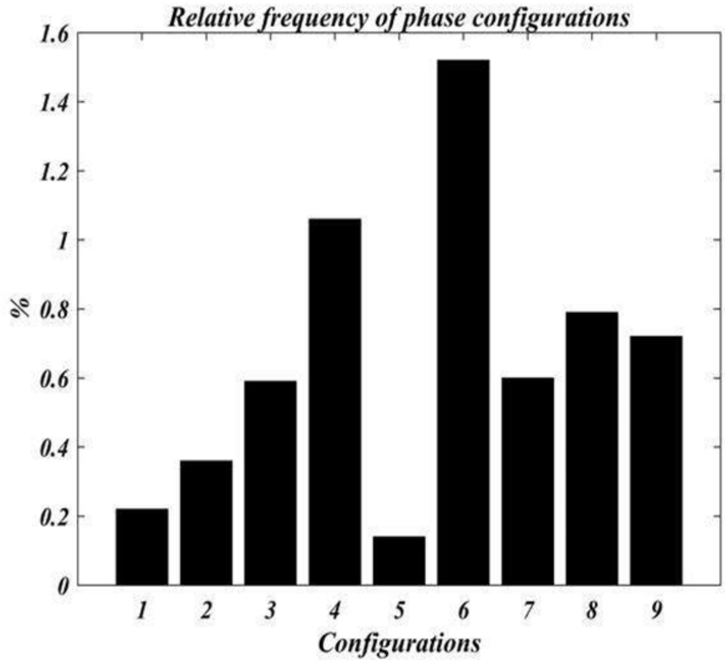

Figure 5. Relative frequency of TC formation related to each Phase Configuration and the number of days in which each configuration is present during the time period 1981-2019.

3.3 ENSO-MJO-TC Correlations

We used the covariance function to explore the statistical relationship between ENSO, MJO, and TC formation time series. Yearly time series for the period 1981-2019 are formed as follows for this task: number of TC formed during each season (June 1 to November 30); ENSO phase for the season (-1, 0, +1); and the number of days of MJO presence during the season.

The normalized time-series covariance matrix is presented in Table 2. There is a significant negative covariance (-0.55) between TC formation and ENSO phase, confirming a decrease in TC formation during its warm phase and an increase during its cold phase.

Covariance values also show an inverse relation between TC formation and MJO presence (- 0.001) but its value is below the 95% confidence threshold. This result may not represent accurately their interaction; different to ENSO, that establishes an environmental pattern lasting for months, MJO convective phase travels throughout the region in short periods, so its contribution is limited to a short time perturbation that could trigger a TC formation event.

ENSO and MJO have a negative but less energetic covariance (-0.25), which indicates that ENSO alters the periodicity and persistence of MJO along with a decrease in TC formation.

Table 2. ENSO, MJO, TC formation covariance matrix.

	TC	**ENSO**	**MJO**
TC	1	-0.5522	-0.0014
ENSO	-0.5522	1	-0.2488
MJO	-0.0014	-0.2488	1

3.4 Synoptic Environment

In the previous section, it was established which state combinations of ENSO and MJO oscillations favor TC formation: ENSO presence in both its warm and cold phase, along with MJO convection. This section discusses, based on two particular TC cases, the synoptic environmental footprint of the cold phase ENSO and MJO convective phase combination.

On August 31, 1998, Hurricane Earl was named in the southwest GOM as shown in Figure 6a. On that date, the ONI value (-1.1) indicated the presence of a moderate La Niña event, while the RRM index value (1.6) indicating a very active MJO convection. On September 8, 1998, Tropical Storm Frances was named in the west GOM as shown in Figure 6b. ONI value (-1.3) corresponds to a moderate La Niña event and RMM value (2.0) to a very active MJO convection.

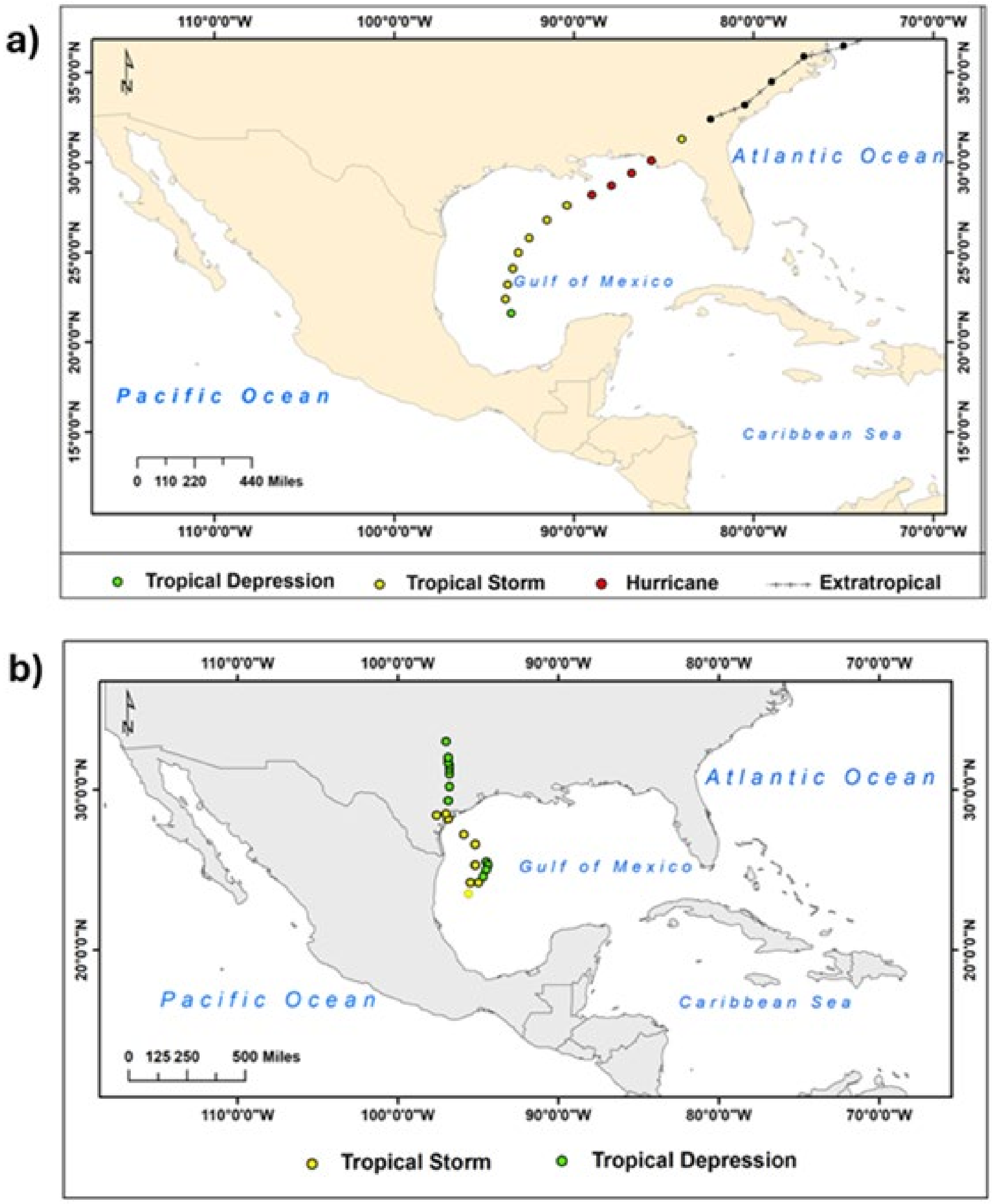

Figure 6. Origin and track of: a) Hurricane Earl, and b) Tropical Storm Frances. National Hurricane Center, NOAA.

Synoptic changes will be described using anomalies from the 1981-2019 means of the SST, 700 hPa Relative Humidity, 200 hPa Wind Divergence, and 850 hPa Wind Relative Vorticity fields.

The first field to discuss is SST, a source of energy for tropical cyclogenesis and development. High temperatures (>26°C as most researchers agree on), as well as a deep mixed ocean layer of at least 50 m, are needed for TC formation. Figure 7 shows the SST anomalies for the two TC formation cases. August 31, 1998, anomalies (Fig. 7a, case 1) have mainly positive values up to 2°C, even for this summer date. Nevertheless, there are two negative anomaly centers north of the Yucatan Peninsula with values less than -1°C.

On September 8, 1998, negative anomalies (Fig. 7b, case 2) have a higher spatial coverage extending to the south GOM coast, north of Tehuantepec Isthmus, suggesting cold Pacific waters influence produced by the cold phase ENSO.

SST anomaly time averages for the period June 1 to November 30, 1998, covering the TC season (Fig. 8a), and for the period August 28 to September 10, 1998, covering the MJO transit over GOM (Fig. 8b), allow for a different analysis. Average anomalies for the 1998 TC season, under moderate La Niña conditions, are positive or close to zero throughout GOM reflecting strengthen in trade winds flow and westward warm water transport as expected. Average anomalies for the transit period of the MJO convective phase (August 28 to September 10, 1998) show distinct negative anomaly regions up to -1°C. These distributions shear light to the fact of why SST anomaly's spatial patterns can be unique for each TC formation case.

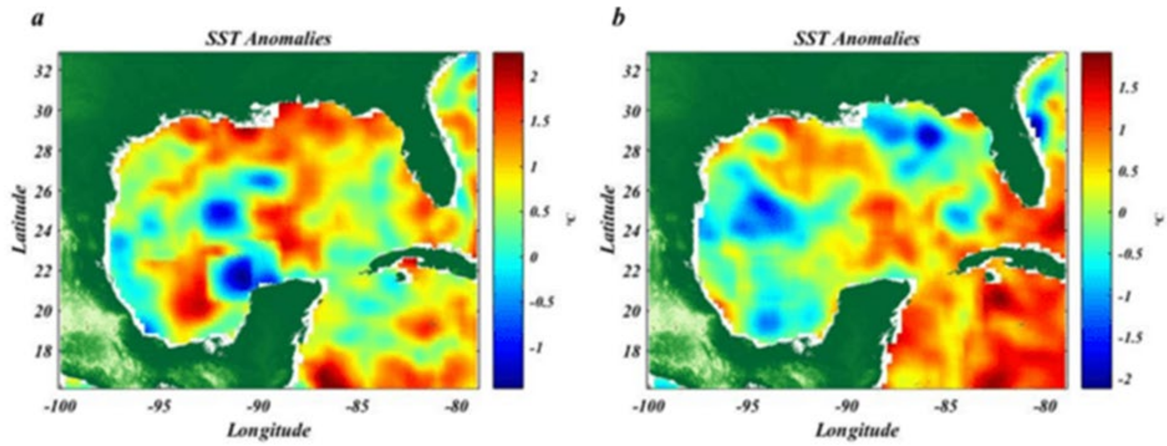

Figure 7. SST anomalies. a) August 31,1998; b) September 8, 1998.

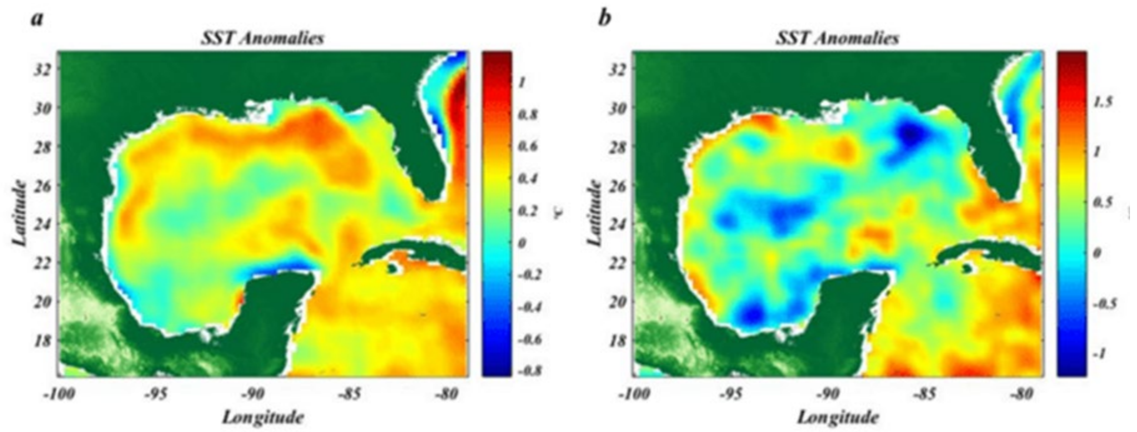

Figure 8. Time average SST anomalies over the GOM. a) Period June1 to September 30, 1998 (TC season); b) Period August 28 to September 10, 1998 (MJO transit over GOM).

The mid-level relative humidity is another key factor for tropical cyclogenesis and subsequent TC development. High mid-level water vapor content means high condensation as air rises releasing latent heat, increasing air temperature, and developing deep convection, ultimately fueling these meteorological organisms.

On August 31, 1998, 700 hPa relative humidity anomalies are high and positive (up to 40%) in the central GOM, with small absolute values near the coasts (Fig. 9a). On the second case, corresponding to September 8, 1998, positive anomalies, with values exceeding 30%, shift towards the western GOM, and a region of negative anomalies develops centered over the Florida Strait with -10% to -20% values (Fig. 9b). As shown, relative humidity values in GOM increase above average under de combined effect of ENSO and MJO oscillations.

200 hPa wind divergence anomalies for August 31, 1998, are positive (above 15x10-6 s-1) over the central GOM and the Mexican coast (Fig. 10a) and have negative, less intense, values (below -5x10-6 s-1) over the Yucatan and Florida straits, and Florida east coast. September 8, 1998, positive anomalies cover the entire GOM (Fig. 10b), having maximum values up to 2x10-6 s-1 over the Campeche Gulf on the south GOM coast. In both TC cases, Earl and Frances, these maximum positive regions correspond to their cyclogenesis positions. 200 hPa wind divergence, used also to monitor MJO and influenced by ENSO atmospheric component, shows changes under the combined presence of these two oscillations, favorable to tropical cyclogenesis.

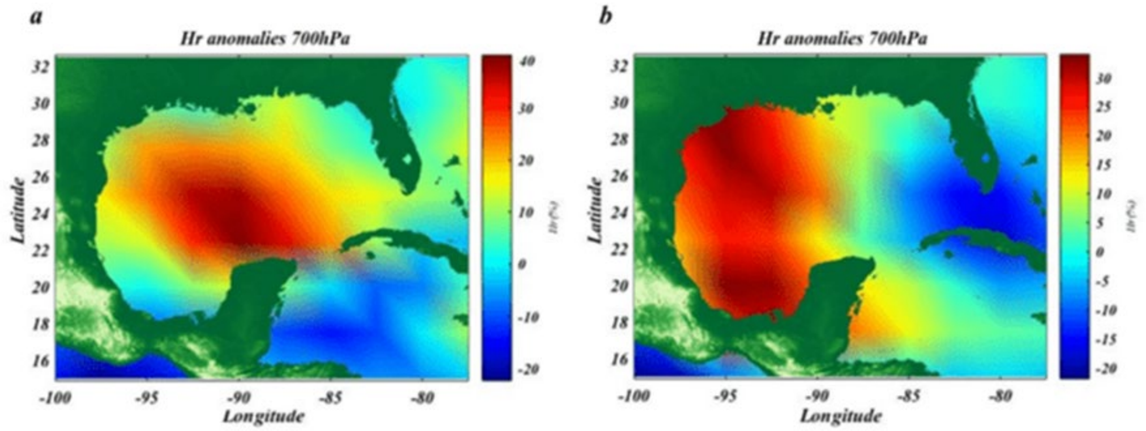

Figure 9. 700hPa relative humidity anomalies. a) August 31, 1998; b) September 8, 1998.

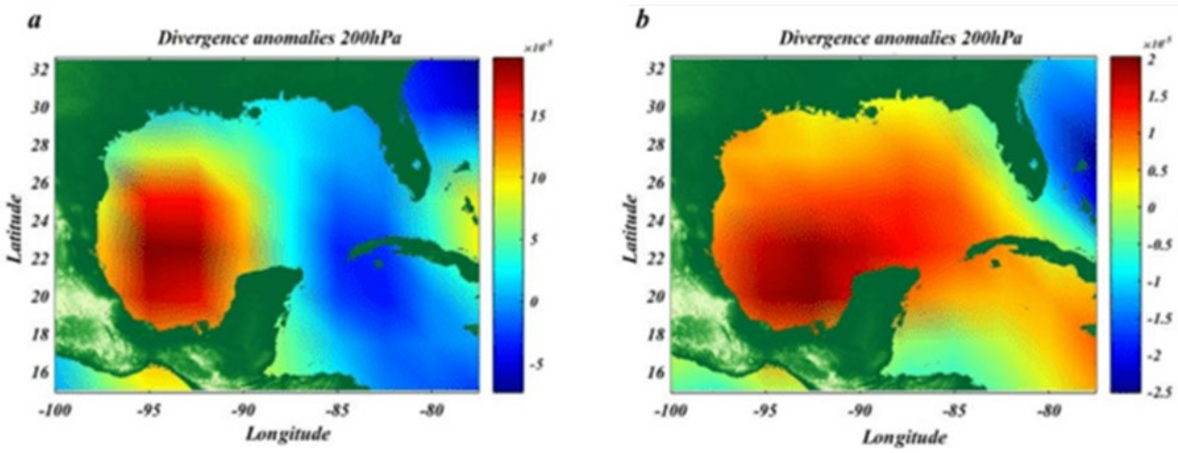

Figure 10. 200hPa wind divergence anomalies. a) August 31, 1998; b) September 8 1998.

850 hPa wind relative vorticity anomaly patterns are similar over the GOM during both dates presented, August 31, and September 8, 1998 (Fig. 11). East GOM anomalies are negative, while West GOM values are positive. Positive anomalies (~ 1.5x10-5 s-1) are present over the Campeche Gulf and Louisiana-Texas coast on August 31; with negative values up to -2x10-5 s-1 occupying the northeast GOM region down to the northwest coast of Cuba. September 8 positive anomalies cover the west GOM region with values around 1x10-5 s-1 from the south coast, up to the USA-Mexico border, and maximum values over the Campeche Gulf (2x10-5 s-1); negative anomalies are present along the north coast from Texas to Florida and the East GOM, with minimum values below -3x10-5 s-1 off the Mississippi-Alabama coast.

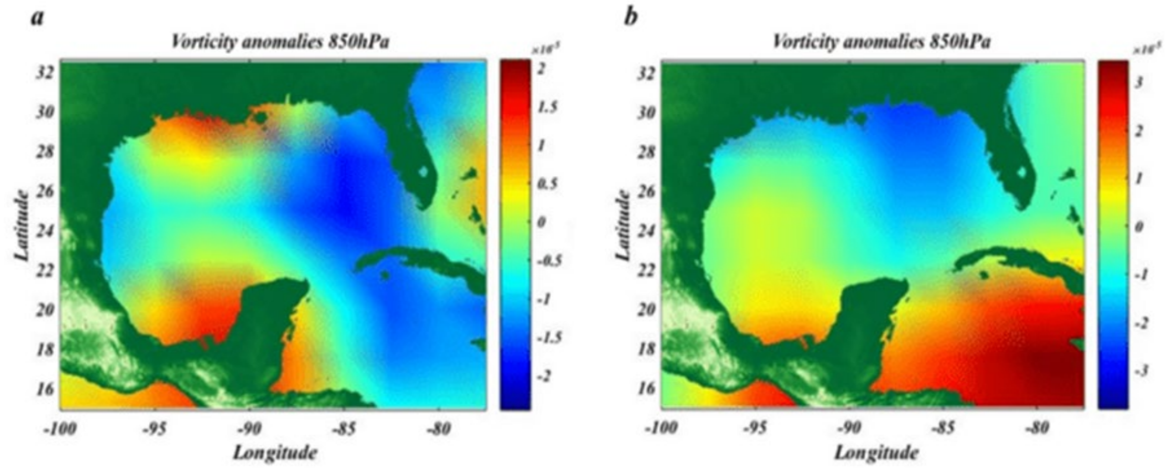

Figure 11. 850hPa wind relative vorticity anomalies. a) August 31, 1998; b) September 8 1998.

4. Discussion

The inherent complexity of climate systems, coupled with the challenges associated with long-term prediction, uncertainty in climate models, and interannual and seasonal variability, underscore the continued need to improve our understanding of climate variability and its effects on the occurrence of tropical cyclogenesis in the Gulf of Mexico region. The scope ranges from tropical cyclone prediction and monitoring to disaster preparedness and policy development for climate change adaptation.

TC formation power spectra show the modulating effect of large-scale phenomena such as MJO and ENSO. At low frequencies, TC formation power spectra show significant variability over 11-year periods, corresponding to a multi-decadal oscillation; 6, 4 and 3.5 years, within the limits of the ENSO periods; and 2.5 years, around the Quasi-Biennial Oscillation. For high frequencies, TC formation shows significant variability in annual and semi-annual periods; and at different periods within the MJO period range (70, 60, 45, 40 days).

The origins of MJO and ENSO can be traced back to a variety of oceanic and atmospheric factors: from changes in the Walker circulation to alterations in equatorial warming; However, they have a particular imprint on environmental variables such as sea surface temperature, relative humidity, wind divergence, and vorticity.

A period of 11.6 years in wind vorticity of 850 hPa is present in the southern portion of GOM (regions II and IV), while in the northern regions (I and III) the decadal to multidecadal periods are centered on 15.5 and 28 years, respectively. The variability of the ENSO period range is represented in regions I and IV by a cycle of 5.6 years, and in regions II and III by a cycle of 3.7 years. The quasi-two-year cycle of 2.5 years is present in Regions II and III, but is not evident in Regions I and IV.

Other studies such as those by Philip and Willian, 2008 have analyzed the multidecadal variability in tropical cyclone activity in the North Atlantic, including the Gulf of Mexico, and its relationship with climatic factors such as El Niño and La Niña.

The response of various variables related to tropical cyclones, including activity in the Gulf of Mexico, to changes in sea surface temperatures, and other global and local climate forcings, such as ENSO and ENSO- are referenced by (Emanuel & Sobel, 2013).

Variability from 46 to 75 days (related to MJO) is present in the southern and northeast regions (II, IV and III) with periods equal to or close to the time series of the MJO index; but being practically absent in region I (northwest), as in the divergence of 200 hPa.

Periods of intraannual variability (90 to 180 days) are present in all the variables analyzed, except for the MJO index. The high-frequency variability of MJO time series is limited to the range of 46 to 75 days.

As shown, ENSO and MJO oscillations play an important role in modulating TC formation within GOM. The ENSO signal dominates for the low frequencies and the MJO signal plays a secondary role in the high frequencies.

The discussion is related to studies by Emanuel (2005) where he examines the increase in the intensity and destructiveness of tropical cyclones during the last decades. It discusses how factors such as El Niño and La Niña may be related to this increase in cyclone activity.

These results indicate that cold-phase favors the formation of TCs in the GOM, unlike the Pacific region where it is warm-phase ENSO that favors it. The influence of MJO is weak in the presence of ENSO, with only two cases. As warming decreases in the ENSO 3.4 region and negative SST anomalies increase, the role of MJO becomes important, presenting 5 TC formation events during the neutral ENSO condition and 6 events during the La Niña condition.

The results indicate the importance of MJO in favoring TC formation conditions when ENSO is absent; configurations with warm-phase ENSO are the least favorable for TC formation; CT formation during the presence of MJO is greater than CT formation without ENSO and MJO.

Maloney and Hartmann (2001) have also examined the relationship between the Madden-Julian Oscillation and tropical cyclone formation in several regions, including the Gulf of Mexico, and provide insights into how MJO may influence tropical cyclone genesis.

Tropical cyclone dynamics is a complex topic, even with some aspects lacking definition, which presents many obstacles to the prediction of tropical cyclogenesis. In this regard, the divergence of high-level winds plays a crucial role; It provides an escape route at altitude for the excess mass provided by vertical convection, allowing the ascent of free air with the consequent increase in heat available by true condensation.

The influence of climate variability on the assessment of tropical cyclogenesis risk in the Gulf of Mexico is closely related to phenomena such as ENSO, ENSO- and the Madden-Julian Oscillation (MJO). During ENSO events, oceanic and atmospheric conditions change significantly, which can increase the likelihood of tropical cyclone formation in the Gulf of Mexico. The presence of warm waters in the equatorial Pacific during ENSO may create conditions conducive to the intensification of tropical storms and hurricanes in this region.

On the other hand, during La Niña events, warm waters are concentrated in the western Pacific, which can reduce the likelihood of tropical cyclone formation in the Gulf of Mexico. During these periods, atmospheric conditions may be less favorable for the development of storms and hurricanes in this area.

As for the Madden-Julian Oscillation (MJO), this large-scale weather pattern may have a significant impact on tropical cyclogenesis activity in the Gulf of Mexico. During the active phases of the MJO, conditions conducive to the formation and strengthening of tropical systems in this region may be generated, while during the inactive phases, tropical cyclogenesis activity may decrease.

Taken together, the interplay between climate variability, represented by ENSO, ENSO- and MJO, plays an important role in assessing the risk of tropical cyclogenesis in the Gulf of Mexico. Understanding how these phenomena influence atmospheric and oceanic conditions in this region is critical to improving the ability to forecast and manage the risk associated with tropical cyclones.

5. Conclusions

In this work, we explored the ENSO and MJO oscillations influence on tropical cyclogenesis within the Gulf of Mexico.

ENSO and MJO oscillation periods are present in different environmental parameters variability, like sea surface temperature, mid-level relative humidity, high-level wind divergence, and low-level wind relative vorticity, as well as tropical cyclone activity, within the Gulf of Mexico. ENSO low-frequency signal dominates TC activity variability, with MJO low-frequency signal playing a secondary role.

Cold phase ENSO (La Niña) in combination with the MJO convective phase constituted the best conditions for tropical cyclogenesis within the GOM. Warm phase ENSO (El Niño) is associated with low tropical cyclogenesis. MJO convective phase is associated with increased tropical cyclogenesis in presence of ENSO (cold or warm phase).

Results indicate combined effects on SST spatial distribution of, positive ENSO, negative MJO, and negative cold Pacific water influence at the Tehuantepec Isthmus limit the usefulness of this variable to determine or predict tropical cyclogenesis. Low-level relative vorticity anomalies spatial distribution depicts no clear evidence of the combined effect of ENSO and MJO oscillations; nevertheless, positive values present over the Campeche Gulf during both dates, along with high-level wind divergence values, constitute favorable conditions for deep convection and tropical cyclogenesis. Mid-level relative humidity and high-level divergence spatial distribution proved the best indicators of combined ENSO-MJO conditions favorable to tropical cyclogenesis.

References

Aiyyer, A., Molinari, J., 2008. MJO and Tropical Cyclogenesis in the Gulf of Mexico and Eastern Pacific: Case Study and Idealized Numerical Modeling. *American Meteorological Society* 65, 2691-2703. https://doi.org/10.1175/2007JAS2348.1

Barret, B., Leslie, L., 2009. Links between Tropical Cyclone Activity and Madden–Julian Oscillation Phase in the North Atlantic and Northeast Pacific Basins. *American Meteorological Society* 137, 727-743. ,https://doi.org/10.1175/2008MWR2602.1

Bell, G.D., Chelliah M., 2006. Leading tropical modes associated with interannual and multi-decadal fluctuations in North Atlantic hurricane activity. *J. Climate* 19, 590-612. https://doi.org/10.1175/JCLI3659.1

Capel, J., 1999. El Niño and the Earth's climate system. Nimbus 4, 157-161. http://hdl.handle.net/10835/1484

Chan, J.C.L., 1985. Tropical cyclone activity in the Northwest Pacific in relation to the El Nino/Southern Oscillation phenomenon. *Monthly Weather Review* 113, 599-606. https://doi.org/10.1175/1520-0493(1985)113<0599:TCAITN>2.0.CO;2

Emanuel, K., 1986. An air–sea interaction theory for tropical cyclones. *Journal of the Atmospheric Sciences* 45, 585–604 https://doi.org/10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2

Emanuel, K., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436, 686-688. https://doi.org/10.1038/nature03906

Emanuel, K., Sobel, A., 2013. Response of tropical sea surface temperature , precipitation , and tropical cyclone-related variables to changes in global and local forcing. *Journal of Advances in Modeling Earth Systems* 5(2), 447–458. https://doi.org/10.1002/jame.20032

Goldenberg, S.B., Shapiro, L.J., 1996. Physical mechanisms for the association of El Niño and West Africa rainfall with Atlantic major hurricanes. *J. Climate* 9, 1169–1187. https://doi.org/10.1175/1520-0442(1996)009<1169:PMFTAO>2.0.CO;2

Gray, W.M., Sheaffer, J.D., 1991. El Niño and QBO influences on tropical cyclone activity. In: M. H. Glantz, R. W. Katz, and N. Nicholls (Eds). *Teleconnections Linking Worldwide Anomalies,* Cambridge University Press, 257–284.

Gray, W.M., 1984. Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb Quasi-Biennial Oscillation influences. *Monthly Weather Review* 112, 1649–1668. https://doi.org/10.1175/1520-0493(1984)112<1649:ASHFPI>2.0.CO;2

Irwin, R., Davis, R., 1999. The relationship between the Southern Oscillation Index and tropical cyclone tracks in the eastern North Pacific. *Geophysical Research Letters* 26, 2251-2254. https://doi.org/10.1029/1999GL900533

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, S., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society* 77(3), 437-472. https://doi.org/10.1175/15200477(1996)077<0437: TNYRP>2.0.CO;2

Kiladis, G.N., Straub, K.H., Haertel, P.T. 2005. Zonal and vertical structure of the Madden–Julian oscillation. *Journal of the Atmospheric Sciences* 62, 2790–2809. https://doi.org/10.1175/JAS3520.1

Knaff, J.A., 1997. Implications of summertime sea level pressure anomalies in the tropical Atlantic region. *J. Climate* 10, 789–804. https://doi.org/10.1175/1520-0442(1997)010<0789:IOSSLP>2.0.CO;2

Lafleur, D., Barret, B., Henderson, G., 2015. Some Climatological Aspects of the Madden–Julian Oscillation (MJO). *J. Climate* 28, 6039-6053. https://doi.org/10.1175/JCLI-D-14-00744.1

Lander, M., 1994. An exploratory analysis of the relationship between tropical storm formation in the Western North Pacific and ENSO. *Monthly Weather Review* 122, 636-651. https://doi.org/10.1175/1520-0493(1994)122<0636:AEAOTR>2.0.CO;2

Landsea, C.W., Pielke, R.A., Mestas, A.M., Knaff, J.A., 1999. Atlantic Basin hurricanes: Indices of climatic changes. *Climatic Change* 42, 89–129. https://doi.org/10.1023/A:1005416332322

Madden, R., Julian, P., 1971. Detection of 40-50 day oscillation in the zonal wind in the tropical Pacific. *Journal of the Atmospheric Sciences* 12, 702-708. https://doi.org/10.1175/1520-0469(1971)028<0702:DOADOI>2.0.CO;2

Magaña, V., Pérez, J., Conde, C., 1997. The phenomenon of El Niño and the Southern Oscillation (ENSO) and its impacts in Mexico. *Ciencias* 51, 14-18.

Maloney, E. D., Hartmann, D. L., 2001. The Madden-Julian Oscillation , Barotropic Dynamics, and North Pacific Tropical Cyclone Formation. Part I : Observations. *Journal of the Atmospheric Sciences* 58(17), 2545-2558. https://doi.org/10.1175/1520-0469(2001)058%3C2545:TMJOBD%3E2.0.CO;2

Pan, Y., 1981. The effect of the thermal state of eastern equatorial Pacific on the frequency typhoons over western Pacific. *Acta Meteorologica Sinica* 40, 24-32. https://doi.org/10.11676/qxxb1982.003

Klotzbach, P.J., Gray, W.M., 2008. Multidecadal Variability in North Atlantic Tropical Cyclone Activity. *Journal of Climate* 21(15), 3929–3935. https://doi.org/10.1175/2008JCLI2162.1

Rao, P.C.S., Nair, S.A., Khole, M., 2017. The Influence of Madden-Julian Oscillation on the Bay of Bengal Tropical Cyclogenesis During the Year 2013. In: M. Mohapatra, B.K. Bandyopadhyay, L.S. Rathore (Eds.). *Tropical Cyclone Activity over the North Indian Ocean.* Springer, pp. 227-232, Cham. https://doi.org/10.1007/978-3-319-40576-6_15

Reyes, S., Troncoso, R., 1993. The impact of the El Niño-Southern Oscillation phenomenon on the generation of tropical cyclones around Mexico. *Ciencia y Mar* 5, 3-21.

Wheeler, M., Helton, H., 2004. An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Monthly Weather Review* 132 (8), 1917–1932. https://doi.org/10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2

Whitney, L. D., Hobgood, J., 1997. The relationship between sea surface temperatures and maximum intensities of tropical cyclones in the eastern North Pacific Ocean. *J. Climate* 10, 2921–2930.https://doi.org/10.1175/1520-0442(1997)010%3C2921:TRBSST%3E2.0.CO;2

Xu, S., Huang, F.J., 2015. Impacts of the two types of El Niño on Pacific tropical cyclone activity. *Journal of Ocean University of China* 14, 191-198. https://doi.org/10.1175/JCLI-D-17-0298.1