

Modulation of Eastern North Pacific Hurricanes by the Madden-Julian Oscillation

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Abstract

A previous study by Maloney and Hartmann hypothesized that the Madden-Julian oscillation (MJO) modulates hurricane activity over the eastern Pacific Ocean during Northern Hemisphere summer. The present study constructs a composite lifecycle of the MJO during May-November 1979-1995 using an index based on the 850 mb equatorial zonal wind. Equatorial Kelvin waves propagating eastward from convective regions of the western Pacific Ocean alter dynamical conditions over the eastern Pacific Ocean. Westerly (easterly) equatorial 850 mb wind anomalies are accompanied by enhanced (suppressed) convection over the eastern Pacific hurricane region.

Previous studies have shown that low-level relative vorticity and vertical wind shear are important time-variant environmental factors in tropical cyclone formation. Cyclonic horizontal shear of the low-level zonal wind and low vertical wind shear support tropical cyclogenesis. Periods of equatorial 850 mb westerly wind anomalies associated with the MJO are accompanied by cyclonic low-level relative vorticity anomalies and near-zero vertical wind shear over the eastern Pacific hurricane region. Easterly periods are accompanied by anticyclonic vorticity anomalies and less favorable vertical wind shear. The vorticity anomalies are associated with variations in the meridional shear of the zonal wind.

Hurricane and tropical storm statistics verify the modulation of eastern Pacific tropical systems by the MJO. Over twice as many named tropical systems (hurricanes and tropical storms) accompany equatorial 850 mb westerly anomalies than equatorial easterly anomalies, and the systems that do exist are stronger. Hurricanes are over four times more numerous during westerly phases of the MJO than easterly phases.

I. Introduction

The Madden-Julian Oscillation (MJO) is a dominant mode of variability in the tropical atmosphere with characteristic periods of 30-60 days. The MJO has a predominantly baroclinic Kelvin wave structure near the equator and is strongly coupled to convection in the Indian and W. Pacific Oceans where off-equatorial Rossby wave structures also exist. Propagation in convective regions is eastward at roughly 5 m/s. Circulation anomalies propagate eastward out of the convective regions at phase speeds of 10-12 m/s. Anomalous winds at 850 mb can extend to the coast of South America where the Andes Mountains appear to block further propagation. Anomalies at 200 mb can travel the entire circuit of the equatorial belt. See Madden and Julian (1994) and Hendon and Salby (1994) for thorough reviews.

Maloney and Hartmann (1998, hereafter referred to as MH), composited the MJO based on an index of the first two empirical orthogonal functions (EOFs) of the bandpass filtered equatorial 850 mb zonal wind. The two EOFs are dominated by zonal winds in the western Pacific and Indian Oceans. During certain phases of the MJO, a modulation of convective activity occurs over the eastern Pacific Ocean near Mexico and Central America, especially during northern hemisphere summer. In the eastern Pacific during the composite lifecycle, westerly 850 mb wind anomalies accompany periods of intensified convection and easterly anomalies accompany suppressed convection. Equatorial wind anomalies of the opposite sign occur at upper levels. Eastward Kelvin wave propagation from the western Pacific is likely responsible for these wind variations. Some of the strongest wind anomalies in the composite lifecycle occur in the eastern Pacific during these times. Cyclonic (anticyclonic) meridional shear anomalies of the low-level zonal wind occur between the equator and 30°N during enhanced (suppressed) periods of convection. MH speculated that the MJO could play a role in regulating tropical cyclone activity in the eastern north Pacific Ocean through variations in this meridional shear. Previous work regarding these connections has been sparse. Although not mentioned in their work, the composites of Hendon and Salby (1994) hint at a similar modulation. Molinari et al. (1997) suggest that MJO wave disturbances and associated shear variations may create periods of barotropic instability over the eastern Pacific through a reversal of the meridional potential vorticity gradient. Cyclogenesis would be favored during these times.

Figure 1 shows the genesis locations of eastern Pacific systems attaining at least tropical storm strength (34 knots) for the years 1979-1995. The figure was derived from NOAA/NWS/

Tropical Prediction Center storm track information. Formation usually occurs over climatologically warm waters near Mexico and Central America during May through November. Typical movement is toward the east-northeast. An average of 16.4 named systems (tropical storms, wind ≥ 34 knots, hurricanes, wind ≥ 64 knots) occur in the eastern Pacific basin each year. The number of hurricanes averages 9.4. By comparison, the Atlantic basin only averages 9.8 named storms per year and 5.8 hurricanes.

The three most important environmental dynamical factors in tropical cyclone genesis are low-level relative vorticity, vertical wind shear, and the Coriolis parameter (Gray 1979, McBride and Zehr 1981, Davidson et al. 1990). Tropical cyclogenesis is favored in environments with highly cyclonic low-level relative vorticity and low vertical wind shear. Development occurs away from the equator where the Coriolis parameter is sufficiently large. Additional environmental factors that may be of some importance are upper-level anticyclonic vorticity and low-level convergence (McBride and Zehr 1981, Molinari and Vollaro 1989, Davidson et al. 1990, Zehr 1992). The present study will concentrate on low-level vorticity and vertical shear, with a brief mention of upper-level vorticity processes. Although low-level convergence will not be emphasized in this study, the composites of MH showed that periods of enhanced (suppressed) convection over the eastern Pacific were accompanied by surface convergence (divergence), as would be expected.

Cyclonic shear of the zonal wind may cause a reversal of the potential vorticity gradient to the north of the strongest shear, a condition favorable for barotropic instability (Nitta and Yanai 1969, Holton 1992, Molinari et al. 1997), although clearly latent heat release is critical to tropical cyclone development. Westerly wind bursts in the western Pacific Ocean associated with the MJO create cyclonic shear zones to the north and south of the equator that frequently initiate tropical cyclone formation (Liebmann et al. 1994, Nieto Ferreira et al. 1996). Tropical cyclones in the western Pacific tend to cluster temporally around periods of barotropic instability on these poleward flanks of these shear zones (Gray 1979, Nieto Ferreira and Schubert 1997). Latent heat release and vortex spin-up can in turn accelerate the low level westerly winds near the equator, creating a positive feedback mechanism (Nitta 1989, Nieto Ferreira et al. 1996). Hartmann et al. (1992) document a similar modulation of typhoon activity in the western Pacific in association with a 20-25 day oscillation that occurs during the typhoon season. Their composites suggest a connection between equatorial low-level winds, surface pressure, and typhoon occurrence. Low-level westerly wind perturbations associated with the MJO propagating into the eastern Pacific

Ocean may foster similar interactions there.

High vertical wind shear does not allow condensational heating to concentrate in an atmospheric column (Gray 1968, McBride and Zehr 1981). Instead, heating at upper and lower levels becomes displaced in the vertical. Since heating is not concentrated in an atmospheric column, the atmospheric circulation cannot strengthen and tropical cyclogenesis is suppressed. The favored position for tropical cyclone formation is along a zero line in the vertical shear of the zonal wind between regions of high positive vertical shear to the north and high negative vertical shear to the south (Gray 1968, Elsberry et al. 1988). Positive shear is defined as upper level winds being more westerly than lower level winds.

This paper examines the dynamical forcing associated with MJO Kelvin wave propagation into the eastern Pacific and its effect on tropical cyclones. A composite lifecycle of the MJO is constructed for May-November using the method of MH. Dynamical factors present during both suppressed and active phases of convection in the eastern Pacific Ocean will be discussed. Records of eastern Pacific tropical cyclones will be used to verify that the MJO modulates hurricane activity in this region. These results suggest that the MJO modulates hurricane activity by creating favorable conditions for development or suppression of tropical cyclones in the eastern Pacific. Section 2 presents the data and compositing technique. Section 3 displays tropical circulations associated with the MJO in a global context. Section 4 examines eastern Pacific 200 mb and 850 mb wind, precipitation, and vorticity anomalies as well as vertical shear of the zonal wind for two extreme phases of the MJO. Section 5 uses hurricane records to quantify hurricane activity over an MJO lifecycle. Conclusions are presented in section 6.

II. Data and Compositing Technique

a. Data

The National Centers for Environmental Prediction- National Center for Atmospheric Research (NCEP-NCAR) gridded reanalysis data ($2.5^{\circ} \times 2.5^{\circ}$) in pentad format were used for winds at 200 and 850 mb for the years 1979-1995 (Kalnay et al. 1996). Microwave Sounding Unit (MSU) gridded pentad precipitation data ($2.5^{\circ} \times 2.5^{\circ}$) were available during this same period

(Spencer 1993). This precipitation dataset is only valid over ocean areas, which is acceptable within the scope of the present study. More detail concerning these datasets can be found in MH. Hurricane and tropical storm tracking data for the northeastern Pacific Ocean (east of 140°W) were obtained from the NOAA/NWS/Tropical Prediction Center. The dataset documents hurricanes and tropical storms back to the year 1949. Storm strength and position were recorded four times daily.

b. Compositing technique

The compositing technique described in detail in MH is reviewed briefly here. The index used for compositing is based on the 20-80 day bandpass filtered 850 mb zonal wind averaged from 5°N to 5°S at every equatorial longitude. EOF analysis on the entire 17 year timeseries (1979-1995) yields two prominent EOFs, the first explaining 32% of the variance and the second 22%. They are shown to be significantly different from the other EOFs by using the criterion developed by North et al (1982). Figure 2 displays the structure of the first two EOFs. Note that the amplitudes of these EOFs peak over the Indian and western Pacific Oceans, but significant amplitude extends into the eastern Pacific. Principal components (PCs) were derived by projecting these first two EOFs onto the original filtered zonal wind timeseries. The amplitude of EOF 2 peaks an average of 10-15 days later than that of EOF 1. Thus, EOF 1 and EOF 2 appear to form a propagating signal in the zonal wind. An index was constructed in the following manner, where t is the time in pentads:

$$Index(t) = PC1(t) + (PC2(t + 2) + PC2(t + 3))/2 \quad (1)$$

The index is a linear combination of PC 1 and PC 2 with contributions from PC 2 reflecting that it peaks an average of 2-3 pentads after PC 1. Results were rather insensitive to reasonable variations in the definition of this index. Since the index tends to oscillate sinusoidally, assignment of phases is relatively straightforward. Key events are chosen by selecting periods in which the peak amplitude of the index is greater than one standard deviation from zero. Phase 5 is assigned to the time in each event with maximum positive amplitude. Phases 1 and 9 are assigned to the times in each event with largest negative amplitude before and after phase 5, respectively.

Phases 3 and 7 are assigned to the zero crossing points, and the remaining phases are placed equidistant between phases 1,3,5,7, and 9. Once the timing of all phases of each event are determined, the events are averaged to produce a composite event. Consecutive phases of the composite event are on average five days apart.

During the eastern Pacific hurricane season of May-November, 58 events were isolated. Phase 2 and phase 6 are the periods of strongest westerly and easterly 850 mb zonal wind anomalies in the eastern Pacific respectively, and they are also the times of greatest and least convection and precipitation in the composite. The most active period of the hurricane season according to the NOAA/NWS/Tropical Prediction Center is June through September. Phases 2 and 6 occur with about equal frequency throughout the June through September period, so the differences between these two phases that we observe are not the result of seasonal biases in the sampling. The same is true for the expanded period of May-November.

One point must be mentioned here. Previous studies have show that the MJO signal has minimum amplitude during the Northern Hemisphere summer season (Salby and Hendon 1994, Madden and Julian 1994). In fact, the fewest events in our composites occur during July. However, a significant number of events still occur within the hurricane season and in the most intense June-September period. We do not claim that all eastern Pacific hurricanes are affected by the Madden-Julian oscillation. Instead, we claim that significant MJO events can modulate tropical cyclone activity over the eastern Pacific Ocean through eastward propagating wind anomalies associated with Kelvin wave dynamics.

III. Global lifecycle composites

Figure 3 details phases 2,4,6, and 8 of the MJO in a global context. The phases are determined from the 850 mb zonal wind index (1). Winds at 850 mb bandpass filtered to 20-80 days and MSU precipitation anomalies are plotted. Precipitation anomalies are constructed by removing the annual cycle. The composites include events from May through November, corresponding to the eastern Pacific Ocean hurricane season.

Growing precipitation anomalies in the Indian Ocean peak at phase 4 and then shift into the western Pacific at phase 6. This convection shifts slightly eastward and weakens during phase 8. Easterly wind anomalies form near and to the east of Indian Ocean convection during phase 2,

propagate eastward, and then peak over the eastern Pacific Ocean at phase 6. These anomalous easterlies coincide with suppression of convection near the Central American and Mexican coasts. Anomalies at 200 mb (not shown) are out of phase with these 850 mb anomalies, as is consistent with the structure of equatorial Kelvin waves associated with the MJO.

Enhanced convection in the eastern Pacific Ocean is associated with strong 850 mb westerly wind anomalies at phase 2. These westerly anomalies propagated eastward from the western Pacific Ocean and are associated with the previous cycle of MJO convection. Initiation of the westerly wind anomalies occurs near and to the west of western Pacific convection during phases 6 and 8. These anomalies then propagate into the eastern Pacific by phase 9 (not shown). Although the MJO is not perfectly periodic, phase 9 composites are very similar to phase 1 (not shown). The westerly wind anomalies then achieve their peak magnitude over the eastern Pacific at phase 2. The propagation of these westerly anomalies into the eastern Pacific is also consistent with Kelvin wave dynamics.

IV. Eastern Pacific composites

Phases 2 and 6 represent the periods of peak westerly and easterly 850 mb equatorial wind anomalies over the eastern Pacific during the MJO lifecycle. They also correspond to the times of peak enhanced and suppressed convection. This section will focus on these two phases in the context of the eastern Pacific hurricane region. Particular emphasis will be placed on the fields of low-level vorticity and vertical wind shear, since these are the two most important time variant environmental variables for tropical cyclone development (Gray 1979, McBride and Zehr 1981).

Figure 4 displays 850 mb wind anomalies and 850 mb relative vorticity anomalies at phases 2 and 6 for the region 150°W to 60°W, 20°S to 40°N. Strong westerly wind anomalies at 850 mb are present to the north of the equator during phase 2. Strong cyclonic relative vorticity anomalies ($\sim 0.5 \times 10^{-5} \text{ s}^{-1}$) lie just to the north of the strongest wind anomalies. These strong vorticity anomalies, due mainly to meridional shear of the zonal wind, are coincident with positive precipitation anomalies (Figure 5). Precipitation anomalies in Figure 5 are plotted at higher resolution than those in Figure 3. The unfiltered vorticity field (not bandpass filtered, not shown) is strongly cyclonic at this time. Low level wind anomalies during phase 2 may be creating a favorable environment for tropical cyclone formation due to instabilities caused by cyclonic meridional shear of the zonal wind (Gray 1979, Molinari et al. 1997, Nieto Ferreira and Schubert 1997). The westerly

wind anomalies may be further enhanced by tropical cyclone growth and associated latent heat release. The situation in the eastern Pacific may be similar to tropical cyclone formation during periods of westerly winds in the western Pacific Ocean (Nitta 1989, Hartmann et al. 1992, Liebmann et al. 1994, Nieto Ferreira et al. 1996). Strong easterly 850 mb wind anomalies occur during phase 6. Strong anticyclonic vorticity anomalies ($\sim -0.5 \times 10^{-5} \text{ s}^{-1}$) are located in the hurricane region just to the north of the maximum wind anomalies and coincide with suppressed convection (Figure 5). The unfiltered relative vorticity field (not shown) is also anticyclonic at phase 6. Some of the strongest 850 mb wind anomalies in the global composites occur in this region during phase 6.

The difference between 850 mb relative vorticity anomalies at phases 2 and 6 is plotted in Figure 6. Differences greater than $1.0 \times 10^{-5} \text{ s}^{-1}$ can be found over the eastern Pacific hurricane genesis region. A comparison with the results of McBride and Zehr (1981) indicates that these differences are similar to those seen between environments supporting developing tropical systems and environments in which tropical systems do not develop. Low-level vorticity differences of $0.4 \times 10^{-5} \text{ s}^{-1}$ were seen in their composites between periods in which strong developing systems existed and periods in which only weak developing systems existed. Therefore, the low-level relative vorticity changes between phases 2 and 6 are significant in the context of tropical cyclone development. Tropical cyclones may magnify the vorticity anomalies through latent heat release and associated circulation intensification. However, since the location and sign of relative vorticity anomalies during phases 2 and 6 are consistent with MJO Kelvin wave dynamics, the MJO is likely the primary driver behind these anomalies.

Figure 7 displays 200 mb wind anomalies and 200 mb vorticity anomalies. Easterly (westerly) 200 mb equatorial wind anomalies occur at phase 2 (phase 6). The strongest wind anomalies at 200 mb during both phases occur to the south of the equator. Vorticity anomalies associated with these wind anomalies show anticyclonic (cyclonic) vorticity at 200 mb centered well to the south of enhanced (suppressed) convection centers (see Figure 5). Other vorticity centers occur to the north of the hurricane region. However, *mean* 200-mb vorticity is highly anticyclonic over the eastern Pacific hurricane genesis region. Upper-level wind anomalies alter these values little. Low-level vorticity anomalies seem to be more important than upper-level anomalies for cyclone development in the context of an MJO lifecycle. Upper level wind anomalies may however con-

tribute to vertical shear variations.

Tropical cyclones tend to form near areas of zero vertical shear of the zonal wind between strong positive vertical shear of the zonal wind to the north and strong negative vertical shear of the zonal wind to the south (Gray 1968, McBride and Zehr 1981, Elsberry et al. 1988). Positive shear is defined as upper-level winds being more westerly than lower-level winds. Cyclone formation is preferred near regions of zero shear because higher vertical shears tend to inhibit the concentration of latent heating in an atmospheric column and suppress strengthening of the disturbance circulation (Gray 1968, McBride and Zehr 1981). Figure 8 shows the unfiltered vertical wind shear between the 200 mb and 850 mb levels for phases 2 and 6. Only the zonal wind is used in the vertical shear computations since the shear of the meridional wind in the composites is insignificant. The zero shear line lies over the hurricane genesis region during phase 2 with strong negative shear to the south and strong positive shear to the north. The zero shear line lies to the south of the hurricane genesis region during phase 6. The magnitude of positive (negative) vertical shear to the north (south) of the zero line is smaller during phase 6 than phase 2. Thus, wind anomalies associated with the MJO would tend to create a vertical wind shear profile favorable for tropical cyclone development during phase 2 and one less favorable during phase 6.

In summary, the MJO composites show more favorable low-level vorticity and vertical wind shear profiles for eastern Pacific hurricane development during 850 mb equatorial westerly anomalies (phase 2) than during 850 mb equatorial easterly anomalies (phase 6). These environmental conditions coincide with enhanced phase 2 convection and suppressed phase 6 convection. Actual records of eastern Pacific hurricanes and tropical storms must now be examined to confirm that the MJO modulates eastern Pacific tropical systems.

V. Tropical cyclone composites

Figure 9 displays the number of named systems in the eastern Pacific hurricane region (east of 140°W) occurring during each phase of the MJO for 1979-1995, May through November. The t statistic was used to determine 95% confidence limits. Named systems include tropical storms (winds \geq 34 knots) and hurricanes (winds \geq 64 knots). A particular tropical system may span more than one phase and therefore can be added to the count of more than one phase. A discernible cycle in the number of named systems is observed as one progresses from phase 1 to phase 9.

Over twice the number of named tropical systems exist in both phase 1 and phase 2 than in phase 6. Phase 2 has 56 named tropical systems as opposed to 27 in phase 6.

The average strength of tropical storms and hurricanes as a function of phase is plotted in Figure 10 along with confidence limits. The strength of a particular tropical system in a phase category is defined as the strongest sustained wind speed (in knots) recorded in associated with that system during that phase. The same system can contribute different strengths in two different phase categories. A pronounced cycle is again seen during the progression through the phases. Average system strength at phase 2 is 88 knots as opposed to 67 knots at phase 6. Figures 9 and 10 indicate that fewer named tropical systems exist in phase 6 (equatorial 850 mb easterlies) than phase 2 (equatorial 850 mb westerlies), and the ones that do exist are weaker. These facts would suggest that hurricanes are more likely during phase 2 than phase 6.

Figure 11 plots the number of hurricanes as a function of phase along with confidence limits. Over four times as many hurricanes are present during phase 2 than phase 6 (44 vs. 10). Precipitation anomalies seen in the composite lifecycle over the eastern Pacific do indeed coincide with a modulation of the number and strength of tropical systems. This statistically robust result indicates that the MJO significantly alters environmental conditions over its lifecycle to modulate hurricane activity in the eastern Pacific.

VI. Conclusions

A pronounced cycle in the number of named tropical systems in the eastern Pacific Ocean occurs during a composite lifecycle of the Madden-Julian oscillation. Periods of westerly equatorial 850 mb wind anomalies over the eastern Pacific account for twice as many hurricanes and tropical storms as periods of easterly anomalies. Average system strength is also significantly affected. Hurricanes in westerly periods outnumber those in easterly periods over 4-to-1.

The modulation of hurricane activity over an MJO lifecycle can be attributed to changes in environmental conditions in the eastern Pacific. Eastward Kelvin wave propagation from western Pacific convective areas is responsible for these changes. Low-level relative vorticity and vertical wind shear are important environmental dynamic variables associated with tropical cyclone formation. Periods of 850 mb westerly equatorial wind anomalies over the eastern Pacific are characterized by anomalously high 850 mb relative vorticity and a zero line in vertical wind shear near

the hurricane genesis region, which are conditions favorable for cyclone development. Easterly wind periods coincide with anomalously anticyclonic 850 mb relative vorticity and a less favorable vertical shear profile, which are conditions detrimental to cyclone development. Upper level vorticity anomalies do not seem to play a consistent role in altering environmental conditions over the eastern Pacific during an MJO lifecycle since they are not collocated with the hurricane genesis region. Upper level mean vorticity is however highly anticyclonic during the eastern Pacific hurricane season. Since the MJO is weakest in Northern Hemisphere summer, it is likely that not all tropical cyclones in the eastern Pacific are affected by the MJO. The results of this paper suggest that MJO events can significantly modulate hurricane activity over this region, however.

Westerly wind bursts in the western Pacific have a tendency to support tropical cyclone formation due to strong cyclonic shear on the flanks of the equatorial wind anomalies. A similar process might be occurring over the eastern Pacific during certain phases of the MJO. Cyclone intensification can then reinforce wind anomalies toward the equator creating a positive feedback. In fact, some of the strongest wind anomalies in the global MJO composites occur in the eastern Pacific Ocean region.

Future work might be needed to address the contribution of cyclogenesis to strengthening the wind anomalies in the eastern Pacific at upper and lower levels. The contributions of the signal that come from Kelvin wave propagation and from cyclone enhancement need to be separated if possible. A modeling study addressing the effects of tropical cyclone latent heating and vortex spin-up on zonal wind distributions and shear zones might be applicable to this problem. Such work would be relevant for other hurricane regions such as the western Pacific as well. Regardless, zonal wind anomalies associated with Kelvin wave propagation from the west would appear to be the principal driver in altering environmental conditions for cyclogenesis in the eastern Pacific during an MJO lifecycle.

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Genesis Locations of Eastern Pacific Systems

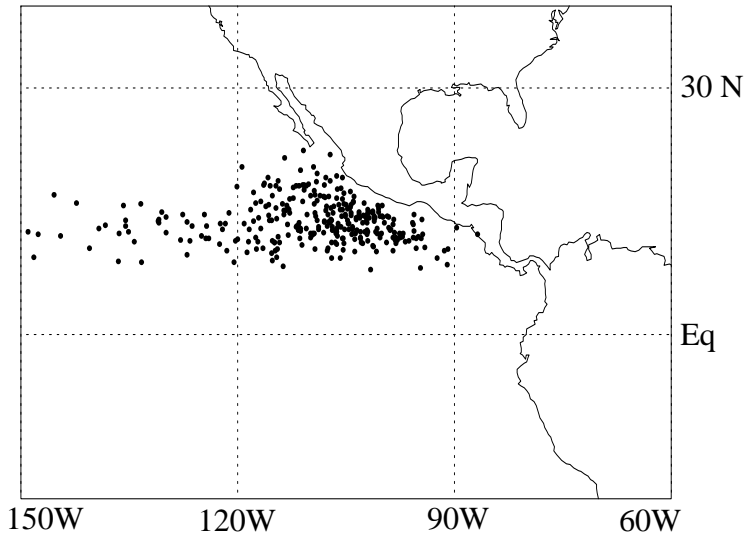


Figure 1: Genesis locations of eastern Pacific Ocean tropical systems attaining wind speeds of tropical storm force (34 knots) or greater during May-November 1979-1995.

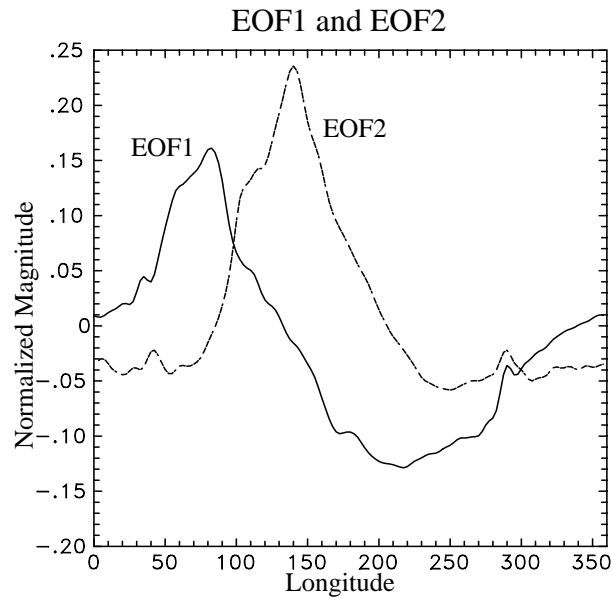
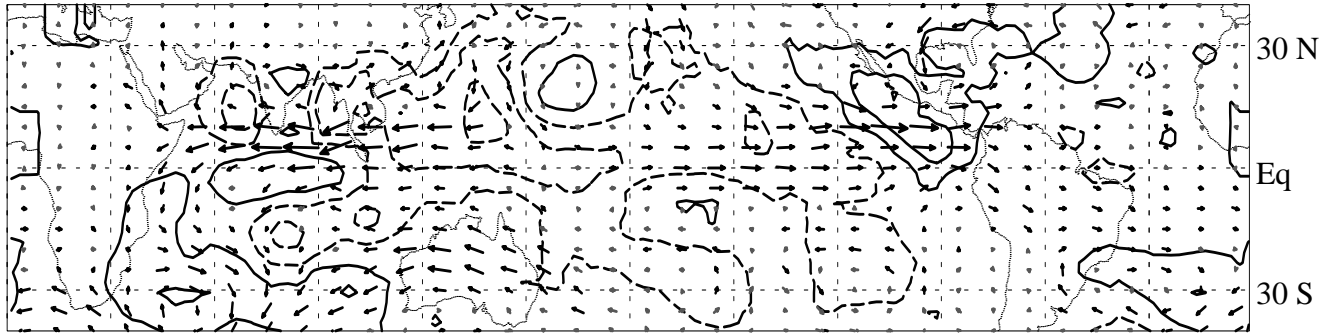


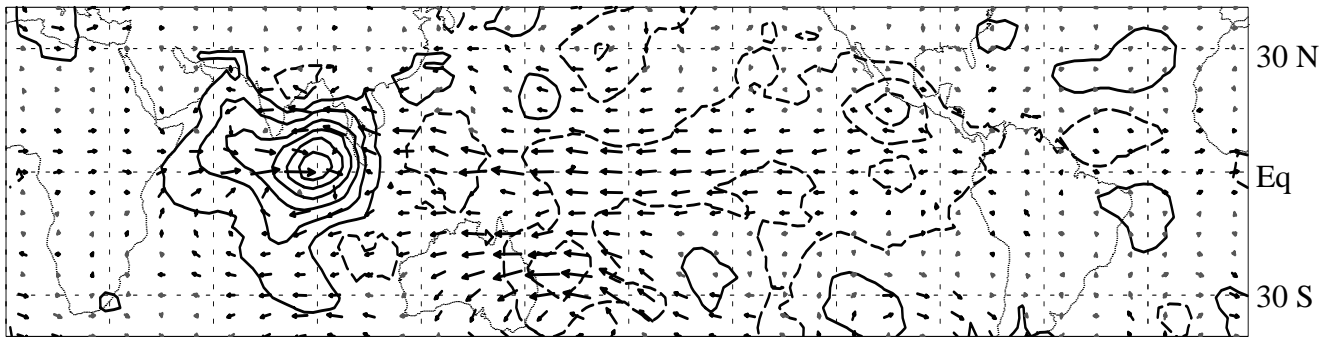
Figure 2: EOF1 (solid) and EOF2 (dashed) of the 850 mb zonal wind as a function of longitude. Data during 1979-1995 in all seasons are used. Magnitudes are normalized.

MSU Precipitation and 850 mb Wind Anomalies

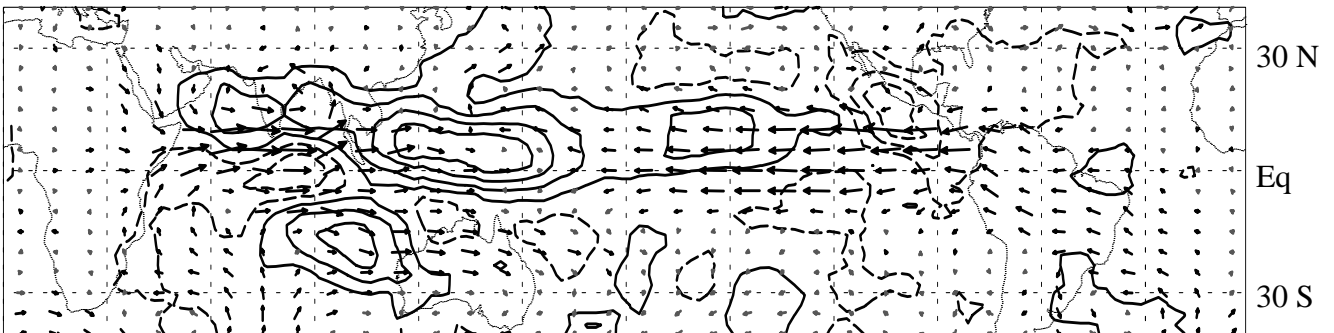
Phase 2



Phase 4



Phase 6



Phase 8

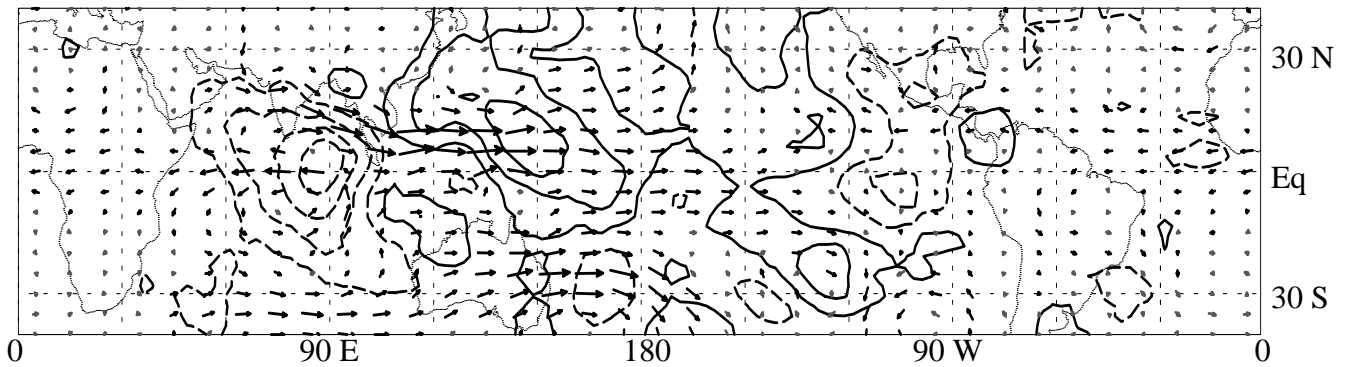


Figure 3: Composites of bandpassed 850-mb wind anomalies and MSU precipitation anomalies during May-November 1979-95 for phases 2,4,6, and 8. Maximum vectors are 3.0 m s^{-1} . Precipitation contours are at intervals of 0.6 mm day^{-1} starting at 0.3 mm day^{-1} . Negative contours are dashed.

850 mb Wind and Vorticity Anomalies

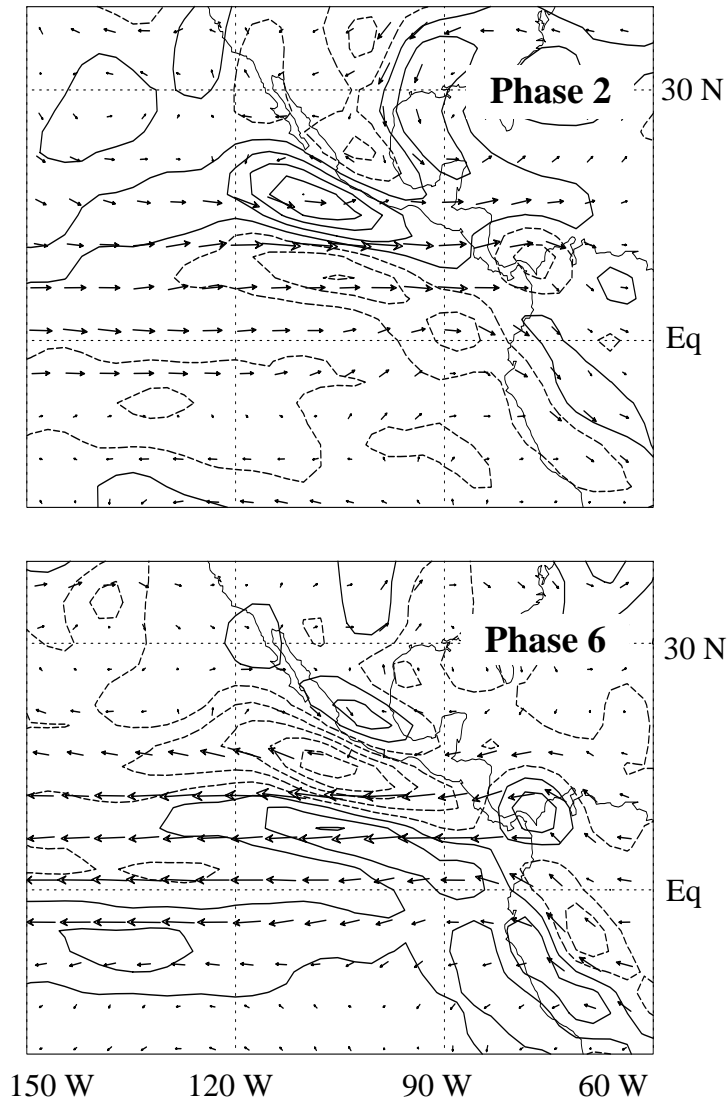


Figure 4. 850-mb bandpassed wind anomalies and 850-mb relative vorticity anomalies during 1979-1995 May-November for phases 2 and 6. Maximum vectors are 3.0 m s^{-1} . Contours are every $1.2 \times 10^{-6} \text{ s}^{-1}$ starting at $0.6 \times 10^{-6} \text{ s}^{-1}$. Negative contours are dashed.

MSU Precipitation Anomalies

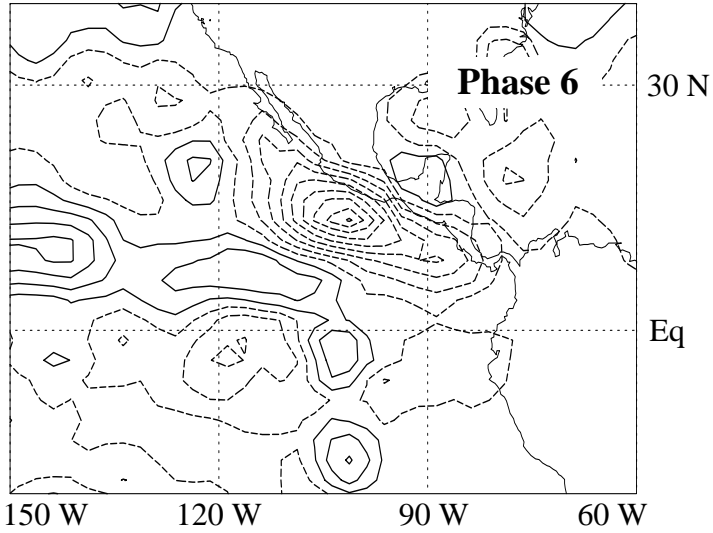
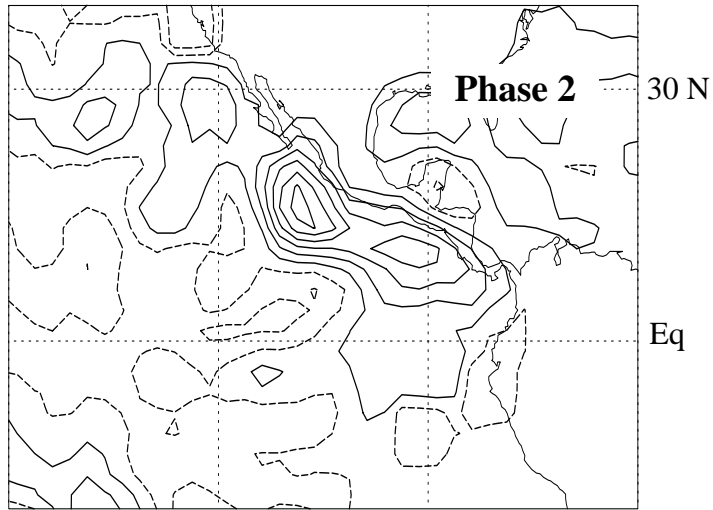


Figure 5: MSU precipitation anomalies during 1979-1995 May-November for phases 2 and 6. Contours are every 0.6 mm day^{-1} starting at 0.3 mm day^{-1} . Negative contours are dashed.

P2 minus P6 850 mb Relative Vorticity

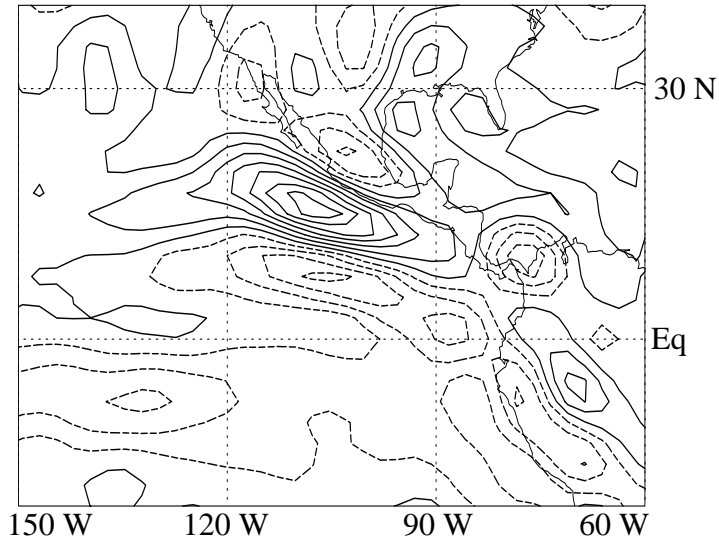


Figure 6. The difference between 850 mb relative vorticity anomalies at phases 2 and 6 (phase 2 minus phase 6), during May-November, 1979-1995. Contours are every $1.6 \times 10^{-6} \text{ s}^{-1}$ starting at $0.8 \times 10^{-6} \text{ s}^{-1}$. Negative contours are dashed.

200 mb Wind and Vorticity Anomalies

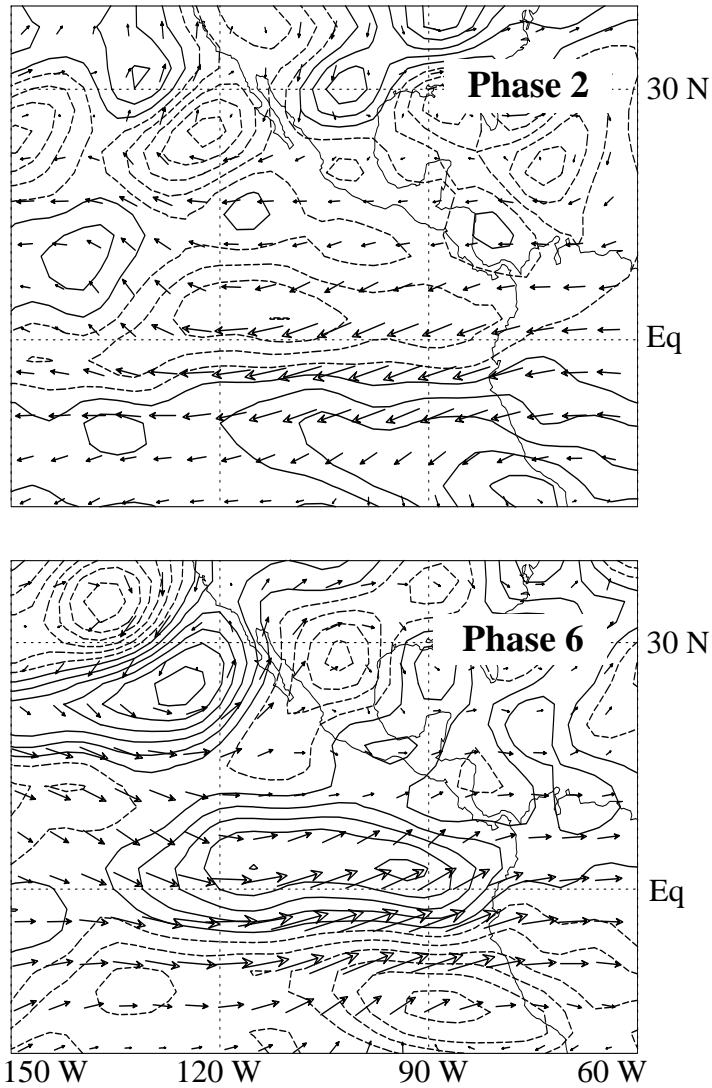


Figure 7. Bandpassed 200-mb wind and 200-mb relative vorticity anomalies during 1979-1995 May-November for phases 2 and 6. Maximum vectors are 7.0 m s^{-1} . Contours are every $1.2 \times 10^{-6} \text{ s}^{-1}$ starting at $0.6 \times 10^{-6} \text{ s}^{-1}$. Negative contours are dashed.

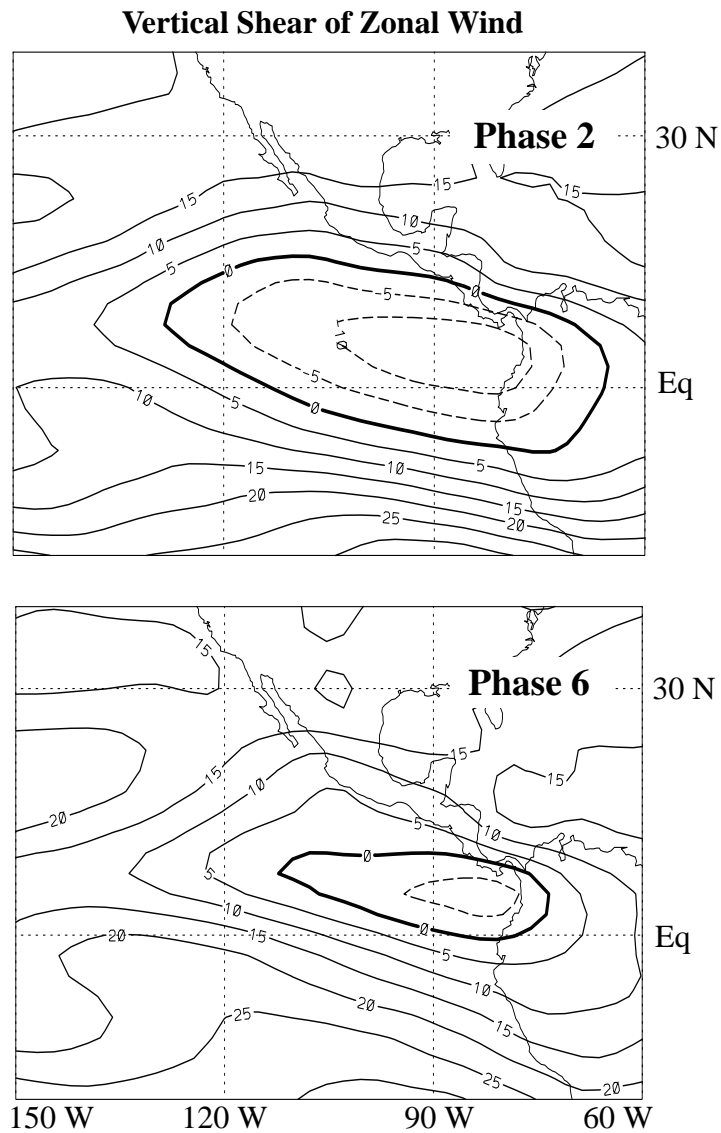


Figure 8. 200-mb zonal wind minus 850-mb zonal wind during May-November 1979-1995 for phases 2 and 6. Values are not anomalies but total shear values. Contours are every 5.0 m s^{-1} starting at 0.0 m s^{-1} . Negative contours are dashed. Positive values mean that 200-mb winds are more westerly than 850-mb winds.

E. Pacific Hurricanes and Tropical Storms

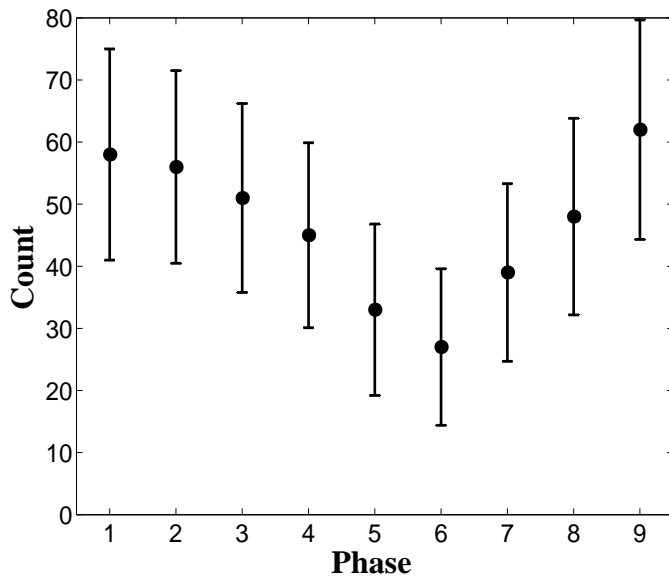


Figure 9: Number of hurricanes and tropical storms as a function of MJO phase for the eastern Pacific Ocean hurricane region during May-November 1979-1995. Error bars represent 95% confidence limits.

E. Pacific Mean System Strength

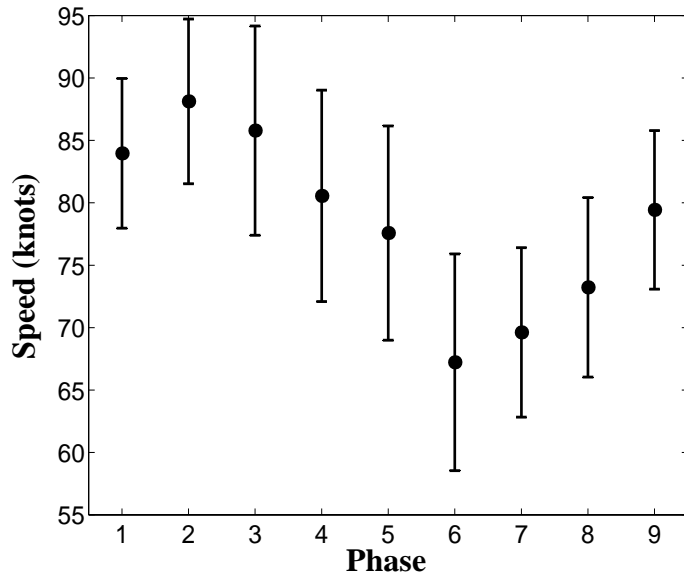


Figure 10. Average strength (in knots) of hurricanes and tropical storms as a function of MJO phase for the eastern Pacific Ocean hurricane region during May-November 1979-1995. Error bars represent 95% confidence limits.

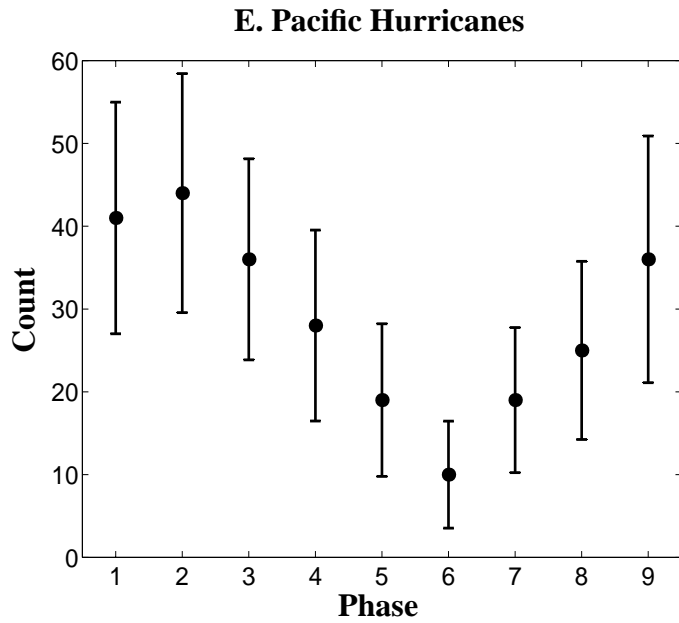


Figure 11. Number of hurricanes as a function of MJO phase for the eastern Pacific Ocean hurricane region during May-November 1979-1995. Error bars represent 95% confidence limits.