The Relationship Between Tropical Cyclones of the Western Pacific and Indian Oceans and the Madden-Julian Oscillation

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Abstract

We document a relationship between tropical cyclones of the Indian and western Pacific oceans and the Madden-Julian oscillation (MJO). Cyclones preferentially occur during the convective phase of the oscillation, and cluster around the low-level cyclonic vorticity and divergence anomalies that appear poleward and westward of the large-scale convective anomaly along the equator.

Although the absolute numbers of storms and typhoons are enhanced during the convective phase of the oscillation, the ratios of storms and typhoons formed per depression are the same in the convective phase as the dry phase of the oscillation. There exist more storms and typhoons simply by there being more depressions in the convective phase.

The third result of this study is that the increase in cyclone activity during active periods of convection is not restricted to MJO activity. In fact, we find that an equal increase occurs during the convective phase of an arbitrarily chosen, completely independent band from the MJO. We conclude that the MJO does not influence tropical cyclones in a unique fashion, but it is important because of the relatively large proportion of tropical variance that is explained by it.

1. Introduction

The clustering of tropical cyclones in time and space is the subject of this report. Clustering has been observed on a wide range of temporal scales, which hints at the possibility of long-range forecasting of these destructive storms. Gray (1979) found that globally there are 1-2 weeks of active cyclogenesis, followed by 2-3 weeks of quiescence. Hartmann *et al.* (1992) identified a 20-25 day oscillation in the western Pacific during northern fall, and determined that the recurrence interval of tropical cyclones entering a 10 degree radius circle at a carefully

chosen grid point in that region to peak at 20-25 days. Cyclones prefer the phase of the oscillation that is characterized by low surface pressure.

Clustering presumably results from the episodic occurrence of favorable large-scale environmental conditions. Gray (1968, 1979) identified several large-scale climatological features that are related to cyclone development on seasonal time scales. He found that in addition to a preference for warm SSTs, cyclogenesis occurs favorably in regions of low-level positive vorticity, a minimum of vertical wind shear, high mid-tropospheric relative humidity, and non-zero Coriolis force.

The basis for the present study is the hypothesis that large-scale, slowly varying anomalies can

Fig. 1. Composite seasonal cycle of OLR variance for eastward wavenumbers 1-3 and 35-95 day periods. Time series at each latitude is smoothed with 100 day running mean before plotting. Units are arbitrary. Stripes represent times when signal is significant at 95% level relative to a composite background spectrum based on a Chi-square test. Adapted from Salby and Hendon (1994).

enhance climatologically favorable conditions to produce clustering. The Madden-Julian oscillation (Madden and Julian 1971, 1972; MJO) is one such candidate to produce the necessary anomalies. The MJO is an eastward propagating disturbance with a period near 50 days, predominantly in the zonal wind field of the equatorial plane, confined mainly to the Indian and western Pacific oceans (see Madden and Julian (1994) for a comprehensive review). Low-level (~ 850 mb) cyclonic gyres straddle the large-scale convection anomaly along the equator (*e.g.*, Knutson and Weickmann 1987, Hendon and Salby 1994). Surface convergence, which at the equator is displaced eastward of the OLR signal, extends westward and poleward such that off-equator surface convergence is beneath the low-level cyclonic gyre (Hendon and Salby 1994). These gyres and surface convergence would appear to provide the large-scale conditions necessary for tropical cyclogenesis.

In fact, there is some evidence that the MJO may be related to the temporal clustering of cyclones. Nakazawa (1986) found that cyclones tended to occur during the negative phase of 30-60 day filtered OLR anomalies during 1979 (the FGGE year). Sui and Lau (1992) noted that cyclones seemed to form upon the arrival of a super cloud cluster associated with the MJO. A super cloud cluster is the largest scale of convection embedded within the envelope of convection associated with the MJO (*e.g.*, Nakazawa 1988).

Hendon and Liebmann (1994) showed that synoptic-

scale (periods 2-15 days) convective activity increases by 50-100% in the wet phase of the MJO compared to the dry phase. The purpose of this research is to judge whether the modulation of synoptic-scale activity by the MJO carries over to cyclones, and if so, to identify the mechanism by which this modulation occurs. This study builds on the work of Nakazawa (1986), using additional data and analysis techniques.

2. Data

Best estimates of the centers of tropical disturbances, depressions, storms, and typhoons / hurricanes at six hour intervals are provided by the Joint Typhoon Warning Center at Guam, and archived by the National Climatic Data Center. We include reports from 1979-1989, from 60°E to the dateline, in this study. Disturbances, which are identified mainly by satellite techniques (Dvorak 1975), are defined as regions of organized convection with diameter of 200-600 km and having a non-frontal migrating character. As their identification is highly subjective and they are only sporadically included in the archived data set, we do not include them in this study. Depressions are weak cyclones with a definite closed circulation and with highest sustained winds of less than 17 ms^{-1} . They too are routinely identified by satellite techniques, but the requirement of a closed circulation allows for a more definitive identification than for disturbances (*e.g.*, Elsberry 1987). Storms

Fig. 2. (a) Spatial distribution of variance of OLR in 35-95 day band, converted to brightness temperature. Contours start at 7.5 K², with an interval of 7.5 K². Statistically significant areas, defined as gridpoints where average variance in 35-95 day band exceeds the average of the 18 contiguous frequencies in each of the two adjacent bands (periods of 23-35 days and 95-163 days), are striped. (b) Dots represent all six-hourly cyclone reports of depression strength and greater from 1979-1989.

are defined as cyclones with winds from 17 ms⁻¹ to 32 ms⁻¹. Typhoons / hurricanes are cyclones with winds in excess of 32 ms⁻¹.

Depending on the availability of reconnaissance aircraft, errors as large as 50 km can occur in the estimates of cyclone centers, with the largest errors generally occurring in the weakest cyclones (Elsberry 1987). These possible errors are not deemed a problem to the present study, however, because we are concentrating on the modulation of cyclones by planetary scales.

Large-scale convection and circulation are defined through the use of daily averaged outgoing longwave radiation (OLR) and gridded wind analyses. Winds from 1980-1989 are obtained from the European Centre for Medium Range Forecasting.

3. Results

a. The MJO-Tropical Cyclone Association

The modulation of cyclone activity by the MJO is first explored by binning cyclones according to phase of convection of the oscillation. The signal of the MJO in convection at the equator is in eastward zonal wavenumbers 1-3 with periods between 35-95

days (Salby and Hendon 1994). The signal has a strong annual cycle and peaks between 5° and 15° latitude of the summer hemisphere (Fig. 1; Hendon and Liebmann 1994). That tropical cyclones are also most prevalent at the same latitude and time of year (*e.g.*, Gray 1977) suggests that there may be a connection between them and the MJO.

All subsequent analyses are based on data which are bandpass filtered to 35-95 days. Note that this range of frequencies, defined according to the signal in convection, is much broader than that in the dynamical fields (*e.g.*, Madden and Julian 1971, Salby and Hendon 1994).

The spatial distribution of 35-95 day power in convection is shown in Fig. 2a. Statistically significant power (see caption) is evident in the tropical Eastern Hemisphere, with peaks over the eastern Indian Ocean and near the dateline. A rough correspondence between the location of climatological mean cyclone activity (Fig. 2b) and statistically significant 35-95 day power is apparent, although in regions where there is large 35-95 day power there is inevitably an increase of power in every other frequency band as well (Salby and Hendon 1994,

Fig. 3. (a) Number of first reports of depressions, storms, and typhoons that occur per 100 days of activity at the longitude of the report. Left-most column of each pair represents convective phase of OLR, 200 mb divergence, and 1000 mb convergence. OLR and divergence have been averaged between 9.5°N and 14.5°N and filtered with a 35–95 day bandpass filter. Cyclone reports are included if they lie between 7°N and 17°N, and between the longitudes of 60°E and 180°. (b) As in (a), except quantities are centered at 12°S.

Fig. 4. As in Fig. 3, except that quantity shown is ratio of storms to depressions at 12°N and 12°S.

(a) 850 MB VORTICITY COMPOSITED FROM BAND-PASS OLR

Fig. 5. Composite vorticity anomaly based on 35–95 day band-pass OLR anomalies between 60°E and 180° that have been rotated to a relative longitude of 0° at (a) 12°N and (b) 12°S (see text). Positive relative vorticity anomalies are thick in (a) and negative anomalies thick in (b). The contour interval is $5 \times 10^{-7} \text{ s}^{-1}$ with contours starting at $\pm 5 \times 10^{-7} \text{ s}^{-1}$. The vorticity fields have been band-pass filtered to include periods from 35–95 days and spatially truncated at T12. Shading represents composited filtered OLR anomalies of more than 7 W m^{-2} . Asterisks represent reports of tropical disturbances of depression strength and greater, plotted relative to the OLR anomaly. The total number of cyclone reports in each 45° octant is written above each figure.

Hendon and Liebmann 1994). This coincidence suggests the possibility that tropical cyclone activity may indeed be related in some manner to the MJO, although the coincidence may also be due to the importance of warm sea surface temperatures (SSTs) for both the MJO and cyclone activity (*e.g.*, Gray 1968).

The modulation of cyclone activity by the MJO is

examined by binning the first occurrence of cyclones according to the phase of the MJO. The phase of the MJO was deduced by calculating filtered OLR anomalies averaged between 9.5° and 14.5° latitude in each hemisphere for the domain 60°E to 180°. Each first report of depression, storm, and typhoon between 7° and 17° latitude was then binned according to the phase of the OLR anomaly at that lon-

gitude. The first pairs of columns of Fig. 3a and 3b show cyclone reports binned by the phase of band-pass filtered OLR at 12°N and 12°S. Nearly twice as many reports occur in each category during the wet (negative OLR anomaly) phase of the MJO as during the dry phase in each hemisphere.

The second and third sets of columns are like the first except that now the cyclone reports are segregated on the basis of band-pass filtered divergence anomalies at 200 mb and 1000 mb (and 1979 is not included). These results are consistent with the results based on OLR; 200 mb divergence and 1000 mb convergence are both associated with increased cyclone activity. There is sufficient sample population that the difference of the means is statistically significant.

It is evident from Fig. 3 that nearly the same ratios of storms to depressions occur during the wet as during the dry phase, though many more depressions occur during the wet phase. This point is further emphasized in Figs. 4, in which the number of first storm reports of Fig. 3 are divided by the depression reports in that column. The ratio of storms to depressions is about the same during the wet and dry phases, suggesting that the reason more storms are reported during the wet phase is simply that more depressions are spawned. The same percentage of depressions become storms during either phase. The ratio of typhoons to depressions (not shown) varies somewhat more between quantities than does the storms to depressions ratio, presumably due to the small sample size of typhoons.

To give a physical basis for understanding the enhancement of tropical cyclone activity during times of active MJO convection, we construct composites of circulation anomalies and cyclone activity based on minima in filtered OLR. The minima in OLR are determined by averaging OLR within 2° of a given latitude. Then a longitude-time Hovmöller diagram is constructed at that latitude. From that we pick out all minima from 60°E to 180° that are the largest to occur within ± 5 days in time and $\pm 30^\circ$ of longitude. If the average OLR anomaly within that 10 day by 60° box is less than -15 Wm^{-2} , we rotate the peak to 0° relative longitude and composite all circulation fields and cyclone reports relative to that. This somewhat elaborate compositing procedure is designed to ensure that we capture only truly large-scale convective anomalies.

Figure 5 shows filtered 850 mb relative vorticity and OLR anomalies (which have been truncated at T12 prior to plotting) composited against OLR anomalies at 12°N and 12°S. The composite vorticity and OLR fields are consistent with the results of Hendon and Liebmann (1994), who used a wavenumber filter as well. In particular, a cyclonic circulation anomaly is evident westward and poleward of the convection anomaly. Enhanced low-level vorticity is also con-

sistent with the modeled linear response of a quiescent atmosphere to a heat source placed off the equator (Gill 1980 - his Fig. 3). In each hemisphere this vorticity anomaly augments the planetary vorticity at 20° latitude by about 5 percent, although in the individual events that make up the composite the vorticity anomaly is undoubtedly larger than in the composite itself due to phase shifting relative to the OLR anomaly. The striping indicates composited negative OLR anomalies.

Figure 5 also contains each cyclone report of depression strength and greater. These reports are observed to cluster around the low-level vorticity anomaly. In fact, for the Northern Hemisphere composite (Fig. 5a), nearly as many reports occur from 0° to 45° west of the OLR anomaly as in the other 7 octants combined. In the Southern Hemisphere, nearly 45% of the reports occur in the first octant west of the OLR anomaly.

The 1000 mb divergence composites (Fig. 6) also agree well with the large-scale composites made by Hendon and Liebmann (1994). Surface convergence anomalies more or less coincide with enhanced cyclonic vorticity. This coincidence has been attributed to frictional effects at the surface (Hendon and Salby 1994, Hendon and Liebmann 1994). Fig. 6 also includes each report of storm strength and greater.

Figure 7 is a composite of 200 mb divergence and each report of typhoon strength, again based on OLR. The divergence center at 200 mb is nearly twice as strong as the convergence at 1000 mb and, like the 1000 mb composite, is located slightly poleward and west of the OLR base grid point.

This clustering of cyclones around increased low-level relative vorticity is entirely consistent with the results of Gray (1979), who found that if all other factors are equal, cyclogenesis is preferred in regions of enhanced climatological low-level vorticity. Again, the hypothesis of this study is that the slowly varying anomalies associated with the MJO have sufficiently long time scales compared to the life-cycle of a tropical cyclone such that their effect on the cyclone is the same as if it were a favorable climatological base state. Apparently, even though the low-level vorticity is increased by less than 10% due to the presence of the wet phase of an MJO, this small increase is enough to statistically favor tropical cyclogenesis.

b. Other Frequencies

In order to determine whether the 35-95 day band is unique in its relationship to tropical cyclones, we also examined the 18-27 day band. We chose this band because it is of high enough frequency to be independent of the 35-90 day band where the MJO signal is concentrated (Salby and Hendon 1994), yet of low-enough frequency to be longer than the life-

1000 MB DIVERGENCE COMPOSITED FROM BAND-PASS OLR

Fig. 6. As in Fig. 5, except that the composited field is 1000 mb divergence. The contours start at $\pm 4 \times 10^{-7} \text{ s}^{-1}$, with an interval of $2 \times 10^{-7} \text{ s}^{-1}$. Thick contours denote convergence. Asterisks represent reports of storm strength and greater.

cycle of a tropical cyclone. There is little evidence of a spectral peak in OLR at this range of frequencies (*e.g.*, Lau and Chan 1988, their Fig. 1), and composites based on OLR filtered at 18–27 days (not shown) show no coherent signal. Hartmann et al. (1992), however, found evidence of a 20–25 day peak in surface pressure and 850 mb wind during Northern Hemisphere fall at certain stations located in the western Pacific north of the equator.

Cyclones were composited by the same method in Fig. 8 as they were in Fig. 3 for OLR. The difference

is that in Fig. 8 results are shown for the two frequency bands, and all (not just first) cyclone reports are included. The first pairs of columns are similar to Fig. 3 for OLR at 12°N and 12°S. The middle pairs of columns show the result of the same technique applied to the 18–27 day band. The increase during the wet phases of the 18–27 day band is about the same as it is during the wet phases of the MJO. Thus the relationship between the MJO and tropical cyclogenesis appears to be no stronger than in a completely independent frequency band with no significant spec-

Fig. 7. As in Fig. 6, except that the composited field is 200 mb divergence. Asterisks represent reports of typhoon strength and greater.

tral peak.

The rightmost columns of Fig. 8 were constructed using the same technique as before, but with a band-pass filter that extends from 18-95 days. The differences in cyclone activity between the wet and dry phases of this extremely wide band-pass filtered data are even more pronounced than they are within the two frequency bands that contribute to it. This point is further illustrated in Fig. 9, which shows cyclone reports binned according to whether the 35-95 day band and the 18-27 day band are both in their wet phases, one is wet and the other dry, or both bands

are in their dry phase. Cyclones clearly prefer times of enhanced 18-27 and 35-95 day convection to times when convection is depressed in both bands. About the same number of cyclones occur when one band is positive and the other negative as in the reverse case, consistent with Fig. 8.

That cyclones seem to have no preference for the period of slowly varying convection perhaps is not surprising, as the period of environmental influence should not matter as long as it is much longer than the period of the cyclone. It is surprising, however, that even though there is more power in the 35-95

Fig. 8. As in Fig. 3, except all cyclone reports are counted, and the pairs of columns are the number of cyclones per 100 days of activity for the convective and dry phases of OLR with periods from 35-95 days at 12°N, 12°S, 18-27 days at 12°N, 12°S, and 18-95 days at 12°N, 12°S.

Fig. 9. Count of depressions, storms, and typhoons as in Fig. 3, except that first four columns include times when both 35-95 day and 18-27 day OLR is convective, 35-95 day convective and 18-27 day dry, 35-95 day dry and 18-27 day convective, and both frequency bands dry. Second four columns are like first four, except at 12°S.

day band than in the 18-27 day band, and therefore one would expect stronger convection and subsidence associated with the former than with the later, as

many cyclones (per day) occur during the wet phase of the 18-27 day band and dry phase of the 35-95 day band as during the reverse situation.

4. Summary and conclusions

The hypothesis of this study is that large-scale, slowly-varying circulation anomalies can affect the climatological base state such that conditions are more favorable at certain times than at others for the development of tropical cyclones. The MJO is an obvious candidate by which to test this hypothesis because it is associated with planetary scale convection and circulation anomalies. We demonstrate that the MJO does indeed influence the development of tropical cyclones. We find that depressions, storms, and typhoons preferentially develop during the wet phase of the oscillation. Development seems to be related to the large-scale low-level cyclonic relative vorticity and convergence anomalies that develop westward and poleward of the anomalous MJO convection. Although we feel that this association is an interesting result, its application to long-range forecasting, at least presently, would appear to be extremely limited; the results presented are from data that were heavily filtered in both time and space, and they are composite analyses. Additionally, the phase of the MJO is not a well-forecast quantity (e.g., Storch and Xu 1990).

We also find that the ratio of storms per depression is preserved in both the wet and dry phases, indicating that a depression is no more likely to deepen into a typhoon during the wet phase than during the dry phase; there are simply more depressions that develop during the wet phase. This result concurs with the results of Hendon and Liebmann (1994), who found that the shape of the OLR power spectrum between 2 and 15 days is nearly identical for dry and wet phases but that twice as much variance occurs in the wet as in the dry phase.

The third finding of this study is that other frequency bands (with periods longer than the life cycle of a tropical cyclone) exhibit the same ratio of depressions during the wet phase to those during the dry phase as does the 35–95 day band. Thus, although there is more power in the 35–95 day band (the MJO) than in adjacent bands, and that power stands out above the background as a statistically significant signal, this enhanced power does not appear to increase cyclogenesis more than the less active low-frequency bands.

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西太平洋及びインド洋における熱帯低気圧とMadden-Julian振動との関連

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当論文においては、西太平洋及びインド洋における熱帯低気圧とMadden-Julian振動(MJO)との関連を記述する。熱帯低気圧は振動の積雲対流活動活発期に生じ易いし、雲塊は下層の低気圧性渦度の周辺に存在し、発散場はMJOに伴う積雲対流活動の西方極側に現れる。

熱帯低気圧や台風の絶対数は振動の積雲対流活動活発期に増大するが、弱い熱帯低気圧から転化する熱帯低気圧と台風の比率は、積雲対流活動活発期と乾燥期において同一である。積雲対流活動活発期においてより多くの熱帯低気圧や台風が存在するのは、当時期により多くの弱い熱帯低気圧が存在することによる。

当研究の第三の結果は、積雲対流活動活発期の熱帯低気圧の活動度がMJOの活動度に限定されていない点である。事実、我々はMJOと独立かつ無作為に選ばれた積雲対流活動活発期において熱帯低気圧の活動度が同等に増大することを見いだした。結論として、MJOは熱帯低気圧に影響を及ぼす独自の機構を持つと言うより、むしろそれに伴う熱帯の変動度が大きな割合を占めるという点で重要である。