3D.2 TEMPORAL CLUSTERING OF TROPICAL CYCLONE OCCURRENCE ON INTRASEASONAL TIME SCALES

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1. INTRODUCTION

Over the global tropics, the Madden-Julian Oscillation (Madden and Julian 1994, MJO) explains a significant amount of the variability in circulation and convection on intraseasonal time scales. However, significant variation exists in the spatial extent and seasonal occurrence of the MJO. While the upper-level divergent flow associated with MJO is often traced around the globe, the low-level wind circulations and regions of enhanced and reduced deep convection have maximum amplitudes over the Indian and Pacific Oceans. Furthermore, the MJO appears to be stronger during the Northern Hemisphere winter.

Over each tropical ocean basin in which tropical cyclones form, the potential for tropical cyclone formation has been linked to several dynamic and thermodynamic conditions. Many of the characteristics associated with the MJO are similar to the dynamic and thermodynamic factors that govern the potential for tropical cyclone formation. Therefore, several studies have examined the physical relationship between the MJO and tropical cyclone activity over the Southern Indian and Pacific Oceans (Hall et al. 2001), the western North Pacific (Liebmann et al. 1994), the eastern North Pacific (Maloney and Hartmann 2001) and the Atlantic Ocean (Mo 2000). Statistically, Hall et al. (2001) illustrated that there was a significant increase (decrease) in the probability of a tropical cyclone occurrence relative to a climatological value in the South Indian Ocean and South Pacific Ocean when the enhanced (reduced) convection phase of the MJO propagated through the region of the Australian monsoon trough.

While the MJO may impact the daily probability of tropical cyclone formation, there has not been a strict statistical examination of temporal variability as it relates to clustering of tropical cyclone activity in time due to the quasi-periodic nature of the MJO. In this context, a cluster is defined as a temporally bound group of tropical cyclone occurrences of sufficient size and concentration to be unlikely to have occurred by chance. Furthermore, the cluster of tropical cyclone activity is defined such that the individual occurrences in the cluster are related through a common physical mechanism (i.e., the MJO).

The study of Hall et al. (2001) was based on a count of tropical cyclone formations on days associated with each phase of the MJO. The hypothesis test for a significant change in probability of formation due to the MJO was examined using a normal approximation to the binomial distribution for the count of tropical cyclone formations. To examine temporal clustering, a Bernoulli random variable is used to identify all days when a tropical cyclone formed. For each tropical cyclone season, a uniform multinomial probability distribution is estimated in which the distribution parameter is defined as the relative frequency of formation for that year. A cluster index (Tango 1984, 1990) is based on a measure of the temporal interval between each formation. The significance of the index is based on the degree of departure from the underlying uniform multinomial distribution. The procedure is applied to examine the clustering of tropical cyclone occurrences during 1979-2004 over several ocean basins during each basin's tropical cyclone season. This clustering algorithm was chosen as it is capable of examining the cyclic occurrence of a phenomenon and is associated in an asymptotic sense to the chi-square distribution such that a level of significance may be identified.

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2. METHOD

Tango (1984) defined an index for identification of the temporal clustering, which is applicable to data grouped into equally-spaced intervals. Furthermore, the index is applicable to both temporal and cyclic clustering. The index is defined by specifying a vector, $\mathbf{f}=(N_1,N_2,\ldots,N_m)$, of the observed frequencies of tropical cyclone occurrence in m equal time intervals, which is defined as a day. The total frequency, $N=\Sigma N_i$ is used to convert the vector **f** to a vector of relative frequencies, **r**. A matrix, $\mathbf{A} = (a_{ij})$, $i,j = 1,2,\ldots,m$ is defined to be a matrix of the closeness between the *i*th and *j*th time interval. The matrix is constructed such that $a_{ii}=1$ and a_{ij} is a monotonically non increasing function of d_{ij}, which is the temporal distance between the *i*th and jth interval. For the detection of cyclical clustering with cycle length *m*, $d_{ij}=\min\{|i-j|, m-|i-j|\}$. The index for the level of clustering in time is defined as $C=\mathbf{r'Ar}$. Tango (1990) analyzed the index further to suggest that the distribution of the index is approximately chi-square for a moderately large sample size. This allows assessment of the statistical significance of the cluster index.

In this study, the index was computed for tropical cyclone occurrence between 1 May and 31 October over the western North Pacific. The index was computed for cycle lengths that varied from 1 day to 60 days. Therefore, it is hypothesized that temporal clustering associated with the MJO would be defined by significant cluster indices in the cycle range of 30-60 days.

The MJO characteristics during this period are defined by the index of Wheeler and Hendon (2004) at http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/.RMM/index.htm. For each May-October period, the percent of days that occur in an MJO cycle as defined by the MJO index is computed (Fig. 1). If 1979 is excluded, the mean percentage is 35.9% with a standard deviation of 9.9. Therefore, if a May-October period contained more than 46% of the days in a MJO cycle, the season was defined as an MJO season. The 10 years, of 1979, 1981, 1986, 1987, 1991, 1996, 2000, 2001, 2002, and 2004 were classified as MJO years.

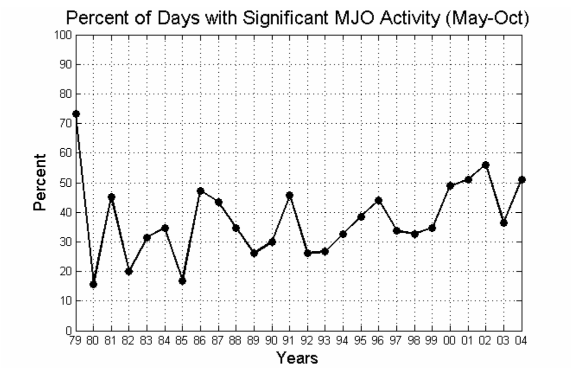

Fig. 1 *Percent of days between 1 May-31 October that are contained in a MJO cycle based on the index of Wheeler and Hendon (2004).*

3. RESULTS

Based on the cluster methodology and MJO classifications, each year was examined for significant clustering in the 30-60 day period and MJO classification (Table 1). Eight of the 26 years contained significant temporal clustering of tropical cyclone activity over the period range of 30-60 days (Figs. 2 and 3). Five (three) of the eight years with temporal clusters were (not) MJO years. Furthermore, five of the ten MJO years did not contain significant temporal clustering (Figs 4 and 5).

Cluster and MJO	79, 81, 86, 87, 91
Cluster and No MJO	90, 92, 93
No Cluster and MJO	96, 00, 01, 02, 04
No Cluster and No MJO	80, 82, 83, 84, 85, 88, 89, 94, 95, 97, 98, 99, 03

Table 1 *Classification of years based on the results of the temporal cluster analysis and MJO classification.*

To compare with previous studies (e.g., Hall et al. 2001) of the impact on the probability of tropical cyclone formation due to the MJO, the probabilities over the western North Pacific due to the MJO are examined for all years (Table 2), years with temporal clusters during MJO years (Table 3), years with temporal clusters in non-MJO years, years without temporal clusters during MJO years (Table 4), and years without temporal clusters in non-MJO years. The methodology is the same as applied in Hall et al. 2001. The null hypothesis is that the probability of tropical cyclone

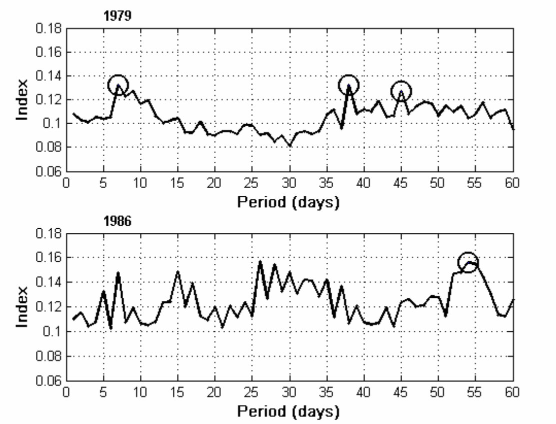

Fig. 2 *Temporal cluster index for the MJO years of (top) 1979 and (bottom) 1986, which also exhibited significant clustering in the 30-60 day period. Index values that are circled represent significant clustering at a .05 level.*

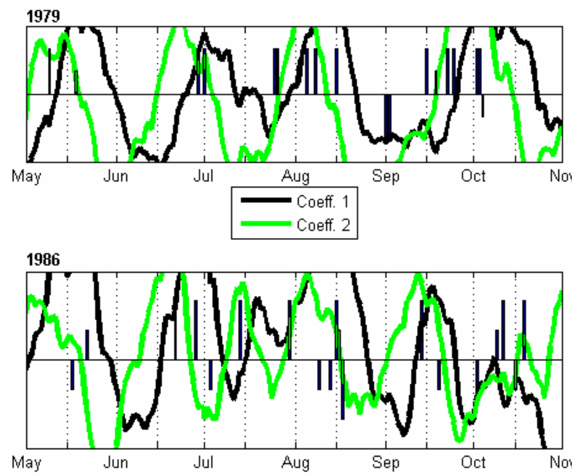

Fig.3 *The two coefficients that define the MJO index during (top) 1979, and (bottom) 1986. The vertical bars represent days on which a tropical cyclone formed south of 20°N (upward-pointing bar), and north of 20°N (downward-pointing bar).*

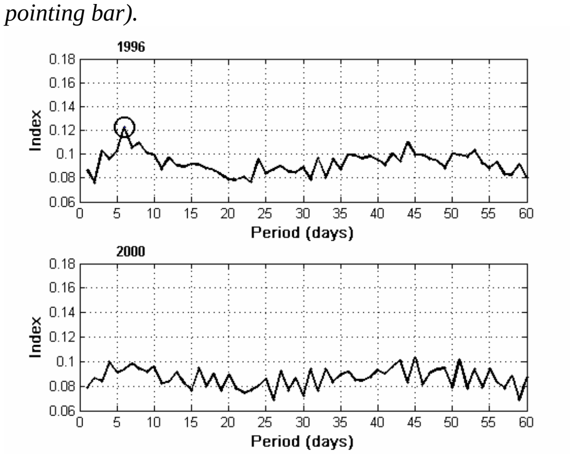

Fig. 4 *As in Fig. 2, except for (top) 1996, and (bottom) 2000, which were MJO years with no significant temporal clustering of tropical cyclone activity.*

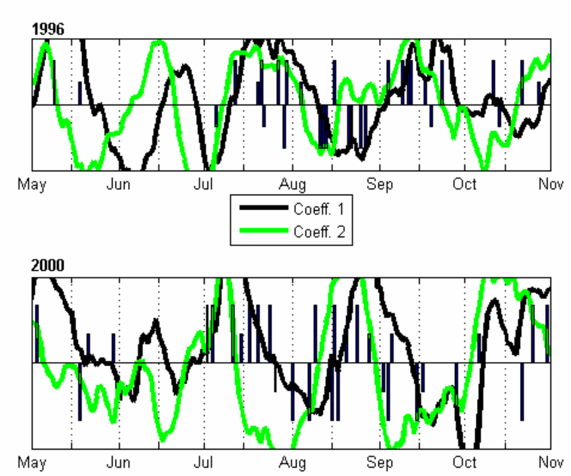

Fig. 5 *As in Fig. 3, except for (top) 1996, and (bottom) 2000, which were MJO years with no significant temporal clustering of tropical cyclone activity.*

formation is uniformly distributed and the alternative hypothesis is that the MJO alters the probability. A two-tailed test is applied to examine reduction in probability associated with the reduced-convective phases of the MJO and an increase in probability associated with the enhanced-phases of the MJO.

For all days (Table 2), results indicate that the inactive convection portion of the MJO is effective in producing temporal clusters via forcing of periods of anomalous low tropical cyclone activity while increased tropical cyclone activity occurs in the active convective phase 6.

MJO Category	Days	%	TCs	%	Significance
1	276	5.8	21	7.6	*
2	245	5.1	18	7.3	*
3	147	3.1	4	2.7	*
4	167	3.5	24	14.4	
5	272	5.7	41	15.1	
6	257	5.4	58	22.6	*
7	186	3.9	27	14.5	
8	248	5.2	31	12.5	
0	3986	83.3	404	13.5	
Total	4784	100	628	13.0	

Table 2 *Summary of tropical cyclone formations over the western North Pacific within each MJO category. An asterisk in the significance column indicates that the tropical cyclone numbers were significantly below or above average at the .05 level.*

During MJO years that exhibit temporal clustering (Table 3), the pattern is similar in that there is a statistically significant reduction in the probability of tropical cyclone activity during the inactive convective phases and an increase in the probability during the active convective phase. However, during MJO years that do not exhibit temporal clustering (Table 4), there is not a significant reduction in probability during the inactive convective phase of the MJO. There are more tropical cyclones that formed during MJO phases 1,2,3, and 8 than would be expected during a reduced convective phase of the MJO Therefore, the inactive convective phase of the MJO did not prohibit tropical cyclones from forming. This is attributed to the fact that there are many factors that contribute to the formation of tropical cyclones over the western North Pacific. Although the MJO may have been in an inactive phase, other factors must have overridden the MJO signal, which failed to result in a significant decrease in tropical cyclone activity.

MJO Category	Days	%	TCs	%	Significance
1	71	7.7	2	2.8	*
2	70	7.6	5	7.1	
3	53	5.8	4	7.6	
4	34	3.7	5	14.7	
5	83	9.0	13	15.7	
6	62	6.7	12	19.2	*
7	53	5.8	8	15.1	
8	43	4.7	0	0.0	*
0	451	49.0	51	11.3	
Total	920	100	100	10.9	

Table 3 *As in Table 2, except for MJO years that exhibited temporal clustering (1979, 1981, 1986, 1987, 1991).*

MJO Category	Days	%	TCs	%	Significance
1	60	6.5	6	10.0	
2	61	6,5	6	9.8	
3	34	3.7	2	5.9	
4	27	2.9	4	14.9	
5	65	7.1	12	18.5	
6	85	9.2	18	21.2	*
7	57	6.2	8	14.0	
8	73	7.9	13	17.8	
0	458	48.8	66	14.4	
Total	920	100	135	14.7	

Table 4*, As in Table 2, except for MJO years that did not exhibit temporal clustering (1996, 2000, 2001, 2002, 2004).*

The results associated with temporal clustering of tropical cyclone activity and the MJO over the western North Pacific are to be compared with similar analyses for other basins. Since the eastern North Pacific and North Atlantic are not as strongly dominated by monsoon conditions, those basins may be more influenced by the MJO to induce temporal clustering. While the Australian monsoon exhibits strong control over tropical cyclone formation in the Southern Hemisphere, the MJO signal is typically much stronger during the Southern Hemisphere summer. Therefore, the inactive phase of the MJO may be able to contribute significantly to a reduction in tropical cyclone activity.

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