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THE INFLUENCE OF THE MADDEN AND JULIAN OSCILLATION ON OCEAN SURFACE HEAT FLUXES AND VERY HIGH SEA SURFACE TEMPERATURE VARIABILITY IN THE WARM POOL REGION

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1. INTRODUCTION

On intraseasonal time scales (30-60 days), the Madden and Julian Oscillation (MJO) is the primary mode of low-frequency variability in the tropical atmosphere (Madden and Julian, 1994). The MJO manifests itself as a slow eastward propagation of atmospheric disturbances with maximum amplitudes in the eastern hemisphere (Hendon and Salby, 1994, hereafter HS94). Since its discovery by Madden and Julian (1971) over two decades ago, the MJO has continued to be a topic of significant interest due to the wide range of phenomena it interacts with.

In addition to involving pronounced variations in the upper and lower troposphere, the MJO signature is also detected near the surface and in the upper ocean (Kessler et al. 1995; Jones and Weare, 1996; and references therein). Indeed, since the MJO is characterized by time scales long enough to interact with the upper ocean, the MJO has been found to be strongly linked to sea surface temperature (SST) variations in the Indian and Pacific Oceans. Although the previous studies have provided some insight on the atmosphere-ocean coupling on intraseasonal time scales, our knowledge of how the MJO modifies SST in the Indian and Pacific Oceans, how it may be related to the onset of El Niño, and how SST variations feedback into the oscillation is still very incomplete.

The objective of this study, which summarizes the results described in Jones et al. (1996), is to examine the following question: what are the observed spatial patterns of surface heat fluxes anomalies and SST during the life cycle of the MJO? Although this topic has been sparsely addressed in previous observational studies (see Jones and Weare, 1996), our aim is to provide an integrated view of the modifications that occur in the surface heat fluxes and SST during the life cycle of the MJO. This is done using two types of observational analyses. The first is a statistical description of the time-lagged covariability between the phase of the MJO, the surface heat flux and the SST. The second is an analysis of the relationship between the MJO and specific SST events, in this case, the occurrence and decay of large-scale regions of very high SST.

2. DATA

In this study, we use the outgoing longwave radiation (OLR) data set which has been frequently used as a proxy for large-scale tropical convective activity (Waliser et al., 1993). In order to filter high-frequency variations, pentads are applied to the OLR, as well as all subsequently discussed fields.

The surface energy balance over the ocean's surface is largely determined by variations in the surface fluxes of net shortwave radiation and latent heat. The net surface shortwave radiation flux (SW) is obtained from the method developed by Gautier and Landsfeld (1996), which uses input parameters derived from the International Satellite Cloud Climatology Project (ISCCP) (Rossow et al., 1991). Pentads of SW with spatial resolution of 2.5˚x2.5˚ latitude/longitude are derived for the period 1-5 January 1985 through 26-30 April 1991 (total of 462 pentads), constrained in length by the availability of ISCCP data.

Surface latent heat flux (E) is estimated with European Centre for Medium-Range Weather Forecast (ECMWF) surface analyses, which provide surface pressure (Ps), surface wind speeds (Vs) at 10 m height, sea surface temperature (SST), air temperature (Ta), and dew point temperature (Td) at 2 m height. Daily averages of E are derived from the bulk formula and the similarity theory model developed by Liu et al. (1979) with input parameters Ps, Vs, SST, Ta, and Td. Pentads of E are then computed for the period 1-5 January 1985 through 26-31 December 1994 (total of 730 pentads). The estimation of E with ECMWF surface analyses has been shown to exhibit significant spectral variations on 30-60 days and be consistent with variations in the large-scale circulation associated with the MJO (Jones and Weare, 1996, hereafter JW96). The surface energy balance is approximated by $Q = SW - E$. Since the available data for SW and E do not completely overlap in time, pentads of Q for the period 1-5 January 1985 through 26-30 April 1991 (total of 462 pentads) are used. Intraseasonal variations in SST are investigated using the ECMWF SST analysis. Pentads from 1-5 January 1985 through 26-31 1994 (total of 730 pentads) are used.

3. RESULTS

3.1 Surface heat flux variations during the MJO life cycle

In order to resolve low-frequency variations associated with the MJO, time filtering is first applied to the fields of OLR, SW, E, Q, SST, and d(SST)/dt for the

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period 1-5 January 1985 through 26-30 April 1991 (total of 462 pentads). Since the atmospheric (40-50 days) and the oceanic (60-75 days) intraseasonal oscillations are offset, anomalous fields are obtained by applying a band-pass Lanczos filter with frequency response of 0.5 at 0.2 pentads^{-1} (25 days) and 0.0385 pentad^{-1} (130 days), which therefore adequately captures both oscillations.

Following the practice of many previous studies (HS94, JW96), we describe the processes of interest, in our case the variability of the anomalous surface heat fluxes and SST, in relation to the life cycle of convective (i.e., OLR) anomalies. To this end, we specify a site in the Indian Ocean (5˚ S-5˚ N; 80˚ E-90˚ E) from which the OLR reference time series is taken (hereafter OLRRTS). This reference site coincides with the one used by HS94, and it has been noted to exhibit the largest OLR signal associated with the MJO. The spatial and temporal evolution of the MJO is then investigated by computing lag correlation patterns between the reference time series and the anomalous fields (OLR, SW, E, Q, SST). For convenience, we employ the same time lags used in the composite study of HS94, and hence our results can complement that study and provide an integrated view of the variations in convection, tropospheric large-scale circulation, surface heat fluxes and SST during the life cycle of the MJO.

The eastward propagation of OLR anomalies over the Indian and western Pacific (not shown) is in good agreement with HS94, despite differences in the time period analyzed and methodology. As discussed above, the MJO involves pronounced variations in convection and large-scale circulation which significantly modify the surface net shortwave radiation and latent heat fluxes. These variations on the other hand strongly affect the difference between SW and E, an estimate for the surface energy balance, as it is shown in the lag correlation patterns between OLRRTS and Q anomalies (Fig. 1). Regions of positive correlations indicate that enhanced convection in the reference site (negative OLR anomalies) is correlated with decreased surface heat fluxes (negative Q anomalies). To the east of the region of enhanced convection, positive Q anomalies are observed, which result from increased net surface shortwave radiation (positive SW anomalies) and decreased surface latent heat fluxes (negative E anomalies). In contrast, in the vicinity of the region of enhanced convection, negative Q anomalies are seen, which arise from reduced net shortwave radiation (negative SW anomalies) and increased surface latent heat fluxes (positive E anomalies). We have determined the time between independent samples to be approximately 6 pentads. Thus, correlations larger (smaller) than +0.23 (-0.23) are significant at 95% level based on local t-test with 69 degrees of freedom (414 pentads / 6 pentads).

The phase relationships between convection, surface heat fluxes and SST is further investigated by computing lag correlations between time series along the equator. Since the cloud field strongly modifies the shortwave radiation transfer in the atmosphere, OLR and SW time series anomalies along the equator show an in-phase relationship (not shown). In contrast, as discussed above and in more detail in JW96, surface latent heat fluxes increase after the eastward movement of convective anomalies due to the increase in westerly wind anomalies.

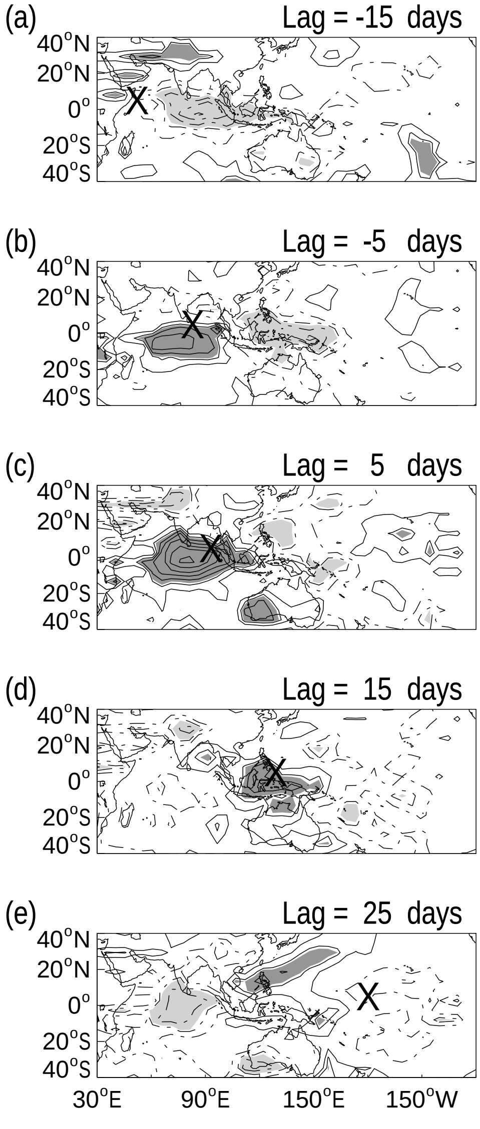

Figure 1. Lag correlation patterns between OLR reference time series (OLRRTS) in the Indian Ocean (5˚ S-5˚ N; 80˚ E-90˚ E) and Q anomalies. Time lag starts at -15 days and the interval is 10 days. Solid (dashed-dotted) contours denote positive (negative) correlations starting at 0.1 (-0.1) and the interval is 0.1. Positive (negative) correlations indicate that convection (subsidence) is associated with negative (positive) Q anomalies. Heavy (light) shaded regions indicate correlations greater (less) than 0.23 (-0.23) and are significant at 95% significance level based on local t-test. The propagation of convective anomalies along the equator is indicated by "X", and has been determined by lag correlations between OLRRTS and OLR anomalies.

Therefore, lag correlations between OLR and E anomalies (not shown) indicate that E lags OLR by one pentad (4 days in JW96). To gain additional insight on the interaction between convection, SST and surface heat fluxes, Fig. 2 shows lag correlations of time series averaged from 5° S to 5° N for every longitude along the Indian and Pacific equatorial regions. As in the lag correlation patterns, the statistical significance is based on a local t-test based on 69 degrees of freedom. Figure 2a shows lag correlations between OLR and SST anomalies such that negative lag correlations imply that positive SST anomalies lead variations in convection. Statistically significant correlations demonstrate that SST leads variations in convection along the entire domain. However, it is interesting to note that correlations are higher in the Indian Ocean than in the western Pacific, and there is also a slight east to west tilt towards increasing negative lags. In the Indian Ocean, SST leads convection by one pentad, while SST leads OLR by two and three pentads in the western and central Pacific, respectively, consistent with other studies (see discussion in Jones et al., 1996).

Lag correlations between OLR and d(SST)/dt anomalies along the equator are shown in Fig. 2b, and negative lag correlations reveal that d(SST)/dt lead variations in convection. Positive anomalies of d(SST)/dt, i.e. warming trend, lead variations in convection by three to four pentads in the Indian and Pacific Ocean as is indicated by the negative lag correlations. It is worth noting however that the lag correlations are higher for positive lags of one to two pentads than negative lags. This indicates the strong effect that subsidence (positive OLR anomalies) has on warming (positive d(SST)/dt anomalies) of the upper ocean. The temporal relationship between surface heat fluxes and d(SST)/dt is shown in Fig. 2c, which shows lag correlations between Q and d(SST)/dt anomalies. Positive lag correlations indicate that Q leads d(SST)/dt variations. Significant and high correlations at approximately one pentad are observed at all longitudes, and demonstrate that surface heating (positive Q anomalies) leads warm SST trend in the upper ocean (positive d(SST)/dt anomalies).

3.2. WESTERN PACIFIC HOT SPOTS AND MJO ACTIVITY

In the previous section, the analysis between MJO and SST variability were examined in terms of the MJO cycle. Characteristics of the other fields, e.g. SST, were then analyzed with respect to the phases of this cycle. In this section, we would like to focus and build the analysis upon an SST feature, and then examine the characteristics of the MJO associated with the different phases of this SST feature. The specific SST feature we would like to use for examination are the occurrences of large-scale regions of very high SST. If a relationship between these features and the MJO is found, this will provide further evidence of the important interaction between the MJO and variability in tropical SST.

In a previous study, Waliser (1996) (hereafter W96) investigated the formation and decay of ocean "hot spots" in the western Pacific in an effort to understand the limiting/regulating mechanisms of high SST. Ocean hot spots were defined as self-contained regions with SST equal or greater than 29.75° C and an area larger than 1.0 x 10^6 km^2. In order to characterize these regions of high SST, we apply the same algorithm used by W96 to unfiltered pentads of SST for the period January 1985 through December 1994 (730 pentads). Each identified hot spot is characterized by its pentad of occurrence, SST-weighted mean latitude/longitude, spatial area, and mean SST value.

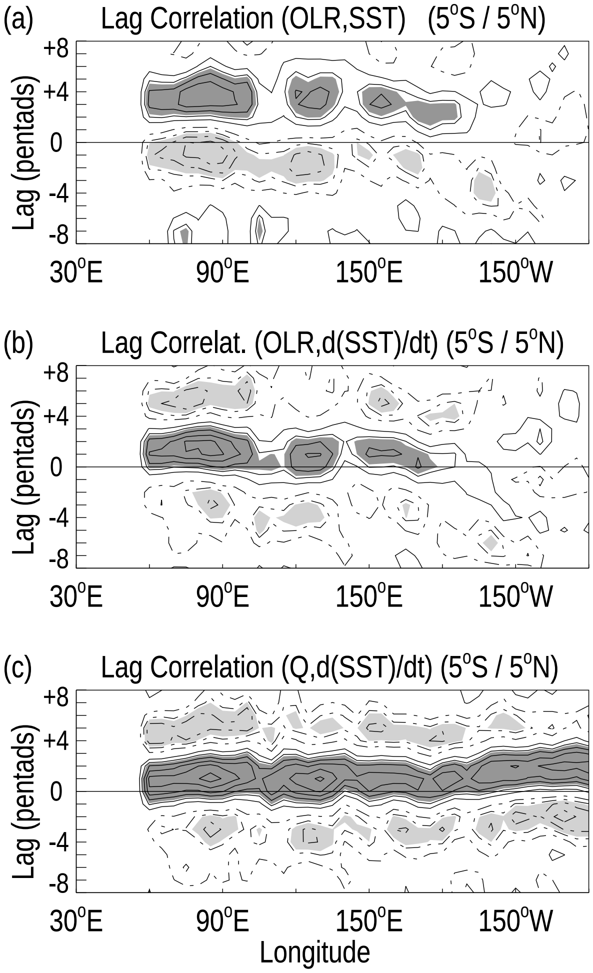

Figure 2. Lag correlations between pairs of time series along the equator and averaged from 5° S to 5° N. (a) Lag correlation between OLR and SST time series. Negative lags indicate that SST leads variations in OLR anomalies. (b) Lag correlation between OLR and d(SST)/dt time series. Negative lags indicate d(SST)/dt that leads variations in OLR anomalies. (c) Lag correlation between Q and d(SST)/dt time series. Positive lags indicate that Q leads variations in d(SST)/dt anomalies. Heavy (light) shaded regions indicate correlations greater (less) than 0.23 (-0.23) and are significant at 95% significance level based on local t-test.

We now examine the influence of the MJO on the formation and decay of hot spots in more detail by first characterizing the occurrence of hot spots in the Pacific Ocean (40° S-40° N; 90° E-120° W) in nearly ten years of data. As before, we attempt to find the influence of the MJO on the hot spots by relating variations in convection (OLR anomalies) and hot spots occurrence (unfiltered SST). We selected the period 1-5 May 1985 through 5-15 May 1994, since this is the period in which OLR anomalies are available. Next, we identified all pentads when hot spots are observed, and tagged their periods of formation and decay. The following example illustrates this procedure. Suppose that hot spots are first observed in the Pacific Ocean starting on 1-5 May 1985 and existed until 4-8 August 1985 and that no hot spots are observed until a hot spot reappeared on 14-18 August 1985 and lasted for only one pentad. Then suppose, hot spots appeared again on 24-28 August 1985 and lasted for several consecutive pentads until they ceased on 15-19 February 1986. The last pentad before a period of absence of hot spots, in this case 4-8 August 1985 and 15-19 February 1986, is defined as a break (hereafter B). A single isolated pentad with hot spots, in this case 14-18 August 1985, is defined as transient (hereafter T). The first pentad of a period of reappearance of consecutive hot spots, in this case 1-5 May 1985 and 24-28 August 1985, is defined as a recurrence (hereafter R). This labeling is performed so that the phase of the MJO can be statistically tied to the development and decay periods of the hot spot. A total of 544 hot spots are observed during 1-5 May 1985 through 5-15 May 1994, with 37 breaks, 37 recurrences and 10 transients.

The relationship between hot spots and the MJO is investigated with respect to the same reference time series of OLR anomalies (OLRRTS) in the Indian Ocean site (5° S-5° N; 80° E-90° E) for the period 1-5 May 1985 through 5-15 May 1994 along with the occurrence of hot spots and the R, B and T events. The OLRRTS indicates that when convection in the Indian Ocean is intense, subsidence or suppressed convection in the western Pacific Ocean tends to be enhanced and vice-versa. This fact will be used to determine any preference of breaks and recurrences of hot spots during particular phases of the MJO.

In order to summarize the relationships between formation and decay of hot spots with respect to the MJO phase in the convection field, Fig. 3 shows a scatter plot of all breaks (B), recurrences (R) and transients (T) pentads during 1985-1994 as a function of OLRRTS and time rate of change of OLRRTS. The phase of convective anomalies can be understood in the following manner. Beginning with the first quadrant, OLR and d(OLR)/dt anomalies are positive, which shows that subsidence is present and increasing in the Indian Ocean, and as it was shown before, convection is present and increasing in the western Pacific Ocean. Proceeding clockwise, in the second quadrant, OLR anomalies are positive, while d(OLR)/dt is negative. This indicates that subsidence has reached its maximum and is starting to decrease in the Indian Ocean, with the same holding true for convection in the western Pacific. In the third quadrant, OLR and d(OLR)/dt anomalies are negative, corresponding to periods in which convection is present and increasing in the Indian Ocean, while subsidence is present and increasing in the western Pacific.

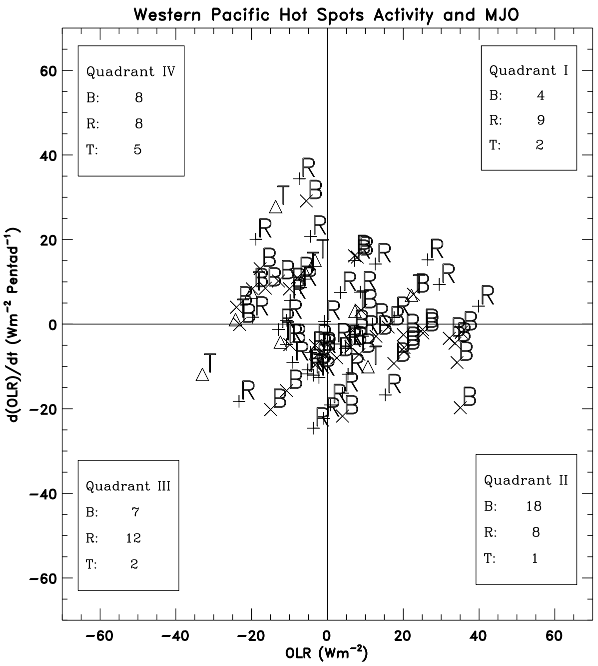

Figure 3. Summary of hot spots formation and decay in the Pacific Ocean during 1985-1994. Horizontal axis denote the OLR anomaly (W m^{-2}) in the Indian Ocean reference site, while the vertical axis denote the time rate of change of the OLR anomaly (W m^{-2} $pentad^{-1}$) in the same geographical location. Breaks (B), transients (T) and recurrences (R) are plotted as function of OLR and d(OLR)/dt. The insets indicate the number of occurrences per quadrant (see text for further details).

Finally, in the fourth quadrant, OLR and d(OLR)/dt anomalies are negative and positive, which points out that convection and subsidence in the Indian Ocean and western Pacific, respectively, have passed the maximum and are starting to decrease. We recall that there are 37 breaks and 37 recurrences in the period 1985-1994. If they were isotropically distributed, i.e. if there were no preference to occur during a particular phase of convective anomalies related to the MJO, one would expect that approximately 9 breaks and 9 recurrences would be observed in every quadrant. In contrast, some preference is observed with 18 breaks and 12 recurrences occurring in the second and third quadrants, respectively. The number of breaks in the second quadrant is twice the expected number corresponding to no preference, which strongly suggests that decay of hot spots in the western Pacific Ocean coincides with periods of increased convection brought on by eastward MJO propagating events. Furthermore, the decay of hot spots takes place after convection has reached its maximum. This is consistent with the previous results on the variations in surface heat fluxes during the life cycle of the MJO, which show that the eastward propagation of convective anomalies induces a cooling trend in SST. On the other hand, a moderate preference is observed for hot spots to occur when subsidence is observed and increasing in the western Pacific, as the 12 recurrences in the third quadrant indicate. Nevertheless, this is also consistent with the previous results and also with W96's results, in which the subsidence that precedes the passage of convective anomalies creates conditions favorable to warm SST in the western Pacific.

4. SUMMARY AND DISCUSSION

This paper examined how intraseasonal variability in SST is related to the MJO. We have taken two complimentary approaches in our analysis. The first focuses on the behavior of the surface heat fluxes and SST relative to the phases of the MJO, while the second focuses on phases of the MJO relative to the development and decay of regions of very high SST. Spectral analysis of SST (not shown) suggests additional observational evidence that intraseasonal variations in SST occur in each of the tropical oceans, over a wide latitude domain. Although the MJO reaches maximum amplitudes over the Indian and western Pacific Oceans, intraseasonal spectral peaks in SST are detected along the entire tropical region including the Atlantic Ocean. This raises the important question of what are the driving mechanisms of the oscillation in SST. This study focused on the Indian and western Pacific Oceans, and it was shown that the variations in convection and large-scale atmospheric circulation strongly modify the ocean surface fluxes of net shortwave radiation and latent heat.

Based on previous studies along with results presented here, an integrated view of the MJO can be summarized in this way. In the lower and upper troposphere of the eastern hemisphere, the intense interaction between convection and large-scale circulation originates an eastward propagating response that resembles a coupled Rossby-Kelvin wave pattern. In contrast, near the date line where the interaction between convection and large-scale circulation decreases, the response appears as radiant Kelvin waves (HS94). As the associated system of subsidence and convection propagates across the Indian and western Pacific Oceans, large fluctuations take place near the surface. Before the passage of convective anomalies, clear skies and subsidence are observed near the surface. In addition, surface wind speeds are minimum before the passage of convection and low-level moisture convergence is maximum (HS94, JW96). These prevailing conditions induce increased surface net shortwave radiation and decreased surface latent heat fluxes, implying positive anomalies in the difference Q = SW - E, which therefore favor positive anomalies of SST. On the other hand, the positive anomalies of SST lead variations in convection. As the convective anomalies propagate eastward across the region, the increase in cloudiness and surface wind speeds due to westerly wind bursts causes a decrease in the net surface shortwave radiation and increase in surface latent heat fluxes, which result in negative Q anomalies and favor negative SST anomalies.

Although changes in the surface net shortwave radiation and latent heat fluxes during the life cycle of the MJO significantly contribute to the SST variability, they are not the only processes that determine the oscillation in SST. The importance of the other two terms of the surface energy balance, net longwave radiation and sensible heat fluxes, should not be underestimated, since the difference SW - E can be comparable in some circumstances to the sum of the neglected terms. However, more important is the role that the upper ocean circulation play in determining the tropical intraseasonal SST variability. Indeed, it is quite possible that the mechanisms that drive the SST oscillation vary with geographical location. In the Indian and western Pacific Oceans, variations in convection and consequently in net surface shortwave radiation are dramatic, whereas in the equatorial Atlantic they are less pronounced. On the other hand, surface latent heat fluxes exhibit sharp intraseasonal spectral peaks in all oceans (JW96). Similarly, horizontal and vertical temperature advection may be different in the upper layers of the Indian, Pacific and Atlantic Oceans. Furthermore, an important unresolved matter concerns how the oscillation in SST may feed back into the oscillation in the atmosphere (W96). The period and amplitude of the MJO is known to vary considerably in time (Madden and Julian, 1994). Since the oceanic (60-75 days) and atmospheric (40-50 days) oscillations are offset, the interaction of SST anomalies with convection is not straightforward to resolve. Modeling studies should address this question, and a comparison of the intraseasonal behavior from different models, e.g. uncoupled GCM, coupled GCM with ocean mixing layer, and fully coupled ocean-atmosphere GCM (General Circulation Model), should provide important clues on the interaction between convection, large-scale circulation and SST. This last topic is currently being investigated by the authors.

Originally examined by W96 and further investigated here, the variability of very high SST in the western Pacific warm pool is shown to be linked to the MJO activity. Development of regions of very high SST (above climatology) in the western Pacific are found to be associated with periods of enhanced subsidence brought on by descending motion of the MJO, while their decay is associated with increases in convection brought on by the ascending motion of the MJO. This emphasizes the need to examine the role internally generated variability, such as the MJO, has on the statistical description of tropical SST, i.e. limiting its maximum value. Although the evidence of the MJO influence found in this study is suggestive, it also points out that the oscillation is not the only process controlling the variations of high SST in the warm pool. Hot spots are also strongly characterized by seasonal and interannual variations, and the intervals between decay and reformation of hot spots vary significantly. Again, future modeling studies of the formation and decay of hot spots should be useful to isolate the circumstances in which different time scales, e.g. MJO and interannual variations, interact with each other to determine the onset and demise of very high SST in the western Pacific warm pool.

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