Seasonal and Interannual Variability of the Madden-Julian Oscillation

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1. Introduction.

Several recent studies have examined the seasonal variability of the "40-50 day" or "Madden-Julian oscillation" (hereafter denoted MJO) in near-equatorial wind and rainfall data (Madden 1986; Hartmann and Gross 1988; Gutzler and Madden 1989). These studies related observed seasonal differences in the variance and presence or absence of a 40-50 day spectral peak to seasonal shifts in the position of convective maxima and the mean wind field. The present study examines the sensitivity of intraseasonal zonal wind variance at near-equatorial rawinsonde stations in the eastern Indian and western Pacific Oceans to interannual shifts in convection and mean winds associated with the Southern Oscillation (SO). As with most SO-related phenomena, the interannual signals are best understood within the context of seasonal variability.

2. Data and analysis procedure.

Daily time series of 200 mb and 850 mb zonal winds from six rawinsonde stations are considered (Table 1 and Fig.1). The stations are all within 10° latitude of the equator and are distributed in longitude between the southern tip of India and the mid-Pacific. Truk and Majuro are located within the COARE domain; Koror and Canton are less than 10° from the proposed western and eastern boundaries of the COARE domain. Daily surface wind time series from the three easternmost stations (Truk, Majuro and Canton) are also considered.

The seasonal cycle (defined as the sum of the Fourier harmonics with periods one year, 6 months, 4 months, and 3 months) was removed from each time series to form time series of anomalies, which were then passed through a band-pass filter with half-power cutoff periods of 31 and 66 days and a central period of 42 days. Each 31-66 day filtered time series is chopped into seasonal segments (Dec.-Jan.-Feb., etc.) and the variance within each seasonal segment is calculated, thus creating seasonal time series of filtered zonal wind variance, denoted σ_{BP}^2, for each station and level. Seasonal values of the variance of unfiltered anomalies about the individual seasonal means σ_A^2, are calculated over the same seasonal segments; σ_A^2 thus represents the total intraseasonal variance. A third variance quantity, $\langle\sigma_I^2\rangle$, is calculated from the time series of seasonal mean anomalies, i.e. $\langle\sigma_I^2\rangle$ is the interannual variance of zonal winds for each season. Brackets denote an average over all years (instead of the average over a single season implicit in σ_{BP}^2 and σ_A^2).

The time series of σ_{BP}^2 and σ_A^2 provide a local measure of low-frequency (seasonal) variations in the amplitude of the MJO, and of variability on all intraseasonal time scales, respectively. The climatological averages of these variances are calculated for each season and compared with $\langle\sigma_I^2\rangle$. The seasonal time series are correlated with seasonal values of the Southern Oscillation Index (the difference between normalized sea level pressure anomalies at Tahiti and Darwin).

TABLE 1

Rawinsonde stations used in the analysis. The beginning and ending dates are the first and last seasons considered in the calculation of seasonal time series of 31-66 day variance; the actual filtered time series are somewhat longer.

Station name	Abbrev	lat	long	begin/end seasons
Trivandrum	TRV	8°N	77°E	MAM 1965 - SON 1977[1]
Singapore	SIN	1°N	104°E	JJA 1963 - SON 1985
Koror	KOR	7°N	134°E	JJA 1963 - SON 1985
Truk	TRU	8°N	152°E	JJA 1963 - SON 1985[2]
Majuro	MAJ	7°N	171°E	JJA 1963 - SON 1985[2]
Canton	CAN	3°S	172°W	JJA 1955 - SON 1966[3]

[1] DJF 1968 - DJF 1970 seasons missing
[2] begin/end seasons for surface wind: JJA 1956 - SON 1978
[3] begin/end seasons for surface wind: JJA 1955 - SON 1966

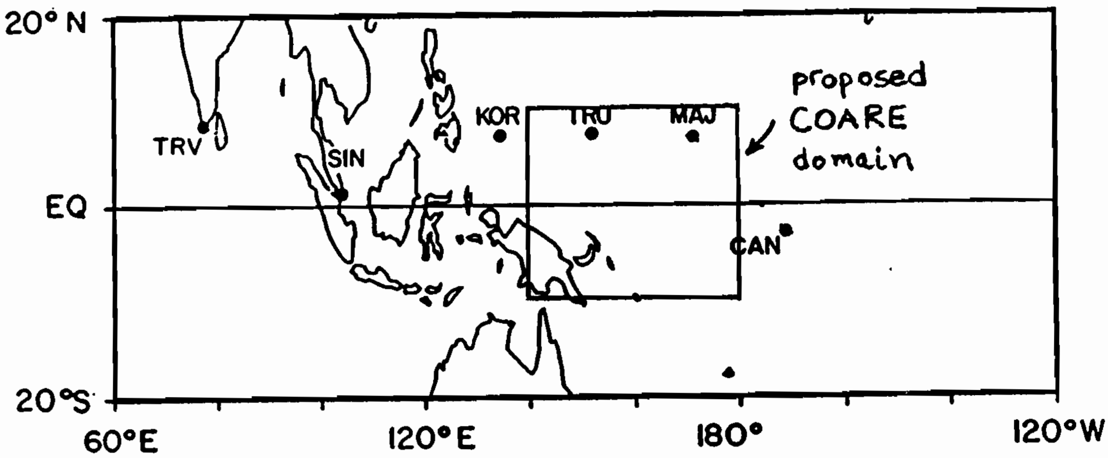

FIG.1. Map of rawinsonde and surface wind stations (see table 1 for key to station abbreviations).

3. Variance and correlation statistics.

Table 2 shows the climatological average values of 31-66 day filtered variance $<\sigma_{BP}^2>$ and the total anomaly variance $<\sigma_A^2>$, and the interannual variance $<\sigma_I^2>$, for u_{200}, u_{850}, and (where available) u_s for each of the stations, stratified by season (DJF, MAM, JJA, and SON). We begin by discussing the 31-66 day variances, the middle number of the entry for each station and level.

The seasonal and geographical distribution of $<\sigma_{BP}^2>$ for u_{200}, u_{850} shown in Table 2 reproduce and confirm previous results of Madden (1986), Hartmann and Gross (1988), and Gutzler and Madden (1989). The 31-66 day variance of u_{200}, is much greater than that of u_{850}, or u_s, and seasonal variations of $<\sigma_{BP}^2>$ are also greatest in the upper troposphere. The value of $<\sigma_{BP}^2>$ at 200 mb is greatest over the Indian Ocean and mid-Pacific (Trivandrum, Singapore and Canton) in DJF and $<\sigma_{BP}^2>$ at these stations is lowest in JJA. At Koror in the far western Pacific, in contrast, $<\sigma_{BP}^2>$ of u_{200} is small in DJF compared to other seasons. The 31-66 day variance is much greater at Canton than at Majuro, but we cannot tell from these data whether the variance gradient is primarily north-south (increasing toward the equator) or east-west (increasing toward the eastern Pacific) between these stations.

The distribution of $<\sigma_{BP}^2>$ of u_{850} is considerably different. The DJF maximum is found only at Canton, and the variance at Trivandrum is exceedingly small. Elsewhere $<\sigma_{BP}^2>$ is largest in the SON season, and at Koror and Truk the u_{850} value of $<\sigma_{BP}^2>$ is smallest in the DJF season.

The 31-66 day variances in surface zonal winds are much smaller than the 850 mb variances. From Table 2 it appears that the MJO has very little amplitude in the surface wind field, except perhaps at Canton in the SON and DJF seasons.

Seasonal variations of $<\sigma_{BP}^2>$ must be put in perspective relative to the total variance of intraseasonal anomalies $<\sigma_A^2>$. The seasonal variability of $<\sigma_A^2>$ is generally smaller than of $<\sigma_{BP}^2>$ in relation to the annual average variance. As a consequence, for example, the ratio $<\sigma_{BP}^2> / <\sigma_A^2>$ for u_{200} at Trivandrum and Canton exceeds 0.25 in DJF and drops to about 0.15 in JJA. At Singapore and Koror this ratio is roughly 0.2 in all seasons at both 200 mb and 850 mb. In contrast, at the surface this variance ratio is less than 0.2 in all cases except at Canton in DJF and SON.

It is also interesting to compare the intraseasonal variances with the interannual variance $<\sigma_I^2>$, much of which is associated with fluctuations in the Southern Oscillation. To the west of Truk, $<\sigma_{BP}^2> > <\sigma_I^2>$, i.e. the MJO typically accounts for more variance than interannual variability, although at Singapore in DJF (both levels) and SON (850 mb) the variances are about equal, and the lower tropospheric intraseasonal variances at Trivandrum are too small to compare meaningfully.

From Truk eastward into the mid-Pacific, interannual variability is proportionately more prominent and the relative amplitude of $<\sigma_I^2>$ and $<\sigma_{BP}^2>$ is a function of level and season. At 200 mb at Truk and Majuro, $<\sigma_{BP}^2>$ is greater in DJF and MAM, but $<\sigma_I^2>$ is greater in SON. The transition from mostly $<\sigma_{BP}^2>$ to mostly $<\sigma_I^2>$ takes place between Majuro and Canton in MAM, and in JJA the variances are about the same. In the lower troposphere, anywhere that either variance is greater than $0.5\ m^2.s^{-2}$ it is the interannual variance that is greater, especially in the surface wind.

Table 3 shows correlations between time series of σ_{BP}^2 and the SOI. Year-round (denoted ALL) and seasonally stratified correlations are tabulated. Formal significance tests are difficult to apply uniformly because the seasonal time series are of different lengths. For convenience, a nominal significance level of 0.4 is adopted and only those correlations exceeding this threshold are discussed. This correlation threshold should be considered a general guide to significance but not a rigorous test thereof.

TABLE 2

Variance ($m^2 s^{-2}$) of (from left to right) $<\sigma_I^2>$, $<\sigma_{BP}^2>$, and $<\sigma_A^2>$, at each station and level. These variances represent interannual variability, 31-66 day filtered variability, and total intraseasonal variability, respectively (see text).

	TRV			SIN			KOR			TRU			MAJ			CAN		
DJF																		
u_{200}	9	24	88	34	37	183	4	6	35	5	8	40	9	11	48	9	21	73
u_{850}	0	1	11	8	9	55	2	6	26	1	2	15	1	2	17	11	8	27
u_s										1.2	0.2	1.1	0.4	0.5	3.0	4.5	2.1	6.7
MAM																		
u_{200}	4	14	53	14	32	143	6	12	52	7	14	56	4	14	63	28	15	75
u_{850}	0	2	13	2	7	40	4	5	20	2	3	17	2	2	14	5	3	15
u_s										1.0	0.3	1.8	0.6	0.4	2.2	1.0	0.5	3.2
JJA																		
u_{200}	6	9	54	15	30	160	4	12	57	8	7	49	8	5	48	8	8	53
u_{850}	1	3	15	4	8	46	5	8	27	5	4	19	2	2	13	1	1	10
u_s										1.0	0.5	2.9	0.4	0.5	3.4	0.5	0.4	2.8
SON																		
u_{200}	7	9	51	16	31	146	5	11	54	14	9	56	18	7	51	22	12	56
u_{850}	2	3	18	12	12	56	5	9	39	5	4	23	5	3	17	5	4	18
u_s										1.0	0.7	4.2	0.7	0.6	4.0	2.0	1.4	5.1

TABLE 3

Correlation coefficients (×100) between seasonal averages of the variance of 31-66 day filtered time series and the Tahiti-Darwin Southern Oscillation Index.

	TRV	SIN	KOR	TRU	MAJ	CAN
ALL						
u_{200}	-01	-18	+02	-06	+11	+25
u_{850}	+02	+07	+11	-12	-12	-34
u_s				-31	-03	-36
DJF						
u_{200}	+09	-20	00	-17	+17	+60
u_{850}	-02	00	+40	+50	+22	-55
u_s				+27	+44	-61
MAM						
u_{200}	-20	-21	+18	+02	+07	-13
u_{850}	-48	+28	+35	+10	+24	-05
u_s				-11	+55	-14
JJA						
u_{200}	-42	-11	+11	-02	+04	+26
u_{850}	+28	+24	+02	-36	-17	+08
u_s				-50	-40	-34
SON						
u_{200}	-22	-23	-23	00	+34	+34
u_{850}	+38	-12	-21	-22	-46	-67
u_s				-53	-48	-52

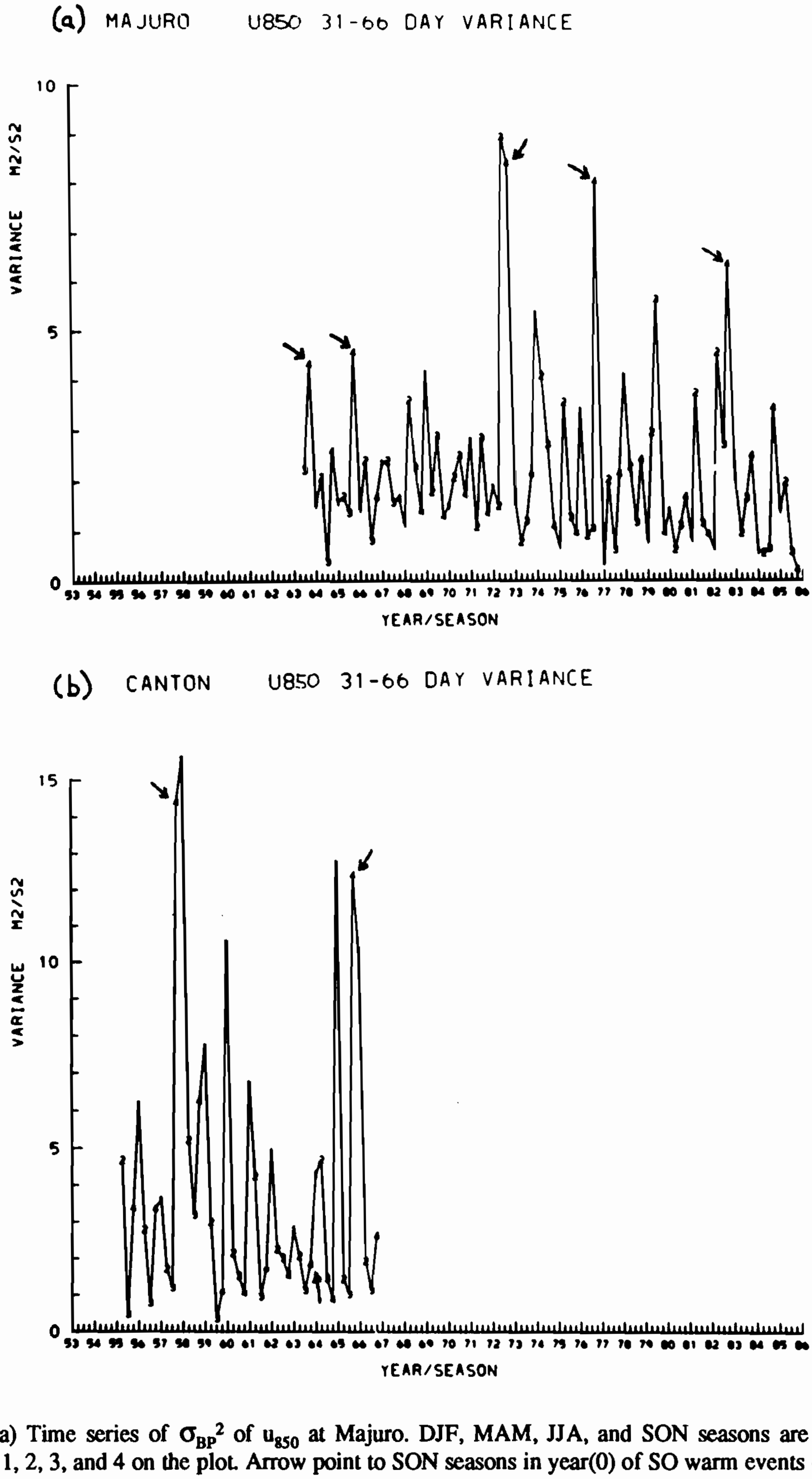

FIG.2. (a) Time series of σ_{BP}^2 of u_{850} at Majuro. DJF, MAM, JJA, and SON seasons are respectively denoted 1, 2, 3, and 4 on the plot. Arrow point to SON seasons in year(0) of SO warm events (1963, 1965, 1972, 1976, and 1982). (b) As in (a), but for u_{850} at Canton. Arrows point to SON season in year(0) of SO warm events (1957, 1963, and 1965).

None of the correlations derived from year-round data exceed 0.4 in magnitude, and most of the year-round correlations are very close to zero. The only significant 200 mb correlations are at canton in DJF and at Trivandrum in JJA. Examination of the time series of σ_{BP}^2 at 200 mb at Trivandrum and Canton (not shown) suggests that the 200 mb correlations exceeding |0.4| at those stations in Table 3 are caused by a few solitary seasons of extremely large variance, and may represent just sampling errors. There seems to be no association between SOI correlations involving σ_{BP}^2 in upper and lower tropospheric zonal winds at the same station.

The seasonally stratified statistics in the lower troposphere exhibit a complex distribution of significant correlations varying not only in magnitude but in the *sign* of the correlation from station to station and season to season. During the DJF season, interannual fluctuations of σ_{BP}^2 in lower tropospheric zonal winds at canton are negatively correlated with the SOI, but stations to the west of Canton exhibit positive correlations between σ_{BP}^2 and the SOI. In MAM the positive correlation between σ_{BP}^2 and the SOI is confined to the surface zonal wind at Majuro. In JJA the values of σ_{BP}^2 of surface zonal winds at Truk and Majuro are negatively correlated with the SOI, and in the SON season negative correlations are found in the lower troposphere between Truk and Canton.

Inspection of the various time series of σ_{BP}^2 sheds light on this complex set of correlations; in this brief report only two time series will be shown. Interannual variability at 200 mb is unsystematic and there is no apparent correspondence between fluctuations of σ_{BP}^2 in the upper and lower tropospheric wind series, a result consistent with the σ_{BP}^2-SOI correlations.

The interannual variability of σ_{BP}^2 in the lower tropospheric series is more systematic. Obvious peaks in the σ_{BP}^2 time series for u_{850} at Majuro (Fig. 2a) are evident in the SON season in years 1963, 1965, 1972, 1976, and 1982; these are SO warm event years (frequently referred to as "year 0"; Rasmusson and Carpenter 1982). SON(0) peaks are also found in the time series for the variance of the surface wind at Majuro and for surface and 850 mb winds at Truk (not shown), and for surface and 850mb winds at Canton (the latter shown in Fig. 2b), where the signature of the 1957-58 warm event is particularly prominent. Other peaks during non-warm event years are also found in the time series, but the tendency for large σ_{BP}^2 in lower tropospheric zonal winds at central Pacific stations during the second half of warm event years(0) is striking. This relationship is actually much clearer than suggested by the correlation statistics in Table 2, because the absence of a correspondingly strong "cold event"/highs SOI signature dilutes the overall correlation between the SOI and the time series of σ_{BP}^2.

At Majuro each of the SON(0) peaks is followed by an abrupt drop of σ_{BP}^2 to values below the seasonal average during the next two seasons, DJF(+1) and MAM (+1). The SOI tends to remain negative (and sea surface temperatures remain warm) during these seasons, which accounts for the change in sign of the correlation between σ_{BP}^2 and SOI between SON and DJF at 850mb at Majuro in Table 3. The time series of σ_{BP}^2 for u_s at Majuro (not shown) has similar peaks during warm events, but because the intraseasonal variance is generally small at the surface (Table 2), warm events account for almost all the seasons in which σ_{BP}^2 exceeds 1 $m^2.s^{-2}$. To the southeast, at Canton, σ_{BP}^2 at 850mb does not diminish between SON(0) in 1957 and 1965 and DJF(+1), but remains large. Therefore the SOI-σ_{BP}^2 correlation also remains negative, in contrast to the change in sign at Majuro and Truk.

Figure 3 contains a summary schematic of the geographical distribution of σ_{BP}^2 anomalies in lower tropospheric zonal winds during JJA(0)-DJF(+1) seasons of warm events, derived from statistics such as the correlations in Table 3 and from inspection of

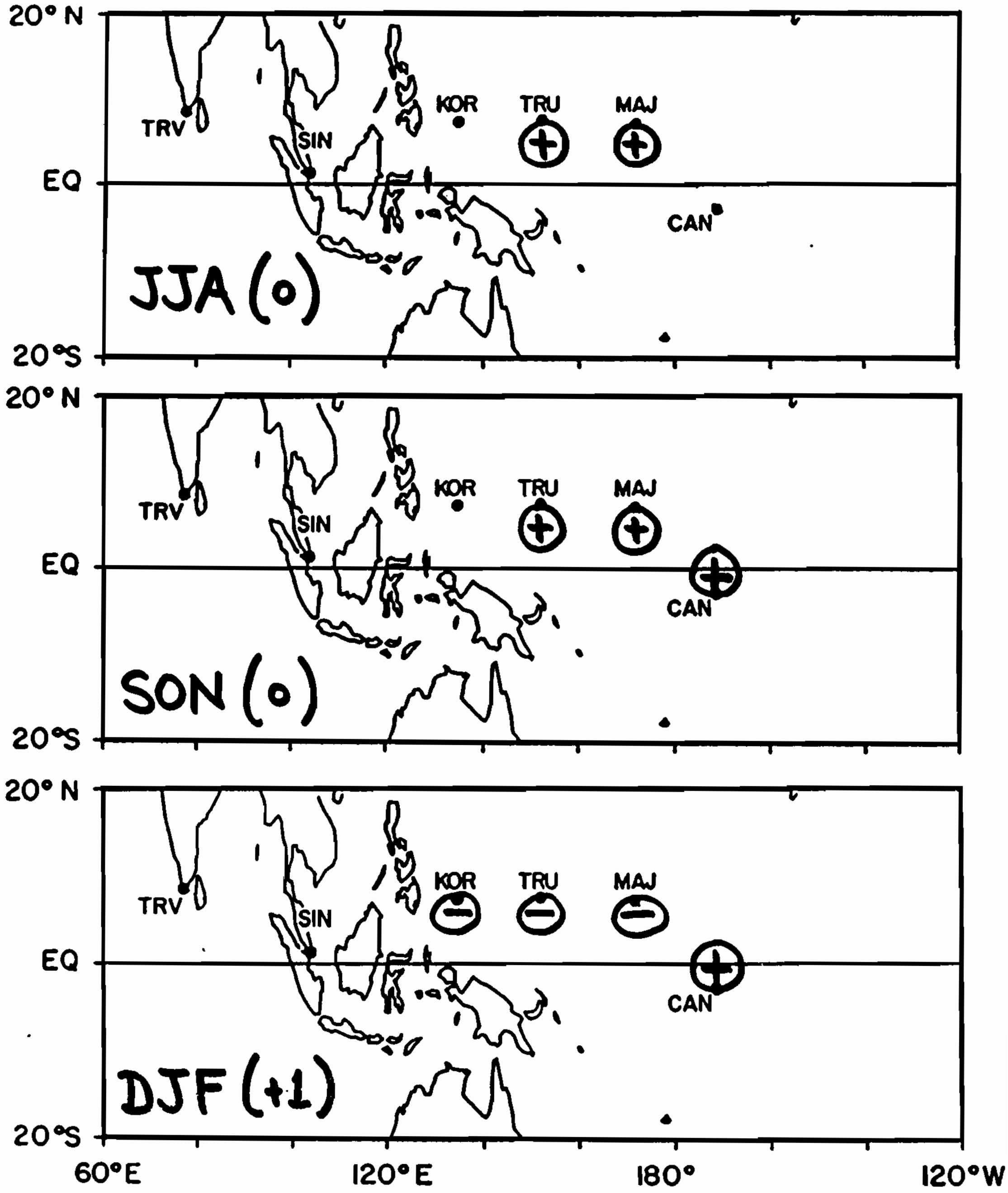

FIG.3. Summary schematic of the modulation of $\sigma_{BP}{}^2$ of lower tropospheric zonal winds during the JJA(0)-DJF(+1) period of SO warm events. Stations exhibiting enhanced of depressed 31-66 day variance are indicated by + and - symbols, respectively.

time series of σ_{BP}^2 at other stations (not shown). The region of enhanced intraseasonal variance shifts eastward from JJA(0) to SON(0), then abruptly shifts either eastward or southward in DJF(+1).

The aforementioned modulation of intraseasonal zonal wind variance during SO warm events, inferred from the seasonal time series of σ_{BP}^2, is evident in the time series of u_{200}, u_{850} and u_s wind anomalies at Canton during the 1965 warm event (Fig. 4). These plots show the output of the 31-66 day filter (with the seasonal cycle removed) superimposed on the bi-daily anomalies. At 200mb (Fig. 4a) the 31-66 day filter provides the best fit to the time series of unfiltered anomalies in the DJF seasons. In DJF 1965/66 a particularly intense episode of intraseasonal variability interrupts the lower-frequency seasonal average westerly anomalies. There is no apparent relationship between seasonal fluctuations of σ_{BP}^2 or σ_A^2 and the mean wind anomaly or the development of the warm event in late 1965.

The 31-66 day time series at 850mb (Fig. 4b) is clearly out-of-phase with its 200 mb counterpart, but there is no systematic correspondence between the amplitudes of the fluctuations in the two time series. Both the 31-66 day variance and the unfiltered variance increase during the period of largest mean westerly anomalies in SON 1965 and DJF 1965/66 (this is also the period of maximum SST anomalies in the central Pacific during this event; Rasmusson and Carpenter, 1982). There is an isolated 31-66 day event in January 1965, which is exceptional for a non-warm event period (cf. Fig. 2b). The surface wind time series (Fig. 4c) is highly coherent with the 850mb time series, but has less variability on all time scales.

Both of the lower tropospheric time series exhibit burst-like behavior not noticeable at 200 mb, with episodes of large positive (westerly) anomalies capping the crests of the westerly phases of the 31-66 day time series. The bursts are organized on MJO time scales during SON 1965 and DJF 1965/66, as demonstrated by the variance ratio σ_{BP}^2/σ_A^2, which is approximately one-third in those seasons. Other isolated bursts of a few days' duration occur (e.g. in April 1965), which are not visibly associated with large variance on MJO time scales. The amplitude of 31-66 day variability during SON and DJF is as large as the magnitude of the seasonal anomalies. Both the seasonal-average westerlies and the large amplitude 31-66 day events cease in MAM 1966.

The effects of the MJO and burst-like variability on the total zonal wind are illustrated in Fig.5, which shows the actual bi-daily u_s values together with the sum of the seasonal cycle, the output from the 31-66 day filters, and the output from a low-pass filter. The latter is designed so that the two filters in combination approximate the effect of a low-pass filter whose half-power point is also 31 days, so the residual time series after implementation of these filters is high-pass filtered to isolate variability on sub-MJO time scales. It is apparent that the bursts are responsible for most of the periods of absolute westerly winds during this warm episode. Note the absence of "easterly bursts" of comparable magnitude during easterly phases of 31-66 day fluctuations (or any other time). The figures suggest that the bursts and the MJO are indeed coupled. Time series of σ_{BP}^2 of the surface wind at Canton during the 1957-58 warm event (not shown) show behavior consistent with these conclusions.

4. Discussion and recommendations for COARE.

The principal systematic interannual modulation of the amplitude of the Madden-Julian oscillation in near-equatorial zonal winds is an increase in the lower troposphere across the western Pacific during the second half of "year 0" of ENSO warm events. This is followed by an abrupt drop in intraseasonal variability during the DJF(+1) and MAM(+1) seasons at stations north of the equator and west of the dateline, but the

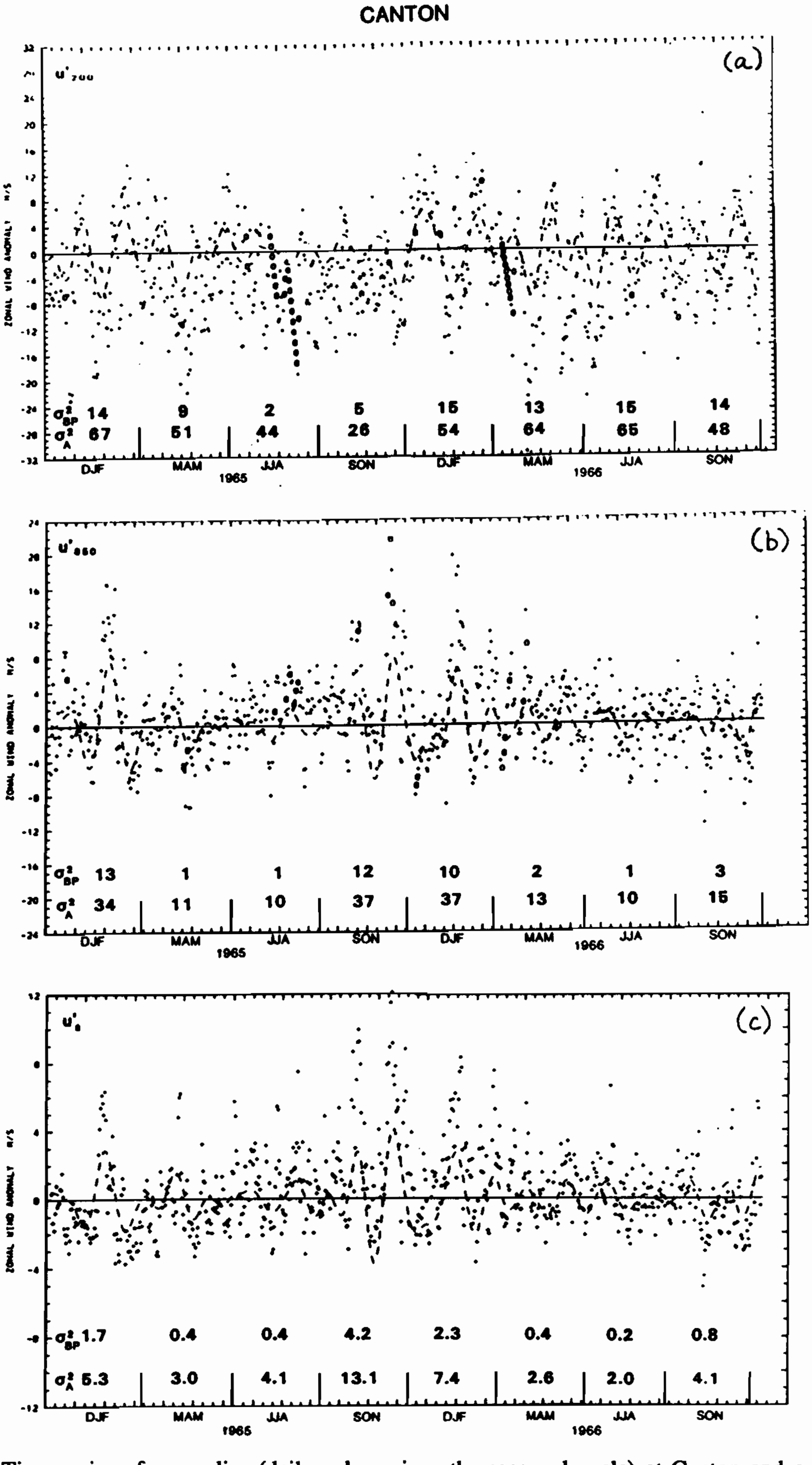

FIG.4. (a) Time series of anomalies (daily value minus the seasonal cycle) at Canton and output of the 31-66 day filter for the period 1 December 1964 - 30 November 1966, for u_{200} at Canton. Every second day of the daily time series is plotted for clarity; ticks on the abscissa are spaced ten days apart. Small crosses denote observed values; zeros are plotted for missing data that have been linearly interpolated. The short horizontal solid lines are monthly mean anomalies. Seasonal values of σ_{BP}^2 and σ_A^2 are plotted for each season. (b) As in (a), but for u_{850}. (c) As in (a), but for u_s.

variance to the south and east remains high during that season and the following MAM(+1) season as well. Correlations between seasonal values of σ_{BP}^2 and the Southern Oscillation Index are generally insignificant everywhere in upper tropospheric zonal winds and from Singapore westward in lower tropospheric winds.

Considering just the lower tropospheric zonal wind, the increase in 31-66 day filtered variance during the second half of years (0) at Truk, Majuro, and Canton is consistent with the more general result that the seasonal variability of intraseasonal zonal wind variance in the lower troposphere shifts north and south along with the region of most intense convection (Gutzler and Madden, 1989; Table 2). The center of mean convective activity shifts eastward across the western Pacific during the second half of year(0) (Rasmusson and Carpenter 1982), during the seasons when intraseasonal zonal wind variance at stations in this region increases. The SON(0)→DJF(+1) transition in the distribution of intraseasonal zonal wind variance may represent an amplification of the seasonal cycle transition, as the anomalous convection and associated mean westerly surface anomalies shift south across the equator from SON(0) to DJF(+1) (Rasmusson and Carpenter 1982), following the seasonal cycle. Here again, it would be very interesting to know whether the important gradient of intraseasonal variance between Majuro and Canton during DJF(+1) is meridional or zonal.

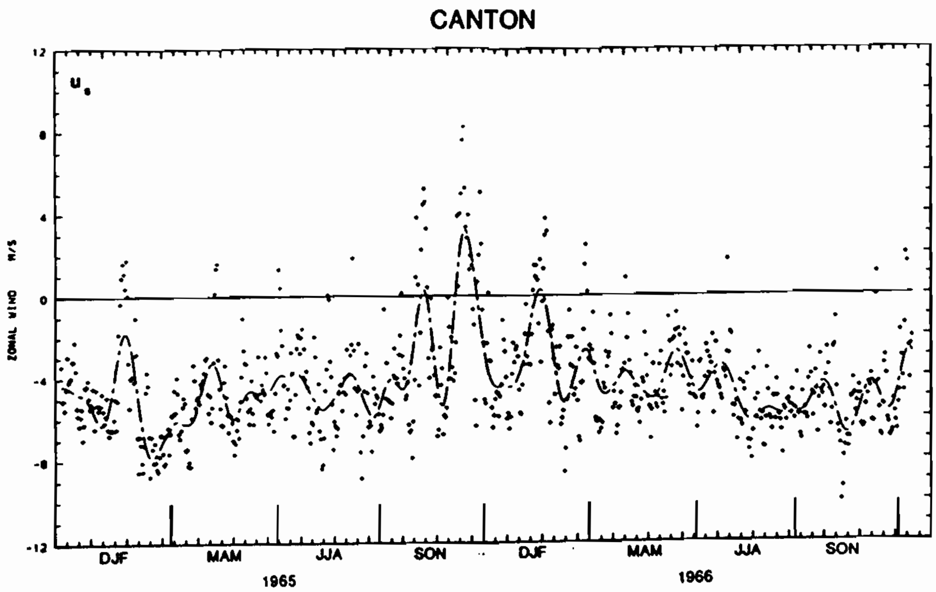

FIG.5. Time series of u_s (not anomalies) at Canton, corresponding to Fig. 4(c). The solid curve is the sum of the seasonal cycle and the outputs of the band-pass filter and a low-pass filter (see text); the sum of these filter outputs is approximately equivalent to a low-pass filter whose high-frequency cutoff is the same as that of the band-pass filter.

Modulation of intraseasonal variance by SO-related interannual variability is observed only in lower tropospheric winds. There is no correlation between the amplitude of 31-66 day anomalies in the upper and lower troposphere, suggesting that the enhancement of lower tropospheric wind variance is not the results of a convective feedback, which ought to affect the amplitude of wind fluctuations in the upper troposphere as well. This results adds to previous evidence for some degree of vertical decoupling of wind fluctuations on 40-50 day time scales, including seasonal variations in the coherence between 150 mb and 850 mb fluctuations (Madden, 1986) and the different geographical structure of the seasonal cycle of 40-50 day zonal wind variance (Gutzler and Madden, 1989). Initial analysis of the filtered surface wind time series suggests that high-frequency westerly bursts are associated with the westerly phase of MJO variability on 40-50 day time scales. These bursts are already known to occur preferentially during SO warm event periods (Keen, 1982; Luther et al., 1983), a result confirmed by the present analysis.

Significant variance of surface zonal winds on intraseasonal time scales (both on 31-66 day time scales and higher frequency bursts) occurs during SO warm phases. The time scale of the MJO is particularly awkward, because monthly means are the standard archival period for most surface wind data sets. Unfortunately, monthly-averaged data contains considerable aliased variance in the presence of a 40-50 day signal (Gray and Madden, 1986). They noted that the use of seasonal averaging reduces the aliasing of variance in this frequency range, but only by eliminating 40-50 day variance almost completely. The time series in Figs. 4 and 5 suggest that enhanced intraseasonal variance is a fundamental component of the atmospheric response to warm event conditions, perhaps more important energetically than the quasi-stationary westerly wind response.

The questions raised by this study are central to the goals of the TOGA program and are highly relevant to COARE. The study is limited by the extremely small sample of six stations, only four of which are located over the Pacific Ocean. There are several other island stations within the COARE domain whose historical surface wind records could be used to augment the present results, but the network of rawinsonde stations over this region is quite sparse. Effort should be directed toward increasing the density of observations during pilot studies and the proposed COARE intensive observation period. The results indicate that there is a sharp increase in intraseasonal zonal wind variance between Majuro and Canton, across the proposed eastern boundary of the COARE domain. If possible it would be worthwhile to extend the eastern boundary of the COARE domain eastward to at least 170°W.

These results also suggest themes for future modeling studies. The effect of intraseasonal surface stress variability on ocean circulation should be evaluated. In the absence of comprehensive wind stress data with sufficient temporal resolution, a good first step would be sensitivity studies with artificial data. The Canton time series suggest that amplitudes of up to 5 $m.s^{-1}$ for quasiperiodic anomalies with periods of about 40 days occur during warm events. Additional studies could superimpose westerly bursts on the 40 day periodic anomalies.

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