

Interannual Variability of the Australian Summer Monsoon Onset: Possible Influence of Indian Summer Monsoon and El Niño

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ABSTRACT

The date of Australian summer monsoon onset (ASMO) is found to be well correlated with the monsoon rainfall of India during the preceding June to September. Years of below (above) normal Indian summer monsoon rainfall (ISMR) are followed by delayed (early) ASMO. Sea surface temperature (SST) anomalies during the September to November season over the tropical Indian Ocean, the equatorial eastern Pacific Ocean, and the ocean north of Australia also correlate significantly with the date of the following ASMO. Delays in ASMO are associated with cold SST north of Australia and warm SST in the tropical Indian and equatorial east Pacific oceans.

Previous studies have shown that a warm SST is created over the tropical Indian Ocean in years of poor ISMR. We hypothesize that a warm SST anomaly over the Indian Ocean delays the seasonal southward and eastward migration of the cloudiness maximum. A delay in the southeastward movement of cloudiness results in a delayed ASMO. A similar hypothesis already has been suggested to explain the variability of the date of monsoon onset over India.

Weak ISMR often is associated with the contemporaneous presence of El Niño, although many weak monsoons occur without El Niño. Thus warm SSTs in the eastern equatorial Pacific are related to a delayed ASMO through the Indian monsoon. Another signature of El Niño is the presence of negative SST anomalies north of Australia, adding to the delay in ASMO. Warm SSTs in the central and eastern Pacific may also act directly to delay ASMO by causing convection near and east of the date line and subsidence near Australia.

1. Introduction

Onset of the Australian summer monsoon is marked by a sudden transition from a dry to a wet regime over northern Australia (e.g., Davidson et al. 1983). Large-scale circulation changes accompany onset (Troup 1961; Davidson et al. 1983; Murakami et al. 1986; Hendon and Liebmann 1990). Since the date of onset exhibits large interannual variability (Nicholls 1984a; Holland 1986; Hendon and Liebmann 1990), an advance knowledge of the approximate date of onset would be useful.

Prediction of the Australian Summer Monsoon Onset (ASMO) date is possible with some degree of success based on antecedent sea level pressure at Darwin (Nicholls and Woodcock 1981; Nicholls et al. 1982; Nicholls 1984a) and sea surface temperature (SST) in the eastern Pacific (Holland 1986). In the present paper we present evidence for an association between the strength of the Indian summer monsoon and the date

of ASMO that follows and also a physical basis regarding the cause of ASMO variability.

2. Data and methodology

ASMO is characterized by a large-scale reversal of low-level winds to westerly and upper-level winds to easterly and a rapid increase of rainfall over northern Australia (Troup 1961; Nicholls et al. 1982; Nicholls 1984a; Holland 1986; Hendon and Liebmann 1990). Typically, the Australian monsoon consists of 2–3 cycles of heavy rainfall, each lasting more than 10 days, followed by a somewhat longer break. The average period from peak-to-peak activity is around 40 days (Holland 1986). Hendon and Liebmann (1990) concluded that onset of the Australian monsoon in most years is a manifestation of the 40- to 50-day oscillation as the seasonal cycle of convection and the 40- to 50-day activity moves south of the equator during the Southern Hemisphere warm season (Murakami et al. 1986; Gutzler and Madden 1989).

ASMO has been defined in various ways. Troup (1961) defined it as the first rainfall event after 1 No-

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Indian Ocean, mainly through a weaker (stronger) surface wind field, which affects the SST through weaker (stronger) fields of evaporative fluxes and coastal and open-ocean upwelling (Joseph and Pillai 1986; Krishnamurti 1981). North Indian Ocean SST cools from May to August, unlike other oceans of the Northern Hemisphere during this period. The amplitude of this cooling is controlled by the monsoon's surface wind field and that controls the intensity and

sign of the SST anomaly from the end of the monsoon until the following monsoon.

The correlation between the east-central Pacific and ISMR is also well known. Previous studies have shown a connection between ISMR and El Niño (Angell 1981; Rasmusson and Carpenter 1983; Mooley and Parthasarathy 1984b; Parthasarathy and Pant 1985).

It is not known why the SST anomalies north of Australia are correlated with ISMR, but the correlation

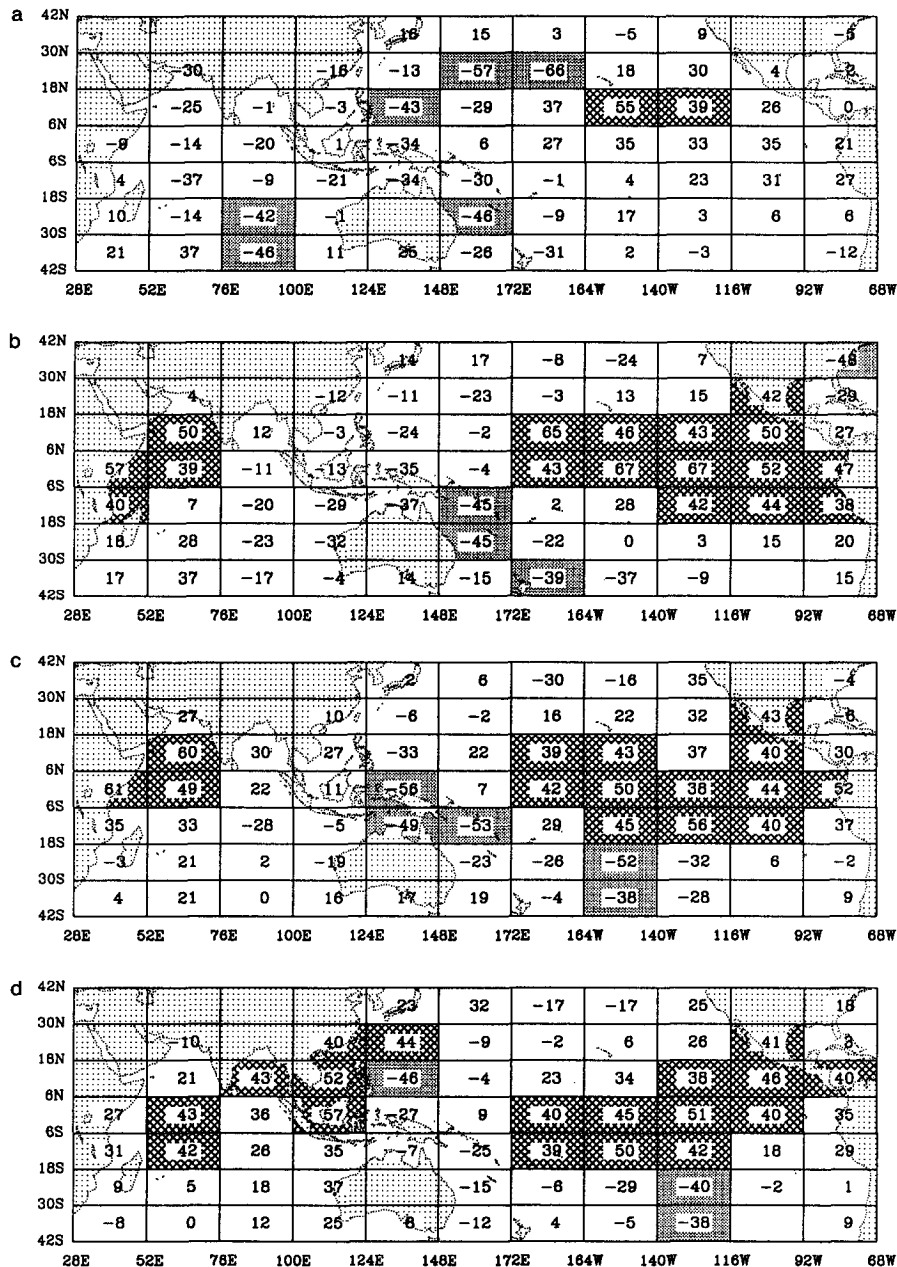


FIG. 4. Correlation coefficient $\times 100$ between the date of ASMO from 1957/58 to 1983/84 and the SST anomaly for (a) preceding MAM season; (b) preceding JJA season; (c) preceding SON season; (d) contemporaneous DJF season. Areas with correlation greater than $+0.37$ are cross hatched, and areas with correlation less than -0.37 are stippled.

may come through the association between ISMR and El Niño (Rasmusson and Carpenter 1983). The relation between SST anomalies north of Australia and El Niño is shown in composite studies of El Niño (Rasmusson and Carpenter 1982; Nicholls 1984c; Halpert and Ropelewski 1989). During SON one year prior to the mature phase of an El Niño, the waters north of Australia are anomalously warm and those in the eastern Pacific are anomalously cold. The anomalies have opposite signs one year later.

Figure 4 shows the correlation between the date of ASMO and SST for three seasons prior to onset and for the season concurrent with onset. The SON season in Fig. 4c corresponds to Fig. 3. There are marked similarities between the two figures, implying (but not proving) that ISMR and ASMO are linked through SST anomalies. The regions of large correlation in Fig. 3 over the northwestern Indian Ocean, north of Australia, and in the equatorial east-central Pacific all roughly correspond to prominent features on Fig. 4c, but are of opposite sign. The anomaly pattern in the northern Indian Ocean actually becomes established during the June, July, August (JJA) season (Fig. 4b), consistent with the creation of the anomalies by the surface wind field during the Indian monsoon. During the SON and the December, January, February (DJF) seasons (Figs. 4c and 4d) the correlations have expanded throughout the northern Indian Ocean, but have weakened slightly during DJF.

The correlations north of Australia grow until SON (Figs. 4a to 4c) and then drop dramatically during DJF (Fig. 4d). Nicholls (1984b) showed that SST anomalies

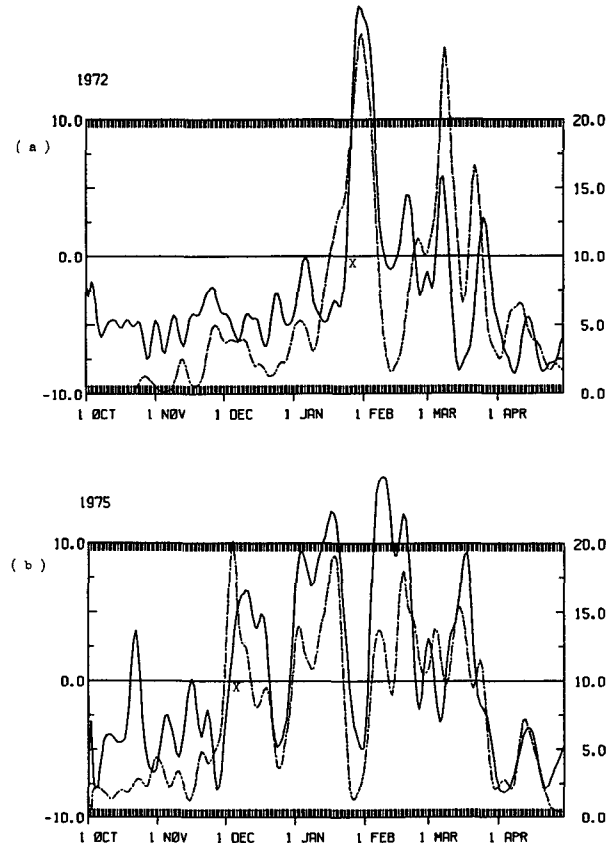


FIG. 5. 850 mb (lightly filtered) daily zonal wind at Darwin (solid line) and area averaged rainfall over northern Australia for October through April (a) 1972/73 and (b) 1975/76. Wind scale is in $m s^{-1}$ (left axis) and rain scale is in mm (right axis). Onset is indicated by an "X."

TABLE 1. Correlations between the SST anomalies of the SON season at areas A, B, and C and those between the SON SST anomalies and the following ASMO for the period 1957–1983. Here, A, B, and C are the stippled or cross hatched areas of the Indian Ocean, the ocean north of Australia, and the equatorial eastern Pacific Ocean, respectively, in Fig. 3.

Correlated pairs	Coefficient of correlation	Coefficient of correlation for significance of	
		95%	99%
SON SST anomaly at A and ASMO	0.52	0.39	0.50
SON SST anomaly at B and ASMO	-0.54	0.40	0.51
SON SST anomaly at C and ASMO	0.47	0.39	0.50
SON SST anomaly (A-B) and ASMO	0.61	0.39	0.50
SON SST anomalies at A and C	0.68	0.43	0.55
SON SST anomalies at B and C	-0.69	0.38	0.49
SON SST anomalies at A and B	-0.47	0.38	0.49

in this region change sign during DJF. The temporal evolution of the correlation pattern north of Australia suggests that anomalies may have a controlling effect on ASMO since they peak during the season just prior to onset. The correlations in the east-central Pacific, however, peak during JJA (Fig. 4b).

Table 1 illustrates the connection between SON SST anomalies averaged in each of the three shaded regions of Fig. 3 and the ASMO that follows, along with the correlations (corrected for serial correlation) necessary for statistical significance at the 95% and 99% levels. The correlation between the SST of the north Indian Ocean or the ocean north of Australia and ASMO is about the same, while that between the equatorial eastern Pacific and ASMO is slightly smaller. Since the Indian and Australian SSTs are each better correlated with ASMO than with each other, it is not surprising that the difference between these shows a large increase in explained variance when correlated with ASMO.

The multiple correlation of the date of ASMO with the SON SST anomalies of the Indian Ocean and the ocean north of Australia is 0.62. Adding the eastern

Pacific SSTs to the regression does not increase the correlation. The multiple correlations of ASMO with SST anomalies in the eastern Pacific and Australian waters and that with the eastern Pacific and Indian oceans is 0.56 and 0.54, respectively. Thus, it may be inferred that the presence of warm waters in the eastern Pacific is not the controlling factor in the variability of the date of ASMO during the period studied in this paper.

5. Two contrasting cases of ASMO

The ASMO dates used in this study are those derived by Hendon and Liebmann (1990) using the combined wind and rainfall index as described briefly in section 2. In this section we give two examples of the wind and rainfall variations that were used to define ASMO.

a. Monsoon onset in 1972/73

Figure 5a shows the variation in daily 850-mb zonal wind at Darwin (lightly filtered) and the area-averaged daily rainfall over northern Australia in a typical delayed ASMO case. The first day of a spell of wet westerlies is identified as monsoon onset day. ASMO date is 23 January 1973, a delay of 29 days from the normal onset date of 25 December. There were two short but intense spells of active monsoon that season, separated by about 40 days. Holland (1986) noted a mean period of 40 days between active phases of the Australian monsoon. A strong El Niño began early in 1972. There also was a major Indian monsoon drought in 1972, with ISMR of 653 mm, 22.2% below the 30-year mean.

During SON 1972, the equatorial trough area of the Indian Ocean had a warm SST anomaly, while the ocean north of Australia had a cold anomaly (Fig. 6a).

b. Monsoon onset in 1975/76

Figure 5b shows the time series of wind and rainfall during 1975/76, a year of early ASMO. The onset occurred on 1 December 1975, 24 days early. During that season's monsoon there were 4 spells of intense monsoon activity, again each separated by about 40 days. A cold event matured in the winter of 1975/76. ISMR in 1975 was 960 mm, 14.4% above the mean. During SON 1975, SST anomalies in the Indian Ocean and the ocean north of Australia were cold and warm, respectively (Fig. 6b), of opposite sign to those during SON 1972.

6. ASMO and Darwin surface pressure

Nicholls et al. (1982) and Nicholls (1984a) have shown an association between the ASMO and the surface pressure at Darwin during the preceding months. The correlation between SON Darwin pressure and the date of ASMO, for the period 1957–1986, is 0.51, significant at the 99% level after correcting for serial correlation.

Shukla and Paolino (1983) have shown that deficient ISMR is followed by a large positive anomaly in Darwin surface pressure lasting several months. The positive pressure tendency at Darwin starts in the Northern Hemisphere winter season prior to a deficient monsoon and continues until the end of the monsoon season

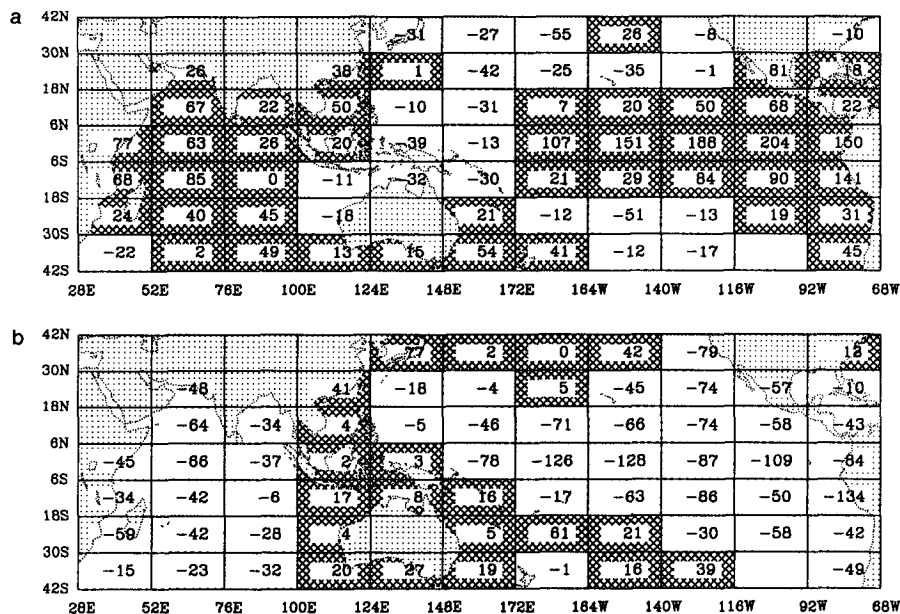


FIG. 6. SST anomalies $\times 100$ (from 11-year running mean) for SON (a) 1972 and (b) 1975. Positive anomalies are cross hatched.

TABLE 2. The change in mean sea level pressure at Darwin, April minus January, in the years of deficient and excess ISMR and in the years of El Niño and cold events. Its long period average for 1939–1984 is 3.0 mb and standard deviation is 1.3 mb.

Deficient monsoons				Excess monsoons			
With El Niño		Without El Niño		With cold event		Without cold event	
Year	Pressure change (mb) (Apr–Jan)	Year	Pressure change (mb) (Apr–Jan)	Year	Pressure change (mb) (Apr–Jan)	Year	Pressure change (mb) (Apr–Jan)
1939	4.4	1968	5.6	1942	1.8	1953	2.0
1941	2.8	1974	4.8	1970	1.8	1956	3.5
1951	4.1	1979	3.7	1973	1.7	1959	2.8
1965	4.9			1975	1.3	1961	1.9
1972	4.8						
Mean pressure change (Mb)	4.2		4.7		1.7		2.5

(Fig. 2 of their paper). Positive (negative) pressure anomaly and pressure tendency are both associated with deficient (excess) ISMR years. They used data of the period 1901–1981, which contained 14 deficient monsoons and 12 excess monsoons. Of the 14 deficient monsoons, only 8 are associated with moderate/strong El Niño (Quinn et al. 1987); of the 12 excess monsoons, only 6 are associated with cold events (Kiladis and Diaz 1989). Shukla and Mooley (1987) listed the values of the change in Darwin pressure from January to April for the period 1939–1986. Nine deficient monsoons have occurred during the common period 1939–1981. Eight excess monsoons have occurred during the same period. The change in January to April Darwin pressure in all these cases, stratified to deficient (excess) monsoons accompanied by El Niño (cold events) or not, are given in Table 2. This shows indirectly the association of the variability of ASMO with that of ISMR.

7. A hypothesis regarding the variability of ASMO

We showed in section 3 that the variability of ASMO is closely tied to that of the preceding ISMR. In sections 4 and 5 we showed that both ISMR and ASMO are associated with SST anomalies of the SON season after ISMR and preceding ASMO.

A schematic of the hypothesized sequence of events leading to a delayed ASMO is presented in Fig. 7; early onset occurs with opposite anomalies. A weak Indian summer monsoon causes positive SST anomalies over the tropical Indian Ocean. These positive SST anomalies in turn delay the seasonal transition of the equatorial trough, which results in a delayed ASMO.

El Niño has a role in ASMO variability in at least two ways. First, since El Niño is associated with deficient ISMR, it is also associated with delayed ASMO. Second, El Niño is associated with anomalously cool waters north of Australia, which can also delay ASMO. Thus, warm SSTs in the eastern Pacific are associated with a delayed ASMO.

A positive pressure tendency at Darwin from January through the northern summer is associated with both El Niño and deficient ISMR. By SON, Darwin has developed a large positive pressure anomaly, which is observed prior to delayed ASMO cases. It is not our intention to show that variability of Darwin pressure and ASMO have a cause and effect relation, but that the two are associated.

Murakami et al. (1986), using OLR data, showed that a delay in ASMO is associated with a delay in the seasonal transition of the equatorial cloudiness maxi-

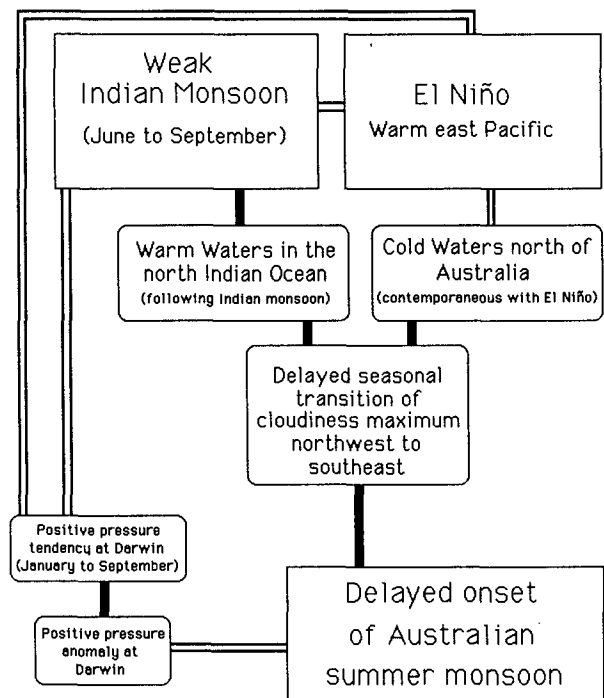


FIG. 7. Schematic of hypothesized sequence of events leading to delayed ASMO. Events (boxes) that have a causal connection (see text) are connected by solid lines. Events (boxes) that occur simultaneously with no causal mechanism implied are connected by double lines.

mum. We show this result directly by compositing cases of delayed and early ASMO for the years during which OLR data are available. Figure 8a is a composite of December OLR for five delayed ASMO cases (1974/75, 1980/81, 1982/83, 1985/86, 1986/87) whose mean date of onset is 9 January. Figure 8b is a similar diagram for five early ASMO cases (1975/76, 1976/77, 1977/78, 1981/82, 1984/85) whose mean date of onset is 5 December.

OLR associated with the delayed ASMO of 1983/84 has been omitted from this composite. The wind and rainfall series used to define onset for this year (similar to Fig. 5) are shown in Fig. 9. An "X" marks the onset as defined by Hendon and Liebmann (1990). The point "Y", about 40 days earlier, shows the requisite increase in wind, but rainfall is slightly short of the required 7.5 mm per day. Had ASMO been defined as occurring during the previous shift to westerlies, it would have been considered an "early" onset (and would have fit the scatter diagram of Fig. 2 almost perfectly). Thus 1983/84 was not included in the composite.

There is a southward and eastward shift of the equatorial cloud band of December between the late ASMO (Fig. 8a) and early ASMO (Fig. 8b) composites. The shift occurs in the direction of the normal seasonal transition of cloudiness as studied by Liebmann and Hartmann (1982) and Meehl (1987) for the northern summer to winter. Thus, the seasonal transition of the cloudiness maximum is later than usual prior to a delayed ASMO.

Figure 8c shows the difference in cloudiness between delayed and early onsets. It is representative of an amplified delayed onset. Excess convection in the western tropical Indian Ocean (denoted by negative OLR differences) and the deficient convection in the ocean north of Australia characterize a delay in ASMO. These are the areas of large positive correlation in the Indian Ocean and negative correlation in the ocean north of Australia in the SON season prior to ASMO (Fig. 4c). Enhanced convection is also evident along the equator east of the date line, characteristic of an El Niño.

It is possible that there is a direct association between SST anomalies in the equatorial eastern Pacific and

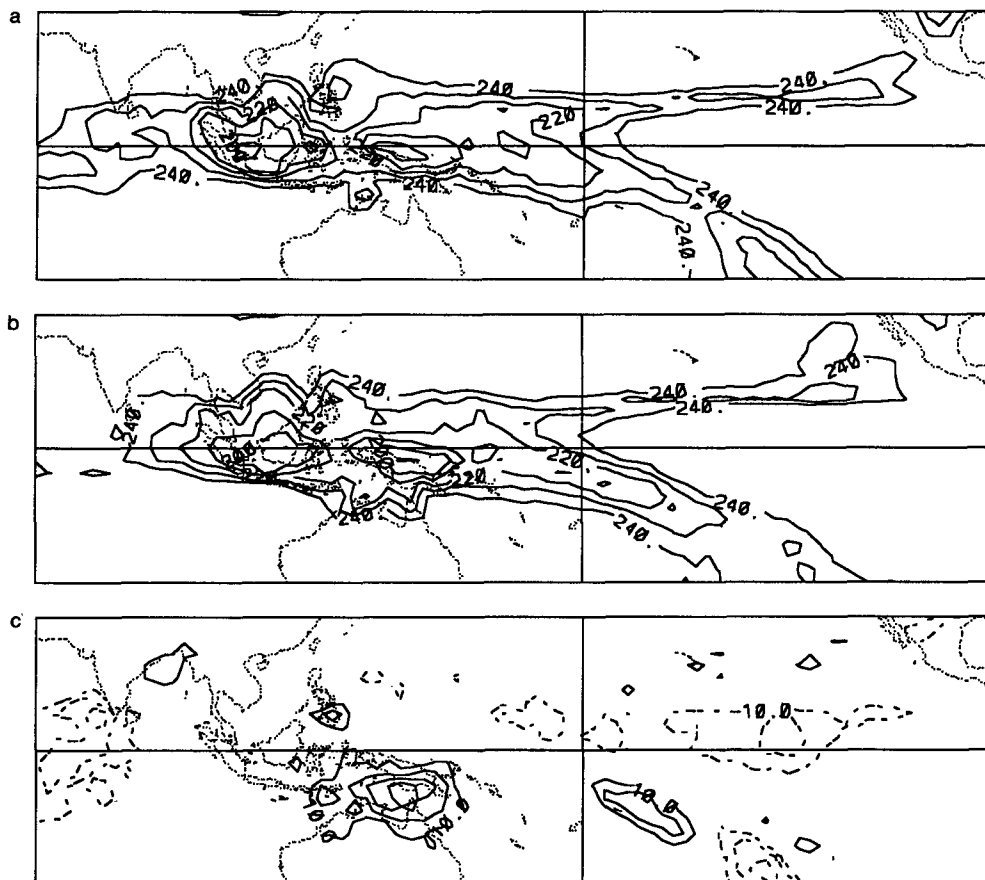


FIG. 8. Composite December OLR for (a) five years with delayed (mean of 9 January) ASMO (see text); (b) five years with early (mean of 5 December) ASMO. Contours decrease from 240 W m^{-2} with an interval of 10 W m^{-2} . (c) Difference (delayed minus early) between (a) and (b). Contour interval is 5 W m^{-2} starting at 10 W m^{-2} . Negative contours are dashed.

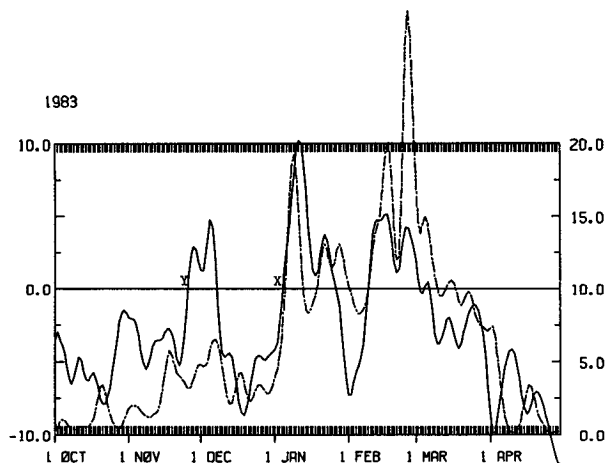


FIG. 9. As in Fig. 5, except for 1983–84. Onset date as defined by Hendon and Liebmann (1990) is marked by "X." The significance of "Y" is discussed in text.

ASMO through changes in the Walker circulation. Figure 8c shows that the convective anomaly near the dateline is as large as the anomaly in the Indian Ocean, although the actual values of OLR are lower over the Indian Ocean than over the eastern Pacific (Figs. 8a and 8b).

A hypothesis similar to the one presented in this paper has been proposed by Joseph (1990) and is supported by data analysis by Joseph and Pyle (1990) to explain the variability of the date of monsoon onset over Kerala in India. According to the hypothesis, monsoon onset takes place there when the SST of the "warm pool" over the Indian Ocean exceeds that of the Pacific warm pool during May to June. Such a situation attracts large-scale moisture convergence to the northern Indian Ocean, in preference to the Pacific warm pool, thus organizing the monsoon onset over India. Most of the cases of delay of monsoon onset are found to be associated with the El Niño warming of the equatorial central Pacific Ocean.

8. Conclusions

We find that deficient ISMR is associated with delayed ASMO and excess ISMR is associated with early ASMO. It is known that deficient ISMR results in warm SST anomalies in the tropical Indian Ocean. We therefore hypothesize that warm Indian Ocean SST anomalies delay the southward and eastward seasonal transition of the equatorial cloudiness maximum during the November to January period, which in turn delays ASMO. Excess ISMR is associated with cold SST anomalies in the Indian Ocean and early ASMO.

Warm and cold events also affect the date of ASMO. Warm events are associated with deficient ISMR, which delays ASMO. Many cases of anomalous ISMR, however, occur in the absence of El Niño/cold events. El

Niño (cold events) can also affect ASMO through the cold (warm) SSTs that occur north of Australia during these times. There may also be a direct link between east Pacific SST and ASMO.

ISMR and antecedent SST anomalies both are able to explain about 40% of the variance of the date of ASMO. The 40- to 50-day oscillation (Madden and Julian 1972) also is important for determining the exact date of ASMO. Hendon and Liebmann (1990) showed that ASMO coincides with the arrival of the convective phase of the 40- to 50-day oscillation. Thus, while SSTs control the latitude of the envelope of the 40- to 50-day oscillation, ASMO does not occur until the convective phase of a 40- to 50-day event reaches Australia.

Our finding that a warm SST anomaly in the equatorial Indian Ocean and a cold anomaly in the ocean north of Australia will lead to a delayed southeastward transition of the equatorial trough, we believe, can be easily tested in a general circulation model. Since these models do not produce a realistic 40- to 50-day oscillation, however, it would be difficult to model the resulting variability of ASMO.

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