

The Dynamics of Double Monsoon Onsets

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ABSTRACT

Double monsoon onset develops when the strong convection in the Bay of Bengal is accompanied by the monsoonlike circulation and appears in the Indian Ocean in early May, which is about 3 weeks earlier than the climatological date of the onset (1 Jun). The initial “bogus onset” is followed by the flow weakening or reversal and clear-sky and dry conditions over the monsoon region. The best example of such a phenomenon is the development of the summer monsoon in 1995, when monsoonlike perturbations that appeared in mid-May disappeared by the end of the month and were followed by a heat wave in India, delaying onset of the monsoon. The climatology of double onsets is analyzed, and it is shown that they are associated with delay of the monsoon rainfall over India. This analysis indicates that the development of bogus onsets depends on the timing of intraseasonal oscillation in the Indian Ocean and the propagation of convective episodes into the western Pacific. There is evidence that an SST evolution in the Bay of Bengal and the western Pacific plays an important role in this phenomenon. It is shown that in the case of the double monsoon onset it is possible to predict hot and dry conditions in India before the real monsoon onset. In the 32 yr of climatological data, six cases of double monsoon onset were identified.

1. Introduction

This paper discusses double monsoon onsets that are related to extremely harsh conditions in India: dry and hot weather (Halpert et al. 1996) just before the real monsoon begins. There is fairly little known about multiple onset climatology, synoptics, or the relationship with the real onset and the mean monsoon circulation. The term “double” or “multiple” onset was apparently first used by Fieux and Stommel (1977). They studied different types of onset of the southwest monsoon over the Arabian Sea using ship reports of surface winds along two densely occupied shipping lines. They divided the monsoon onset into three categories: single, gradual, and multiple (double). The multiple onset was defined as the monsoon beginning with an increase of southwesterlies followed by the wind reversal. For the period between 1950 and 1970 they identified four such cases.

The goal of this paper is to present a conceptual model of the dynamics, climatology, and predictability of double monsoon onsets. To this end we concentrate on two topics: (a) detailed case study of the spectacular 1995 double monsoon onset and (b) double monsoon onset climatology and dynamics. We are not concerned with differences between the gradual and the single onset.

To develop physical understanding of driving mechanisms we discuss the 1995 double monsoon onset and its relationship with the intraseasonal variability in the Indian Ocean. Similar cases are identified in the atmospheric reanalysis data and are compared with the perturbations preceding the 1995 monsoon. The monsoon of 1979, which was widely studied using the First Global Atmospheric Research Program (GARP) Global Experiment data, is an example of the multiple onset case (Schott and Fernandez-Partagas 1981), although this aspect of its development was never emphasized. Pearce and Mohanty (1984) noted that the 1979 summer monsoon started later in the season and that its development was more rapid than in the case of onsets in 1980, 1981, and 1982. Webster (1986) associated the delay of the 1979 monsoon onset with the phase of the intraseasonal oscillation [called also the Madden–Julian oscillation (MJO)], noticing that prior to 20 June, the oscillation contributed the easterlies to the low-level flow, thereby inhibiting the development of monsoon southwesterlies. The role of intraseasonal oscillation in the 1979 monsoon was pointed out by Chen et al. (1988) also, who studied the influence of 30–50-day oscillation on the monsoon life cycle. They observed that the premonsoonal intraseasonal mode in early May 1979 (related to the bogus onset) was almost identical to that in early June, which initialized the real onset. However, the early May perturbation did not cause the onset because the annual-scale divergent circulation was not sufficiently developed at this time.

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The early development of the monsoon in 1995 was similar in many ways to the 1979 onset. It is worth noting that the reversal of monsoonlike circulation was associated with exceptionally hot weather in India (Soman and Slingo 1997; De et al. 1996; Halpert et al. 1996). Temperatures exceeded 38°C in central and northern India and reached 43°C in some areas in the north and northeast. The highest maximum temperature of 49°C was recorded at Anupgarh, India, on 16 May and at Dholpur, India, on 31 May. The heat wave caused widespread water and electricity shortages. Monsoon conditions started to develop again in early June in the southeastern part of the Bay of Bengal. Similar to the 1979 case, the monsoon arrived at the southern tip of India (the Kerala coast) on 8 June, about a week later than usual. The delay of the monsoon related to the bogus onset in early May, and fairly dry conditions preceding the real onset, were also observed two years later, in 1997.

To develop the conceptual model we examine the climatology of bogus onsets using the 33 yr of reanalysis data produced by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR). We use the Climate Data Center's daily interpolated outgoing longwave radiation (OLR) data to study the development in the equatorial Indian Ocean, Arabian Sea, and the Bay of Bengal. We use Reynolds's (Reynolds and Smith 1994) and Jet Propulsion Laboratory's sea surface temperature (SST) from Advanced Very High Resolution Radiometer (AVHRR) to look at the role of the SST in supporting the convection during the bogus onset phase. The local effects of development of the bogus monsoon circulation are assessed from the Arabian Sea moorings (Rudnick et al. 1997; Weller et al. 1995, 1998). This mooring array yielded the first long time series of atmospheric and oceanic variables during the summer and winter monsoon. The results from the moorings' observations (Rudnick et al. 1997; Weller et al. 1998) show the change of wind direction and specific humidity maximum indicative of development of monsoonlike circulation in early May and subsequent wind reversal in late May through early June. Drifting buoy observations are used to examine the response of SST to the wind and surface flux changes in the equatorial Pacific and the Bay of Bengal, between May and June of 1995.

2. 1995—The most beautiful double monsoon onset

a. Development of circulation

The first or "bogus" onset of the 1995 monsoon was initiated by the northward motion of equatorial convection related to intraseasonal oscillation (ISO) that developed in the Indian Ocean around 1 May. Figure 1 shows the time–longitude diagram of the OLR for the

equatorial (5°S–5°N) and north (10°–15°N) Indian Ocean that is related to the passage of this ISO episode. The convection originated in the equatorial area near 50°E and propagated eastward. After triggering a northward moving mode in the Bay of Bengal, the equatorial convection propagated farther east, into the western Pacific. Off the equator, the slow eastward propagation could be observed between 6 and 21 May followed by the westward motion of convective cells originating in the western Pacific, starting at the end of May.

As shown in Fig. 2a, in early May the convection extended throughout most of the equatorial Indian Ocean. Surface westerlies straddled the equator from 60° to 90°E. In the Arabian Sea and the Bay of Bengal the low-level winds were weak and predominantly from the northeast, while the prevailing upper-level winds were from the west. By 6 May (Fig. 2b) the equatorial system broke into twin cyclonic circulations that started to propagate poleward. In the Northern Hemisphere the convection moved into the western part of the Bay of Bengal and formed a deep depression on 6 May, which caused heavy flooding in the coastal areas (De et al. 1996). This propagation pattern resembled the N(S)E mode of ISO described by Wang and Rui (1990), which can take place in late or early boreal summer. The break-up of equatorial convection into twin systems is characteristic of heat sources on the equator (Gill 1980) and can occur in the Indian, as well as the Pacific, Ocean, especially during the transition periods in spring and autumn.

Another mechanism that can influence the generation of twin perturbations in this area involves the lee waves formation west of Sumatra (Mukherjee and Padmanabham 1978). Since the island extends across the equator, the easterly flow over the Sumatra mountains can create cyclonic vortices on both sides of the equator. In early May of 1995, the 500-mb easterlies in the equatorial western Pacific were fairly strong; therefore, this process could contribute to intensification of convection in the Bay of Bengal in mid-May. The convective systems propagated along the western shore of the Bay of Bengal in a clockwise direction, and two more deep depressions were formed on 8 and 14 May (De et al. 1996).

The convection initiated the development of the fairly strong southwesterly flow over the Bay of Bengal and westerly winds over the Arabian Sea (Fig. 2c). The pressure over India decreased, reaching 996 mb, while at 200 mb the subtropical westerly jet moved northward, and the easterly flow started to develop over India. Over the equatorial area the convection was strongly suppressed by the subsidence related to the local Hadley cell with the upward branch in the Bay of Bengal. The Walker cell, triggered by the upward motion in ISO, by 17 May moved into the western Pacific and also contributed to the subsidence in the equatorial Indian Ocean.

These conditions indicated the beginning of the southwesterly monsoon and persisted for about a week. How-

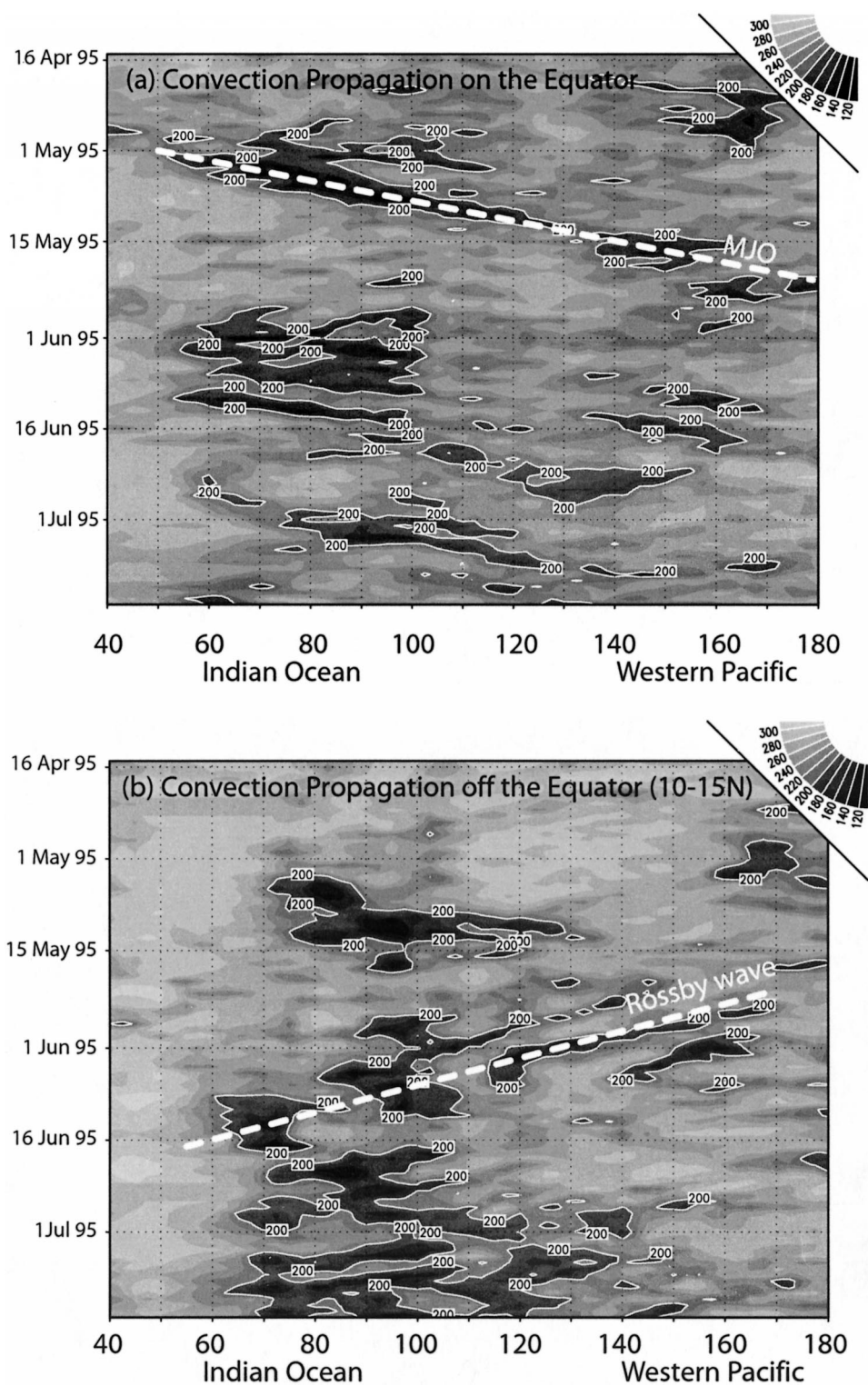


FIG. 1. OLR during the 1995 monsoon.

ever, by the end of May, convection over the Bay of Bengal dissipated (see Fig. 2d). Low-level southwesterly flow disappeared, upper-level westerlies returned over India, and the pressure low filled up. The convection in the western Pacific moved poleward and from 26 May started to propagate westward along 10° – 15° N (cf. Fig. 1b), reaching the Indian Ocean in early June. This counterclockwise propagation of convection resembled the behavior of intraseasonal oscillations during the summer monsoon described by Wang and Xie (1997). Using the simple numerical model, they showed that during the monsoon season (July–September), the MJO move northward in the western Pacific and around 160° E trigger the Rossby wave that propagates back into the Indian Ocean along 20° N. The Rossby wave amplifies in the region of the south Asian monsoon and reinitiates the disturbance in the equatorial Indian Ocean. The Rossby wave is destabilized by presence of large moisture and an easterly vertical shear of the zonal wind. The life cycle of such perturbations is about 1 month. In 1995 because the oscillation related to the bogus onset developed earlier than those analyzed by Wang and Xie (1997), it propagated closer to the equator, where the easterly shear was already developed. At the time, the convection was concentrated in the western North Pacific, and the north Indian Ocean remained clear but a small convective system started to redevelop over the equatorial Indian Ocean. This reversal of an earlier monsoonal circulation created the drought conditions in India in the period just preceding the monsoon (Halpert et al. 1996).

The monsoon flow returned in early June (Fig. 2e), with the official arrival of the monsoon on the Kerala coast on 9 June, about a week later than the average. Initially, the convection was concentrated in the Bay of Bengal, with the eastern Arabian Sea area remaining relatively clear. The convection began to develop in the Arabian Sea after the Rossby wave propagating from the western Pacific reached this region, around 16 June (cf. Fig. 1b). Similar to the case described by Wang and Xie (1997), the whole cycle from the development of equatorial convection in the Indian Ocean to the time when westward-propagating systems reached the Bay of Bengal took one month.

The effects of the double monsoon onset could be directly observed in the results of the moored buoys (Weller et al. 1998) in the Arabian Sea (12° N, 50° E) and Lagrangian drifters in the Bay of Bengal. Figure 3 shows the evolution of the observed SST, pressure, u and v components of the surface wind, and surface specific humidity observed by the Arabian Sea Experiment moorings. To emphasize the intraseasonal variability of these parameters, we filtered out the perturbations with timescales longer than 90 days and shorter than 5 days. The increase of the wind speed in early May, with a maximum on 15 May, is evident in the Arabian Sea data. The changes in circulation are accompanied by the decrease of the surface pressure (not shown). After wind

reversal in late May, the zonal and meridional velocities decrease from 8 and 4 m s^{-1} , respectively, to -1 and -2.5 m s^{-1} .

The changes in circulation influence the moisture flux in the Arabian Sea. The surface moisture increases during the bogus onset, reaching a maximum of 21.3 g kg^{-1} on 15 May. However, the reversal of the wind speed disturbs the moisture buildup, and the specific humidity drops by almost 5 g kg^{-1} in late May. The NCEP–NCAR reanalysis indicates that this drying effect extends to the whole troposphere and is quite significant. As shown in Fig. 4, May and early June precipitable water was smaller than average by about 5–8 cm, with the largest anomaly occurring in early June. Since the moisture from the evaporation in the Arabian Sea provides the water source for the Indian rainfall (Pearce and Mohanty 1984), disturbing this “water loading” process affects the average monsoon precipitation.

b. Modification of SST

In the previous section we have shown that the bogus monsoon onset in 1995 was triggered by a passing intraseasonal oscillation episode. Another factor contributing to the intensification of convection in the Bay of Bengal was unusually high SST in the Bay of Bengal and equatorial Indian Ocean. Figure 5 shows the SST anomaly in the Indian Ocean in April and May of 1995. In April, the positive SST anomaly extended throughout the tropical Indian Ocean, both north and south of the equator, providing the surface energy for development of the twin perturbations. In addition, the positive anomalies were present in the western Pacific warm pool up to the date line and in the South Pacific convergence zone (SPCZ). Weekly SST fields from the AVHRR (not shown here) indicate that, in comparison with previous years, the 1995 Bay of Bengal SSTs were especially large in late April—that is, directly preceding the development of the bogus monsoon.

The high SSTs at the beginning of May were also seen in the Lagrangian drifters data. In April–June 1995 there were four Lagrangian drifting buoys present in the Bay of Bengal—two close to 10° N and 85° E and two farther north, near the east coast of Burma. All the drifters show the maximum SST between the end of April and beginning of May, with the largest temperatures reaching 32°C in the eastern part of the Bay of Bengal (Fig. 6). Following intensification of convection, in the second half of May, there is a rapid decrease of SST, with the largest SST drop of almost 2.5°C in the eastern Bay of Bengal where the strong cyclonic circulation developed.

As a consequence of a large cooling related to development of the bogus monsoon onset, the positive SST anomaly in the Bay of Bengal became negative in May (Fig. 5b). The SST modification by the bogus monsoon is less evident in the Arabian Sea moorings, although Fig. 3 indicates a break in the warming. The

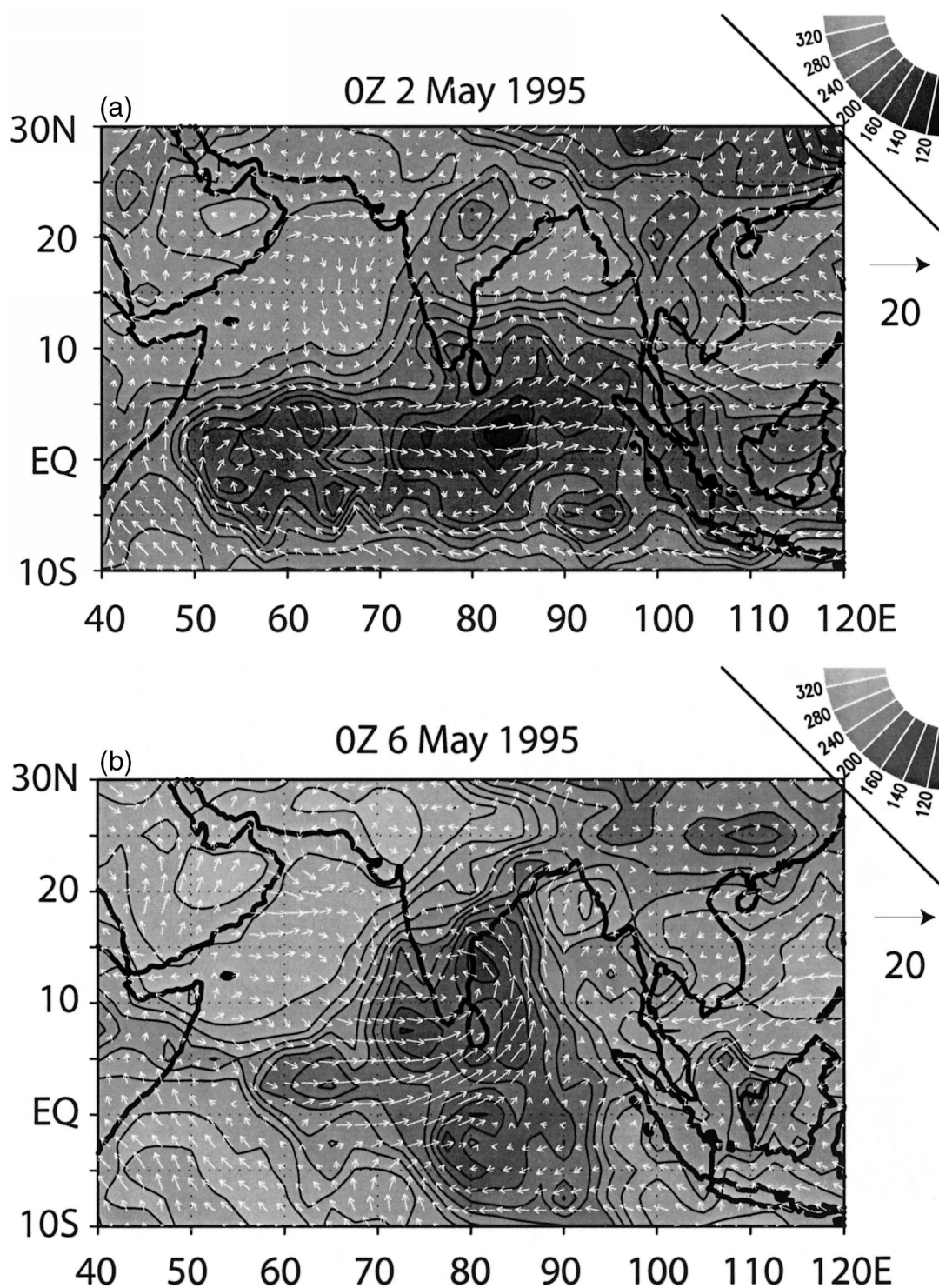


FIG. 2. Evolution of surface winds (m s^{-1}) and OLR (W m^{-2}) for the 1995 double monsoon onset.

weaker cooling in the Arabian Sea can be explained by the fact that in the absence of convection in this area, SST modification was related mainly to the evaporation and mixing caused by the wind stress. In

the Bay of Bengal both large wind stress and radiative fluxes, related to the deep convective systems, contributed to the cooling.

Another feature of the SST anomaly field that could

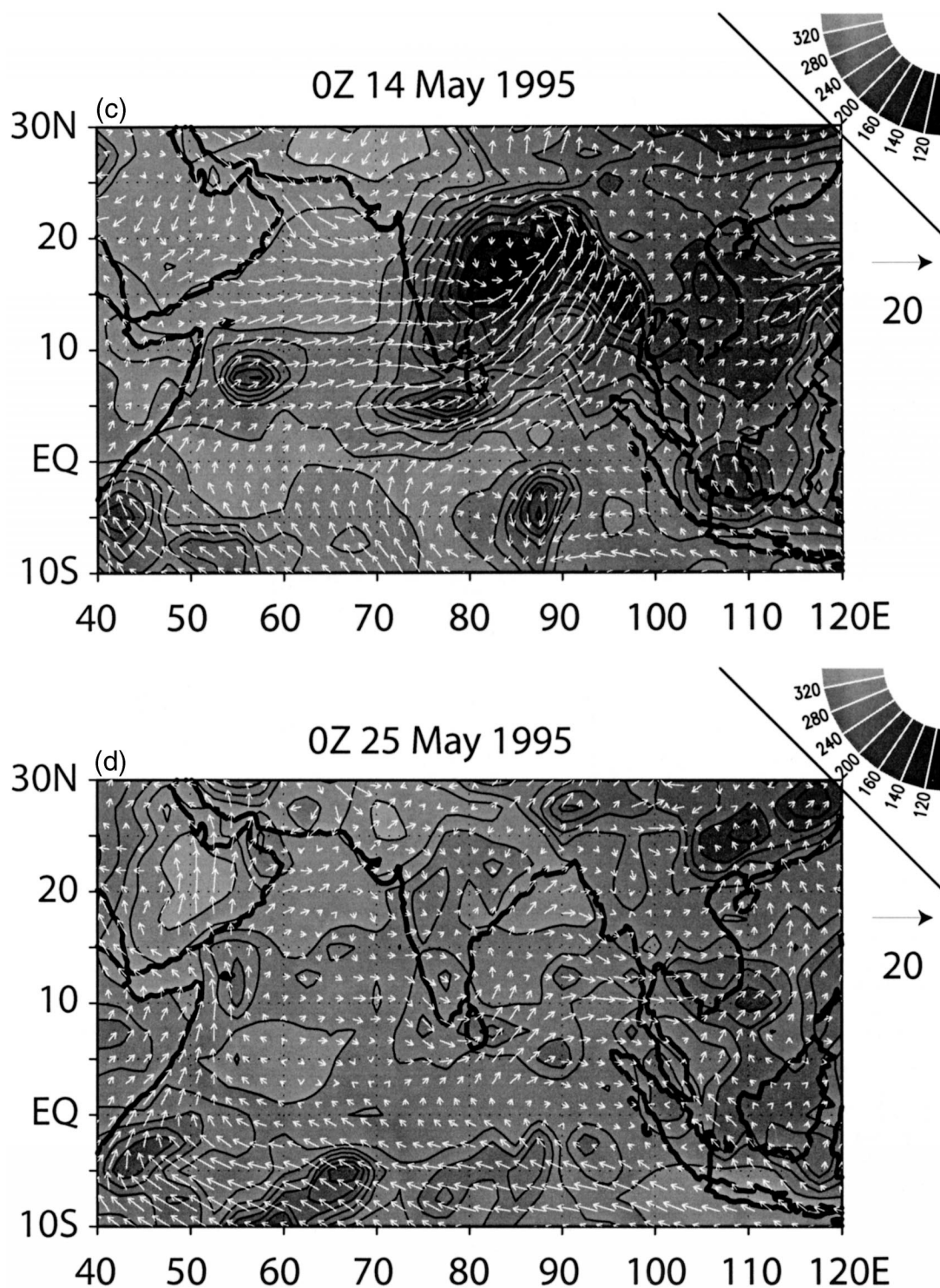


FIG. 2. (Continued)

influence the development of the monsoon onset in 1995 is the presence of the warm anomaly in the equatorial western Pacific and SPCZ (Fig. 2a). These high SSTs in the western Pacific warm pool could contrib-

ute to intensification of convection over the equatorial Pacific and strengthening of vertical motion in the downward branch of the Walker circulation over the Indian Ocean.

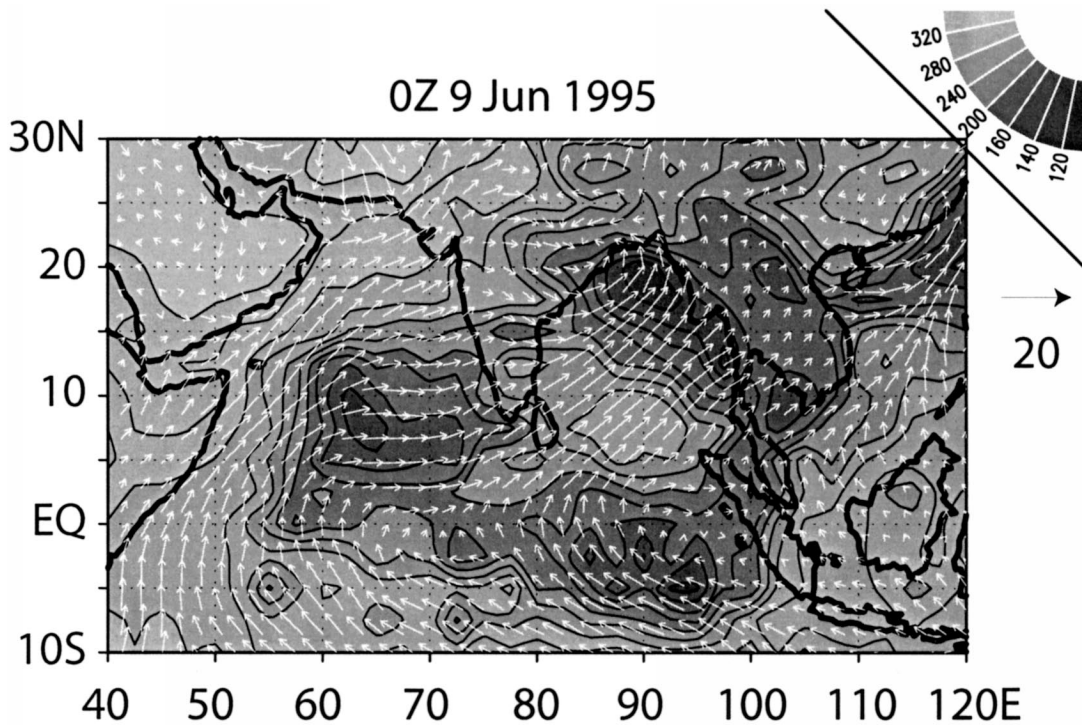


FIG. 2. (Continued)

3. Climatology of double onsets

a. Definitions of multiple onsets

As we have shown, the development of a bogus onset can influence the weather in the premonsoonal period and possibly delay the real onset. Therefore, a full understanding of this phenomenon is important for pre-

dictability of the Asian monsoon. We examine long-term variability of the multiple onsets using 33 yr of NCEP–NCAR data to determine how often multiple onsets develop, what common features they share, and how strong the 1995 case was in comparison with other cases.

Fieux and Stommel (1977), who apparently first introduced the term “multiple onset,” classified monsoon onset on the basis of the surface winds from the shipping lines in the Arabian Sea. They defined three categories

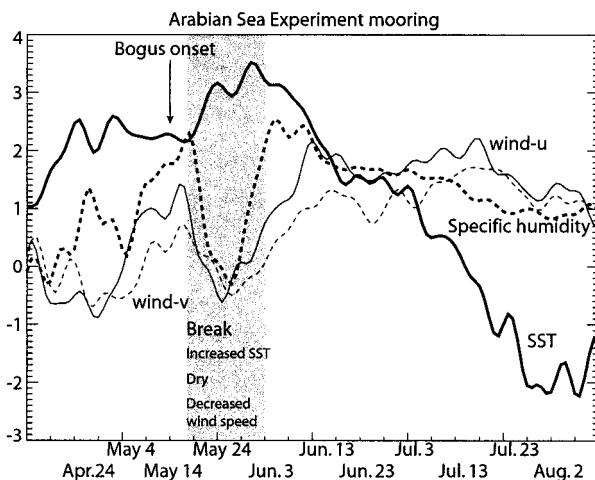


FIG. 3. SST, wind velocity, and specific humidity measured by Arabian Sea Experiment mooring (Weller et al. 1995). The perturbations with a timescale longer than 90 days and shorter than 5 days are removed. The wind values are multiplied by 0.2, specific humidity by 0.5. Thick solid line—SST; thick dashed—specific humidity; thin solid— u ; thin dashed— v .

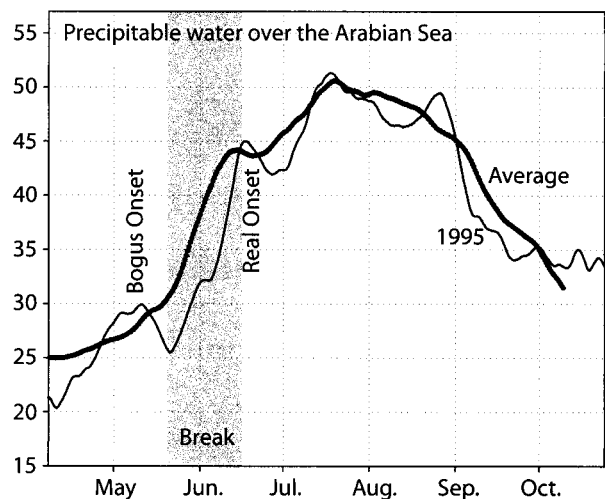


FIG. 4. Precipitable water over the Arabian Sea during the 1995 monsoon.

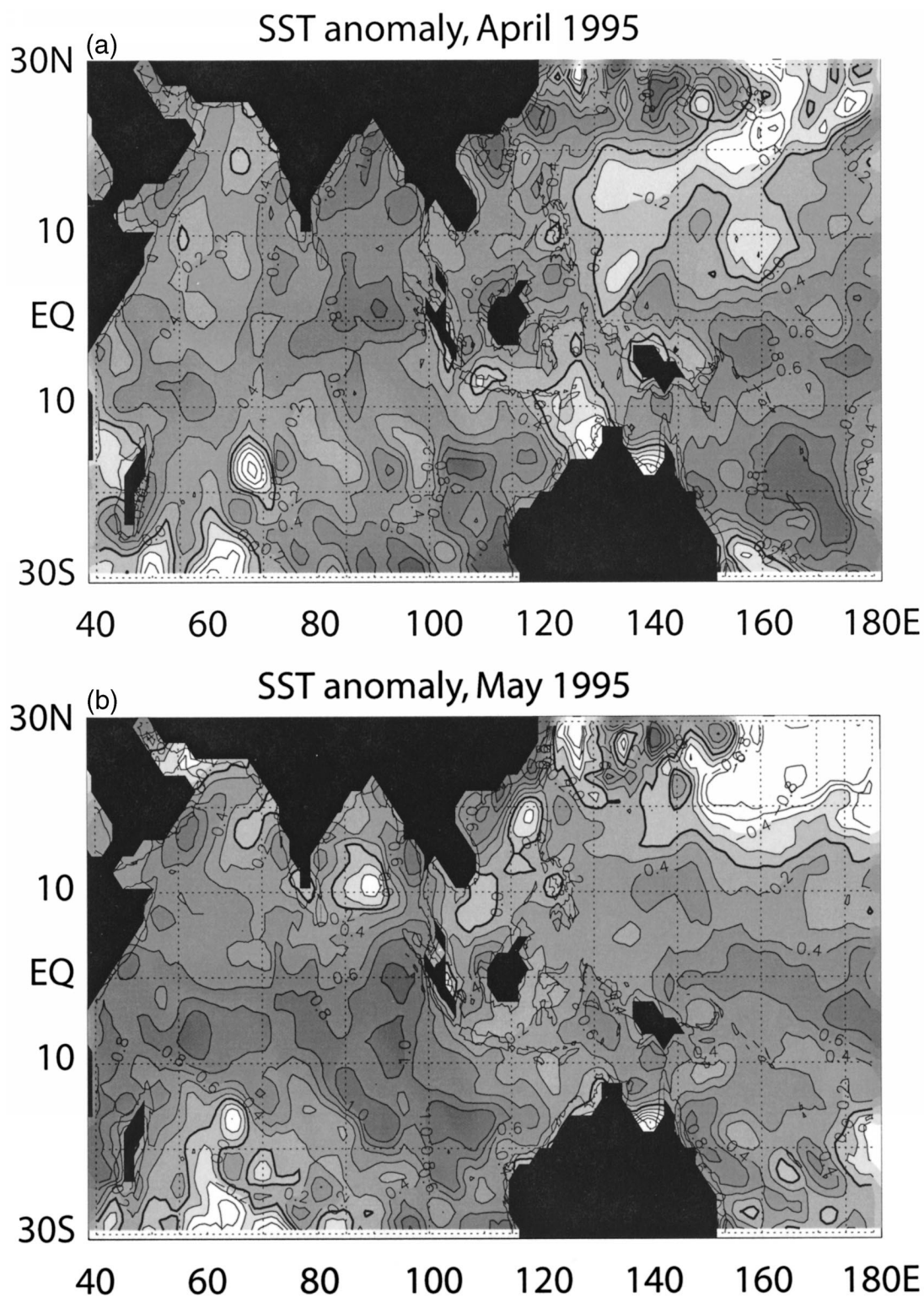


FIG. 5. SST monthly anomaly in the Indian Ocean.

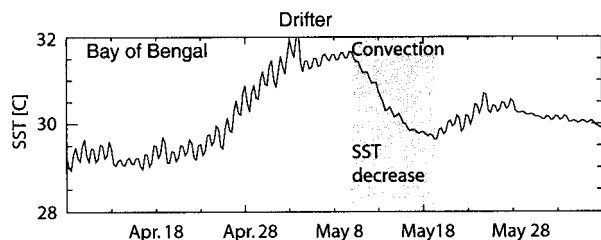


FIG. 6. SST measured by the Lagrangian drifter located in the eastern part of the Bay of Bengal.

of onset: single—with the winds reaching the full strength in less than a week; gradual—with early start and gradual increase; and multiple—with early start, followed by a lull in the monsoon and delayed resumption of the full-strength winds. Using these criteria, they found four cases of multiple onset between 1933 and 1968 with the first, “bogus” onset developing usually in May and the second in early June. According to their classification, the multiple onsets developed in 1946, 1958, 1967, and 1968.

We define multiple monsoon onset using three different criteria: (a) kinetic energy of the surface winds averaged over 5° – 20° N and 40° – 110° E; (b) dynamic monsoon index (DMI) defined as the shear between 850- and 200-mb zonal winds, averaged over 5° – 20° N and 40° – 110° E; and (c) Monsoon Circulation Index (MH) based on the strength of the local Hadley cell and defined as the shear between 850- and 200-mb meridional winds, averaged over 10° – 30° N and 70° – 110° E.

The kinetic energy criterion is the closest to that used by Fieaux and Stommel (1977) since surface winds are used to determine the beginning of the monsoon. However, to avoid the influence of local disturbances we use the value averaged over the large area and smooth the data using a 5-day running mean. The DMI proposed by Webster and Yang (1992) indicates the amount of diabatic heating over south Asia, measured by the first baroclinic mode response to heating. The broad-scale circulation index MH, introduced by Goswami et al. (1999), measures the strength of the local Hadley circulation created by off-the-equator monsoon heating. Of the two indices, the one proposed by Goswami correlates better with the precipitation over India (Goswami et al. 1999) than does DMI. It is related to the fact that the zonal winds (Walker circulation) involved in calculating the DMI may be influenced by equatorial heat sources, which are not directly related to the monsoon. Recently, Lau et al. (2000) have shown that MH is a good representation of the south Asian monsoon and correlates the best with precipitation that includes not only India, but also the Bay of Bengal. Since the development of bogus monsoon onset is related to convection in the Bay of Bengal, the MH index is probably the most appropriate of the three indices shown below to illustrate the double onset phenomenon. Using these three criteria, we examine circulation, looking for the

TABLE 1. The years with multiple monsoon onset arranged according to surface wind energy, shear of the zonal wind, and shear of the meridional wind.

Energy	DMI ($U_{850} - U_{200}$)	MH ($V_{850} - V_{200}$)
1995	1995	1995
1979	1979	1967
1986	1967	1972
1997	1986	1979
1967	1997	1997
1972	1972	
1968		

increase in each index in early May, suggesting the development of the monsoon, followed by substantial decrease at the end of May and beginning of June. Table 1 shows the years with multiple monsoon onsets as defined by the three indices. We order the cases from the strongest to the weakest, as measured by a difference between value of the index at maximum related to the first onset and minimum preceding the second onset. All values are smoothed using the 5-day filter to eliminate short-scale variability.

No matter which criterion is used, the 1995 monsoon stands out as the one in which initial bogus onset was the strongest and reversal the most pronounced (Figs. 7a–c).

Figure 8 shows the case of the “next best multiple onset” for each category (1979 for kinetic energy and DMI and 1967 for the MH index). For all the cases, the changes in circulation are less dramatic than in 1995. In addition, the bogus onset apparent in one index may not be as well defined in another. There are also some cases (such as 1989 or 1973) in which the weakening of the circulation at the end of May appears only in one index, for a few days only. We decided not to include such cases in the multiple onset category. The fact that different indices indicating onset do not necessarily agree is consistent with observations that the mean strength of the monsoon inferred from them is not always the same (Goswami et al. 1999). Therefore, it seems that the meridional and zonal cell of the monsoon do not always develop at the same rate. Of the three definitions we used, the one based on the strength of the local Hadley circulation is the most robust, since the multiple onsets defined by the MH appear in all three categories. Multiple-onset cases identified between 1965 and 1998 include 1967, 1972, 1979, 1995, and 1997. In addition, bogus onset appears in 1986 according to DMI and energy criteria.

b. Relationship between multiple onset and interannual variability of the monsoon

As noted in the previous section, the SST cooling related to the first perturbation and changes in the moisture content may influence the strength of the average system. Therefore, we try to find common characteristics of the multiple monsoon onset cases in an effort

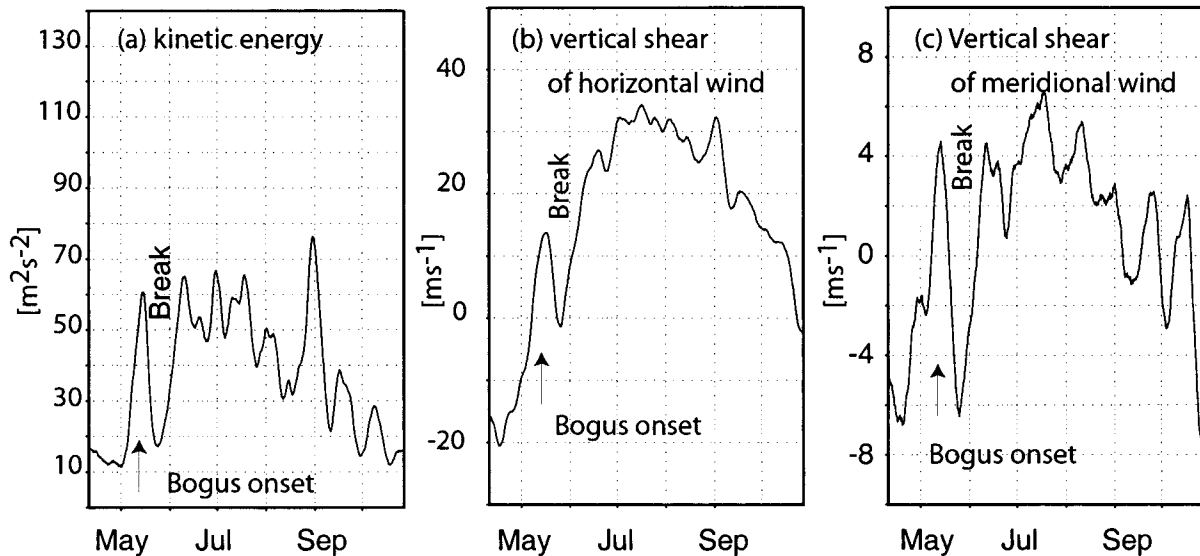


FIG. 7. The indices used to define double onset for the 1995 case: (a) the energy of the surface wind, (b) vertical shear of horizontal wind, and (c) vertical shear of meridional wind.

to predict the probability of such a development. We would like to determine if the multiple onsets are in any way related to the general strength of the monsoon or the amplitude of intraseasonal variability in the area.

The strength of the mean monsoon is usually defined using mean June–September values of horizontal shear (Webster and Yang 1992), meridional shear, or all-India precipitation (Goswami et al. 1999). Since the index based on the meridional shear seems to correlate best with the Indian precipitation (Goswami et al. 1999), we use MH to define the average strength of the monsoon.

Figure 9 shows that even though the 1995 monsoon

was about average, other multiple onset cases seem to be related to rather weak mean monsoon circulation. This may be caused by the fact that initial perturbation contributed to the weakening of the mean monsoon or may be caused by factors influencing both the type of the onset and the average strength of the monsoon. For example some SST patterns may favor both weak mean monsoon and early, bogus onset. During the strong monsoon years, such as 1971, 1980, or 1988, the perturbations that developed in May were usually weak, and no monsoon reversal in the second half of the month was observed. There seems to be no correlation between

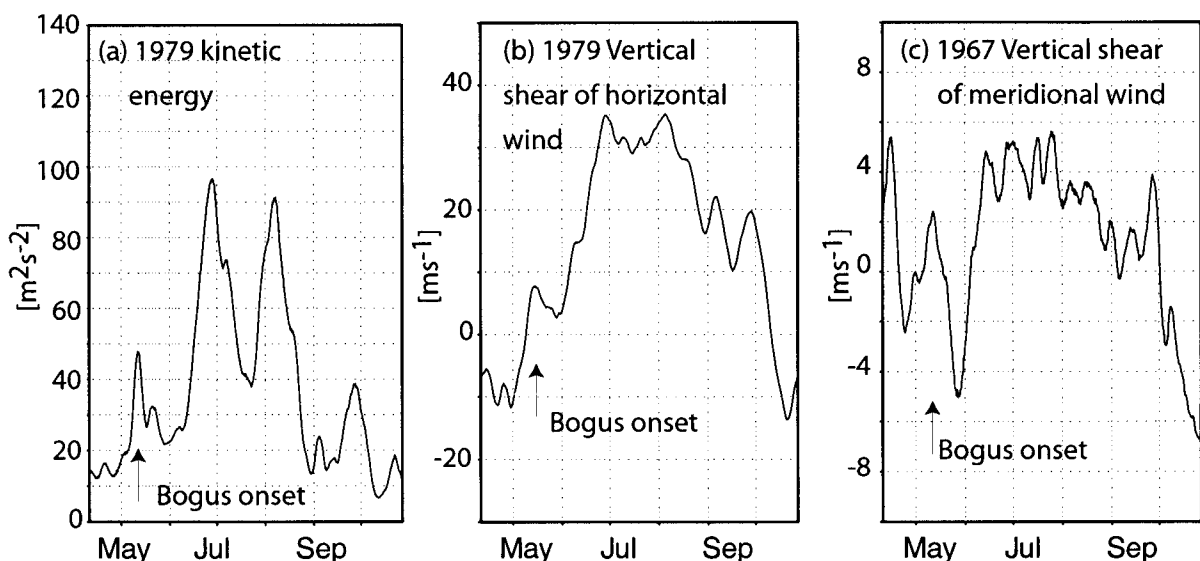


FIG. 8. The same as in Fig. 7 but for the next (after 1995) most pronounced case of double onset: (a) energy of the surface wind for 1979, (b) vertical shear of horizontal wind for 1979, and (c) vertical shear of meridional wind for 1967.

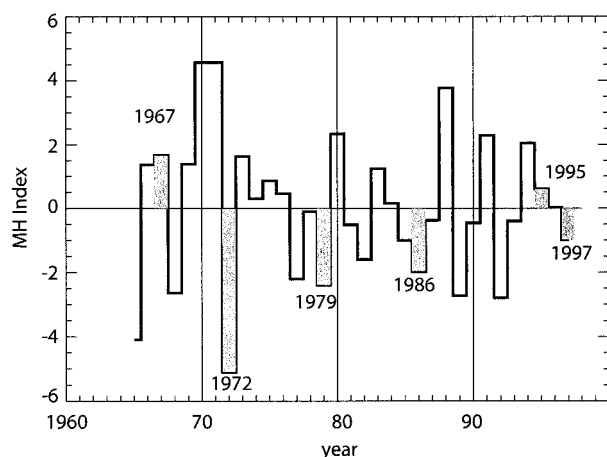


FIG. 9. The averaged strength of the monsoon between 1965 and 1997 measured by circulation index (MH). Gray shading indicates the years with double onset.

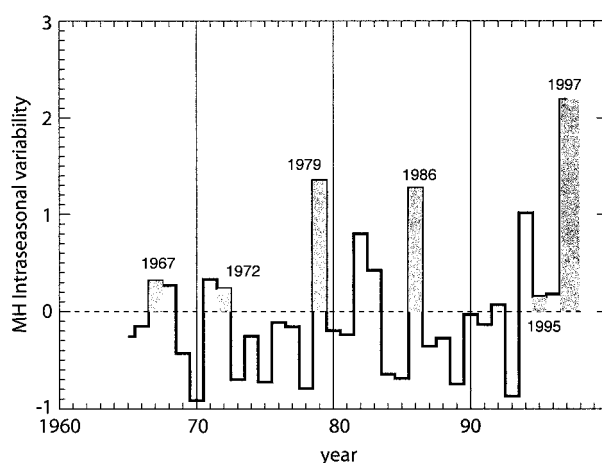


FIG. 10. The averaged-strength 5–90-day perturbations measured by circulation index (MH). Gray shading indicates the years with double onset.

the occurrence of multiple onset and the Southern Oscillation index, Niño-1+2, Niño-3, or Niño-4 temperature anomalies, even though ENSO cycle influences the mean strength of the monsoon (Joseph et al. 1994).

Our analysis of bogus onsets in 1995 indicates that the early May perturbation is triggered by a northward-propagating branch of the MJO. Therefore, we look for the relationship between the strength of intraseasonal modes and the type of monsoon onset. We examine the amplitude of ISO in the monsoon area using meridional shear index (MH). To obtain a quantitative measure of this variability, we first remove all perturbations with periods larger than 5 days and calculate the deviation of shear or the zonal wind from the seasonal (90 days) average. The results are normalized by subtracting the mean and dividing the results by the standard deviation. As shown in Fig. 10, the multiple onset cases appear for the years with the above-average amplitudes of intraseasonal modes. However, there seems to be no direct relationship between the strength of intraseasonal modes and bogus monsoon onset. For example, in 1995 the multiple onset was the most pronounced, but the amplitude of intraseasonal variability was fairly small. In 1986, which was the weakest case of the double onset, intraseasonal variability was much larger than average. Therefore, it seems that the initial perturbation triggering the bogus onset was related to the timing of the ISO rather than the amplitude of variability in this region, which makes the development of the bogus onset very hard to predict.

c. Common features of multiple onset cases

Even though the multiple monsoon onsets did not exhibit any consistent interannual pattern, we could identify features among convective patterns and SST fields that developed for all the cases of the bogus onset between 1981 and 1998—that is, for the years for which

OLR and weekly SST analyses were available. In addition, common intraseasonal-scale circulation features appeared in all the multiple onset cases identified in NCEP reanalysis from 1966 to 1998.

The OLR data indicate that for all these cases, the initial convective perturbation lead to the development of the twin convective systems straddling the equator near 80°–90°E (Fig. 11). As the systems moved poleward and intensified, the circulation in the Northern Hemisphere became monsoonlike. However, circulation reversed or markedly weakened after convection dissipated, and the “real” monsoon onset was usually delayed. The development of the twin convective systems in the initial stage of the monsoon is consistent with Webster (1998) observations indicating the presence of the convective “arc”—that is, convection extending from the equator into the Northern and Southern Hemispheres, directly preceding the onset of the monsoon. In the cases of single or gradual onsets, the OLR in the middle of May shows weaker and scattered convection. Since twin cyclonic circulations observed in 1979, 1986, 1995, and 1997 cases were initiated by equatorial convection that developed in early May, we examined 34 yr of NCEP surface winds for the presence of “westerly bursts” in the equatorial Indian Ocean, which are usually triggered by the equatorial heat source. In all of the cases of multiple onsets the episodes of strong westerlies developed between 1 and 15 May. In addition, the analysis of relative vorticity on both sides of the equator suggested the development of twin tropical depressions in early May, similar to that observed in 1979, 1986, 1995, and 1997.

However, there were cases, such as 1977, 1978, and 1996, in which the equatorial westerlies and twin cyclonic circulations were present without causing the multiple monsoon onset. In these cases the southwest monsoon developed gradually without significant breaks. The largest difference between these cases and

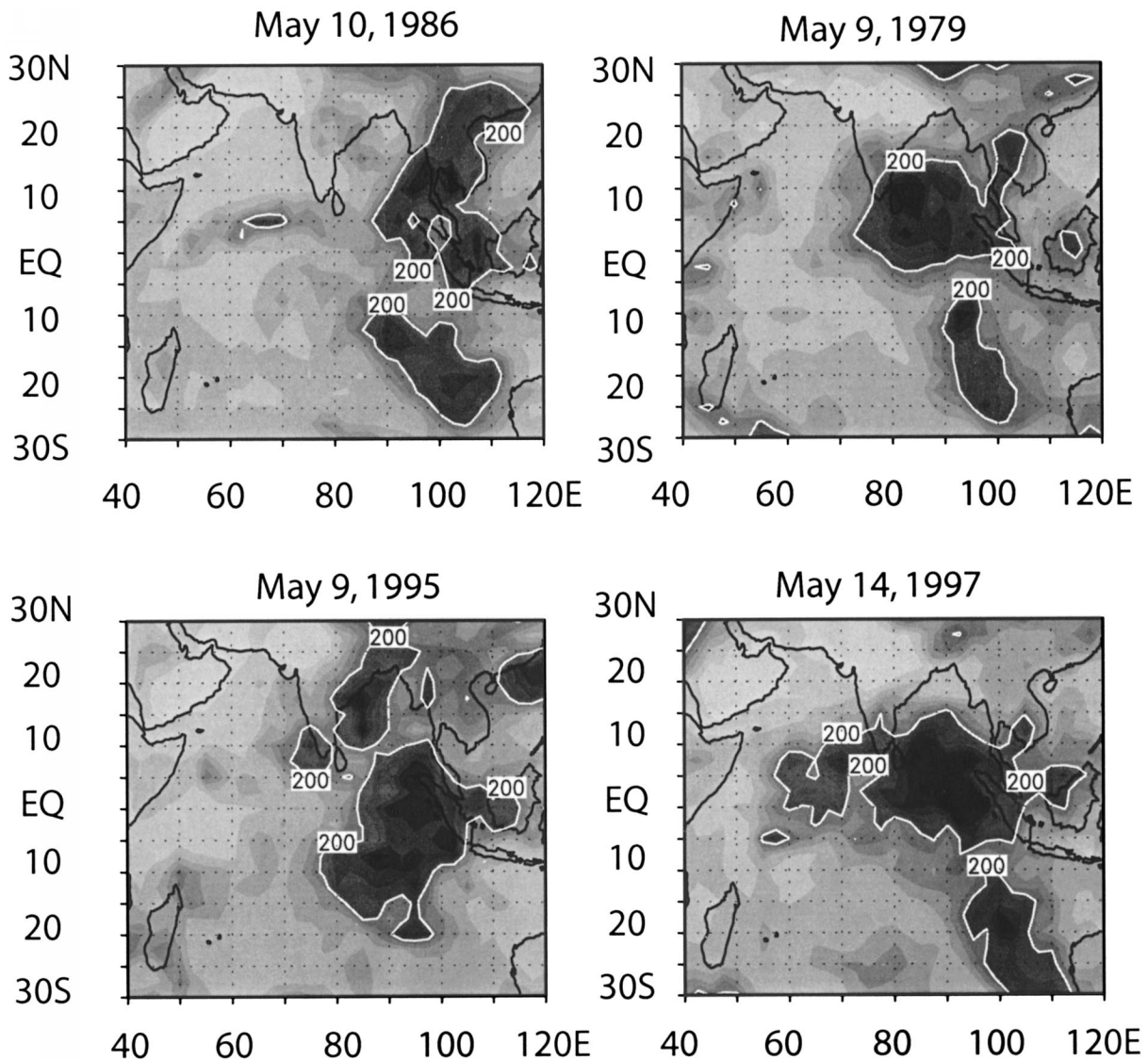


FIG. 11. OLR in the middle of May for the four cases of multiple monsoon onset. OLR contours below 200 W m^{-2} , indicating convection, are dark.

the multiple onsets is in the circulation in the western Pacific. Figure 12 shows the equatorial (5°S – 5°N) zonal winds averaged over the Indian Ocean (60° – 100°E) and western Pacific (140° – 170°E) for the year with multiple onset (1995) and single onset (1977). In 1995 and other years in which the bogus onset developed, the strong westerlies associated with twin convective perturbations appear in the Indian Ocean in early May. About two weeks later, the westerlies move to the western Pacific, suggesting development of a strong convection in the western Pacific warm pool. In 1978, when the monsoon developed gradually, the strong westerlies were apparent in early May on the equator in the Indian Ocean and were accompanied by an increase in cyclonic vorticity in both hemispheres. However, winds in the western

Pacific remained easterly, suggesting the absence of strong equatorial convection.

Another common feature of multiple onset cases is the presence of high SSTs in the Bay of Bengal at the end of April–beginning of May, followed by a large SST drop in May, caused by the development of the bogus onset. Figure 13 shows the SSTs averaged over the Bay of Bengal at the beginning of May and June, obtained from the weekly Reynolds SST analysis. For most of the years, the SST in early June, right before the monsoon onset, is slightly higher than or equal to SST at the beginning of May. However, in the years with multiple onsets—that is, in 1986, 1995, and 1997, the temperatures at the beginning of May were relatively high, higher than the average SST of 29.6°C at this time

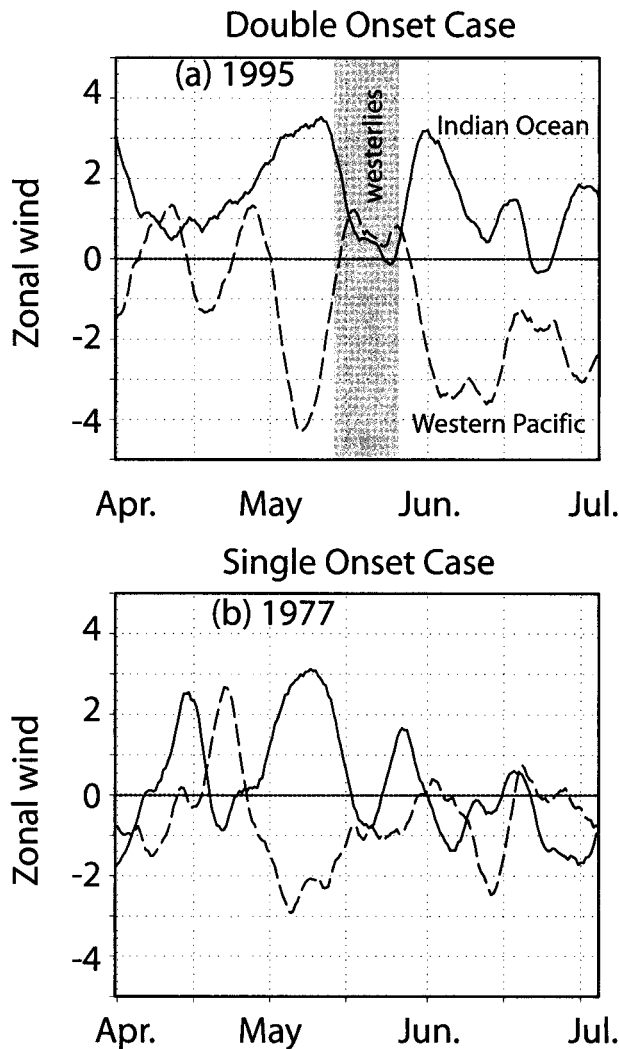


FIG. 12. Equatorial (5°N – 5°S) winds in the Indian Ocean averaged over 60° – 100°E (solid line) and in the western Pacific averaged over 140° – 170°E (dashed): (a) the 1995 case of double onset; (b) the 1977 case of the single onset but with equatorial convection present in the Indian Ocean at the beginning of May.

of the year. At the beginning of June the temperature was significantly lower than the average (29.8°C), showing that the years with multiple onsets had the greatest cooling in the Bay of Bengal in May. There is no cooling related to the bogus monsoon evident in the Arabian Sea, in which SST for all years from 1982 to 1998 increases between May and June.

4. Summary and discussion

a. Conceptual model

The paper examines the origins, development, and climatology of the double monsoon onset. The analysis of 1965–97 NCEP–NCAR data indicates that 1995 was the most pronounced case of such an onset, with a strong convective perturbation in early May that propagated

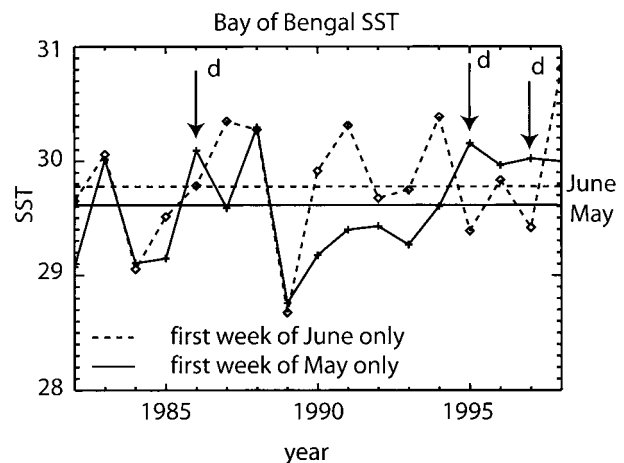


FIG. 13. The SST averaged over the Bay of Bengal (14° – 22°N and 85° – 100°E) at the beginning of May (thick solid line) and at the beginning of Jun (thick, dashed) from weekly Reynolds SST data. Thin solid and dashed lines denote SST at the beginning of May and Jun averaged from 1980 to 1997. During the double onset cases indicated here by “d” (1986, 1995, 1997) SST before the bogus onset was higher than SST before a real onset; i.e., bogus onset cooled the Bay of Bengal.

north farther than in other double onset years and caused the most pronounced monsoonlike circulation followed by a flow reversal in late May. Two factors were important for this development: the presence and timing of an eastward-propagating ISO episode and a positive SST anomaly in the Bay of Bengal and western Pacific. As noticed by Webster (1986), once the insolation over continental region is sufficiently intense (in mid May), the phase of ISO determines the date of the onset. Later in the season, in the second part of June, the large-scale gradient is strong enough to support monsoon regardless of the phase of 40–50-day oscillation. Therefore, in the time window between mid-May and mid-June the onset timing depends on the phase of ISO. In early May of 1995, ISO triggered convection in the Bay of Bengal resembling the monsoon circulation. However, after ISO moved into the western Pacific the convection over the equatorial Indian Ocean became suppressed while the large-scale heating gradient was not strong enough to sustain monsoon circulation with the unfavorable phase of the 40–50-day wave. Thus, the real monsoon onset was delayed. The second important factor, the positive SST anomaly in the Bay of Bengal and the equatorial western Pacific, provided the surface energy for convective activity in early May. The analysis of other cases of multiple onsets in the 1966–98 records indicates that the presence of MJO that is initiated in the Indian Ocean and propagates into the western Pacific is responsible for development of the multiple onsets. The high SSTs at the beginning of May are also a common feature for these cases.

Figure 14 shows the conceptual model of the multiple onset development based on 1995 and other cases of

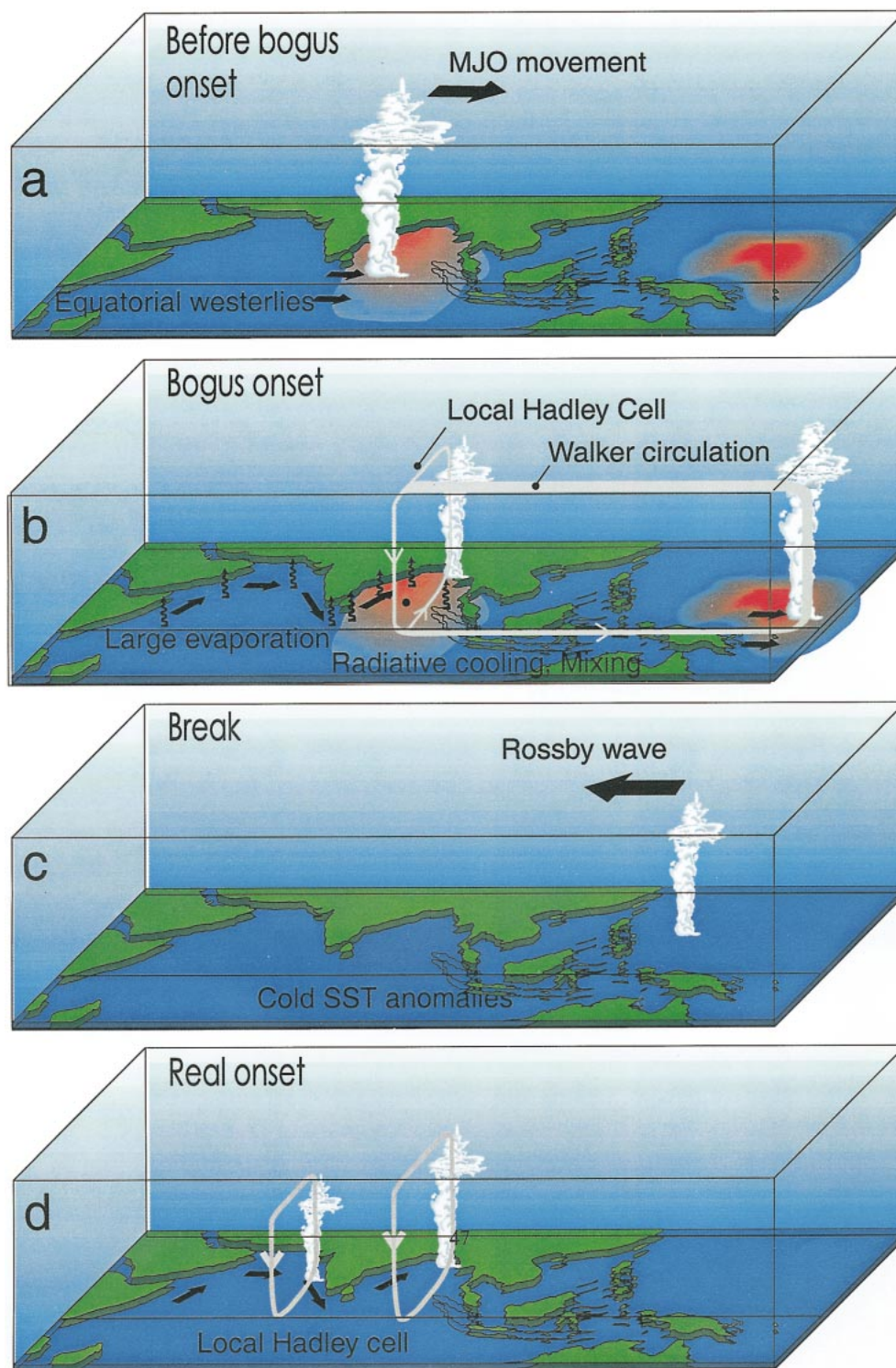


FIG. 14. The conceptual model of multiple monsoon onset development: (a) In early May MJO develops in the equatorial Indian Ocean. Warm SST anomalies are present in the Bay of Bengal and the western Pacific. (b) In mid May the equatorial convection splits, with one branch propagating into the western Pacific and another branch moving into the Bay of Bengal and initializing the bogus monsoon onset. The descending branch of the Walker cell, related to the convection in Western Pacific, and the Hadley cell, related to bogus onset, suppress equatorial convection. (c) In late May and early Jun the Bay of Bengal convection dies. SSTs are low because of the effect of bogus monsoon, but hot and dry conditions dominate over the land. (d) The real onset begins but is delayed because of the previously established conditions.

bogus onset identified in our data. At the beginning of May (Fig. 14a), the equatorial convection developed around 60°E and began propagating eastward. The high SSTs were present in the Bay of Bengal (reaching in some places 32°C), the equatorial Indian Ocean, and the western Pacific. The equatorial convection split into two poleward-moving twin systems, and the one in the Northern Hemisphere intensified as it encountered the warm SSTs in the Bay of Bengal (Fig. 14b). The monsoonlike circulation (the bogus onset) developed over the north Indian Ocean, with low-level westerlies, upper-level easterlies, and a local Hadley circulation driven by latent heat release in the Bay of Bengal. There was no convection over the Arabian Sea, but the strong winds related to the bogus onset increased the evaporative fluxes and the moisture started to build up. The downward branch of this local meridional cell suppressed the convection in the equatorial region. At the same time the ISO continued to move eastward into the western Pacific, creating the downward motion of Walker circulation in the equatorial Indian Ocean. The convective activity over the Bay of Bengal caused the sharp decrease of SST. In the second part of May (Fig. 14c), the convection over the Bay of Bengal died and the westerlies over the north Indian Ocean and Arabian Sea weakened or even reversed. That stopped the moisture buildup over the Arabian Sea. The convection in the western Pacific moved off the equator and started to propagate westward along 10°–15°N. As shown by Wang and Xie (1997) the westward propagation of convection is related to Rossby waves destabilized by the positive vertical shear of zonal velocity. The weak convective systems started to develop again in the equatorial area. By 9 June the equatorial convection moved north. At the same time the westward-moving Rossby wave in the North Pacific reached the South China Sea and the Bay of Bengal, triggering a monsoon onset (Fig. 14d). This westward movement of convection off the equator could be observed in 1995 but not in other double onset years, when the convective disturbances in the western Pacific were limited to the equatorial region.

The development of the convective center over the Arabian Sea was delayed in 1995—probably due to decreased moisture buildup in May. The convection in this area developed on about 16 June, which coincides with the time at which Rossby waves reached the Arabian Sea.

b. Influence on monsoon development

The analysis of the climatology of multiple onset cases indicates that they are precursors of the weak or, at most, average monsoons. However, this relationship is rather weak, and the much more important consequence of the early May bogus onset is the delay of the real onset of the monsoon. The comparison of the multiple onset years with dates of onset (Joseph et al. 1994)

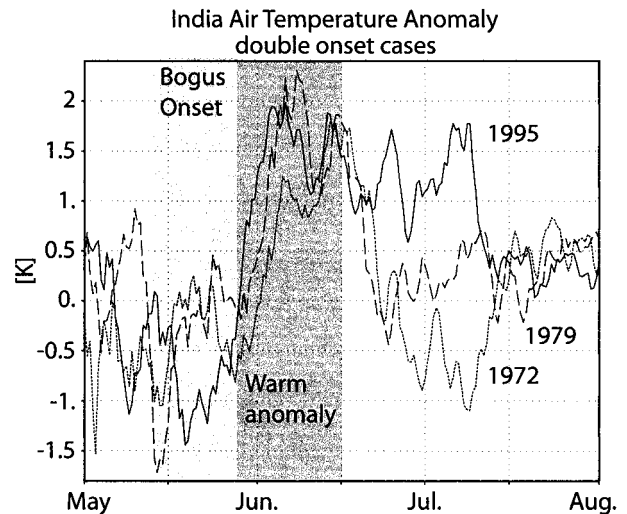


FIG. 15. The anomaly of surface air temperature (at 2 m) from NCEP–NCAR reanalysis for parts of Indian subcontinent (5°–25°N and 70°–85°E, land only), following the bogus monsoon onset. Solid line—1996; long dashed—1979; short dashed—1972. The bogus onset is followed by hot and dry conditions over India during the break, indicated here by “warm anomaly.” Three different years show similar pattern.

shows that the real onset in those years is late. According to Joseph et al. (1994) the most delayed onset years included 1972 and 1979—that is, the years with bogus onset. Also, in 1967 the onset was substantially delayed. The 1986 onset was closest to climatology, but this was also the year in which “bogus onset” characteristics were less clearly visible than in other years.

In 1995 the delayed onset was associated with a heat wave over India in early June (Halpert et al. 1996). To estimate the effect of other bogus onsets on the weather in India we calculated the rainfall and temperature anomalies from NCEP reanalysis, over the Indian peninsula during May and June. Figure 15 shows that the bogus onset in 1979 was associated with a temperature anomaly at the beginning of June similar to that observed in 1995. The anomaly in 1972 was smaller in late May but increased by 16 May. In the second part of June, the temperature in 1979 and 1972 was close to the average; in 1995 it remained fairly high throughout June. In the other three double onset years (not shown) the temperature anomalies before the real onset were positive but smaller, with maximum magnitude from 1.5° in 1986 to 0.9°C in 1967. The years with the three largest rainfall anomalies are shown in Fig. 16. In all three cases there was a positive anomaly around 15 May, related to the bogus monsoon onset, followed by the negative anomaly associated with the delayed onset, in the second half of May and beginning of June. The largest positive anomaly in May developed in 1995 (not shown), but the premonsoon period in this year was not as dry as those depicted in Fig. 16. Overall, the double onsets were associated with dry and hot weather preceding the start of the summer monsoon.

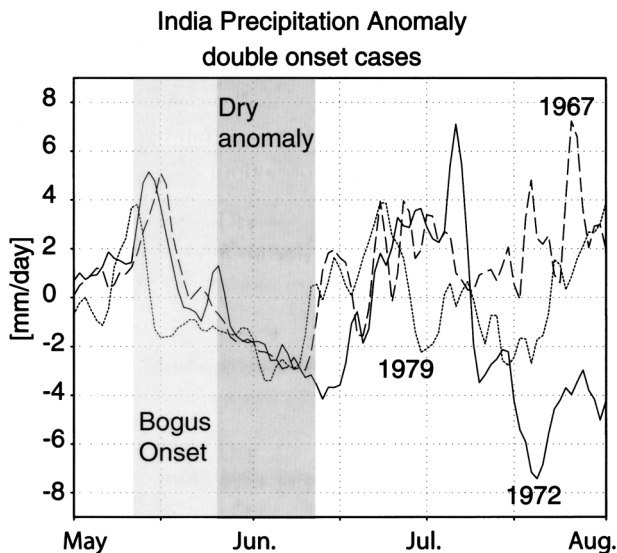


FIG. 16. Same as Fig. 15 but for precipitation anomaly for years 1967, 1979, and 1972. Solid line—1972; long dashed—1967; short dashed—1979.

Another feature observed in the bogus onset years is the delay in development of convection in the Arabian Sea. Usually, the convection in the Arabian Sea develops at the beginning of June, about the same time as the Bay of Bengal convection. The OLR analysis indicates that in the years with multiple onset, especially 1996, 1997, and 1979, the convection in this area lagged behind the Bay of Bengal convection by about two weeks and started around 16 June.

The late arrival of the monsoon after the development of the strong perturbation in May may be related to the following:

- 1) timing of ISO,
- 2) drying in the Arabian Sea during the reversal phase, and
- 3) strong cooling of the Bay of Bengal SST during the bogus monsoon.

The characteristics of the bogus onset described here, such as the influence of intraseasonal oscillation, development of the twin perturbations on the equator and cooling of the Bay of Bengal, are similar to the features related to the first transition of the Asian monsoon (or development of the South China monsoon). In 1995 the ISO episode, which triggered the strong convection in the Bay of Bengal, caused the development of the South China Sea (SCS) monsoon. The development of the westerlies in the South China Sea, which signals the beginning of the SCS monsoon (Lau et al. 1998), was observed in 1995 around 11 May and was related with the transition of the ISO-related convection from the Indian Ocean to the western Pacific. We compared the timing of the bogus onset with the dates of the monsoon's first transition from Hsu et al. (1999), who ex-

amined the onset of the SCS monsoon between 1979 and 1993. The dates of the first transition ranged from 10 May to 7 June. The years in which the bogus onset was observed were characterized by the relatively early date of the first transition. In addition, the dates of the first transition coincided with the dates of the bogus onset, suggesting an intraseasonal oscillation episode that triggered the bogus onset contributed to the early first monsoon transition. However, not every early first transition case was associated with the bogus onset.

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