The Monsoon Year — A New Concept of the Climatic Year in the Tropics

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Abstract

The concept of "monsoon year" is proposed as a unit year of climatic anomalies (i.e., the climatic year) in the tropics. This monsoon year is defined as one year starting just before the northern summer monsoon season. It is also argued that this climatic year in the tropics is physically based upon the characteristic nature of the coupled ocean/land/atmosphere system over the Asian monsoon/ Pacific Ocean sector.

1. Introduction

The concept of the climatic year, which was originally introduced by Russell (1934), implies the year-to-year climate condition categorized based on the definitions of the classical climatic classifications (e.g., Koppen's). He defined it as follows: "In any quantitative definition of a climate we may substitute the meteorological values of a single year for the normals assumed by the original and call the result a climatic year." Many arguments have since then been done in the climatological community on the validity of this concept, particularly in adopting the classification originally for the long-term mean state of climate to the year-to-year climate. However, there seems to be another problem on this concept of the climatic year, which has not been discussed so far. That is the pertinence of adopting "the calendar year" as a unit year for the classification of the year-to-year climate. This problem seems to be particularly important in the tropics both from the scientific and technical viewpoints.

In the humid tropics (e.g., in the equatorial belt of Indonesian maritime continent), there is no apparent rainy (or dry) seasons, where the persistence of one anomaly (with the same sign) of the climatic parameters (rainfall, surface pressure, sea surface temperature, etc.) easily occurs through the two successive calendar years. In this case, the truncation of the anomalies by the boundary of the calendar year may sometimes cause an inappropriate or incorrect climatic year. In the monsoon regions, on the other hand, the rainy (or dry) season of the Northern and the Southern hemispheres appears nearly out of phase in the seasonal cycle with each other. In this case, we may have a problem with how the climatic anomaly of one season in one hemisphere is physically linked with that in the other hemisphere, or, from the climatological point of view, how we could identify the climatic year of one hemisphere as the same climatic year of the other hemisphere. Here, we will discuss these problems, based on the most recent results on the El Niño/Southern Oscillation (ENSO) and related issues.

The interannual variability of the climate system in the tropics, as is typically represented by the ENSO, has proved to show strong phase locks to seasonal cycle in the evolution of the anomalies. For example, the mature stage of the sea surface temperature (SST) evolution in the eastern Pacific during the ENSO events appears most probably in the Northern Hemisphere winter season (Rasmusson and Carpenter 1982).

Meehl (1987) strongly suggested that the interannual anomalies in the coupled atmosphere/ocean system, in the tropical Indian through the Pacific Ocean sector in the globe, start over the Indian monsoon region during the northern summer and propagate southeastward in the course of the seasonal march from the northern summer to winter. That is, the condition of strong (or weak) convection over India and Southeast Asia during summer monsoon persists over the Indonesian maritime continent and Australian monsoon region in the succeeding autumn, and shifts further eastward to the Southern Pacific Convergence Zone (SPCZ) in winter, following the seasonal migration of the convection center. The anomalous east–west circulation field also varies in space and time associated with this seasonal migration of convection anomaly. The changes of sign in these anomalies occur most probably just before the next northern summer (May to July). This characteristic nature of interannual variability in the Indian and Pacific sectors of the tropics inevitably chooses the biennial time scale as a predominant periodicity. Very recently, Yasunari (1990) has substantiated this interesting nature of the coupled atmosphere/ocean system in the tropics by adding more new observational evidences both in the atmosphere and the ocean.

In the following sections, based upon the results

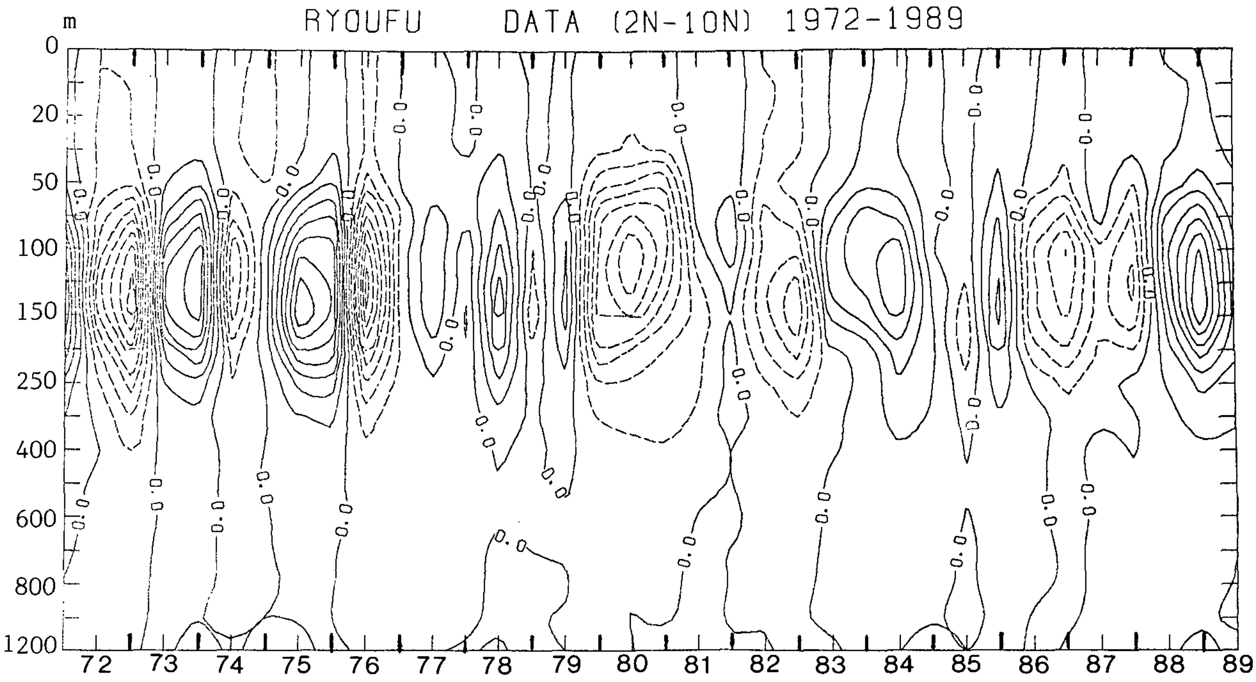

FIG. 1. Vertical time section of sea water temperature anomaly (January and July) from the surface to 1200 m depth averaged for 137°E line from 2°N to 10°N. Contours are 0.1°C and negative values are shown with dashed lines.

described in these papers, the seasonalities in the persistency and transition of climatic anomalies in the tropics are summarized. The role of the Asian summer monsoon on performing these characteristics of climatic anomalies is also discussed, and, finally, a concept of the "monsoon year" is proposed as a unit year of the climatic anomalies in the tropics.

2. Oceanic mixed-layer temperature in the western Pacific

The research vessel Ryofu-Maru of the Japan Meteorological Agency (JMA) has been making marine meteorological observations regularly along 137°E once a year (January) since 1967, and twice a year (January and July) since 1972. Fig. 1 shows the sea-water temperature (SWT) anomalies of January and July, averaged for the western Pacific warm water pool region (2°N–10°N). This time–depth diagram clearly shows a quasi-biennial (i.e., biennial or, otherwise, triennial) oscillation (QBO) of the anomalies in the whole oceanic mixed layer. The maximum variance appears at the thermocline depth (about 150 m), which strongly suggests that this oscillation represents the changes in the thickness of warm oceanic mixed layer. One should note that the anomalies shown here are simply deviations from the long-term mean value of each month without using any time filter.

Another prominent feature of this diagram is that the change of sign in the anomalies occurs most frequently at sometime between January and July, except in the years when the anomaly of the same sign persists through the whole year as part of triennial oscillation (i.e., 1975, 1980, 1984, 1987). This feature is more apparently shown in the scatter diagrams of anomalies of each month (Fig. 2); i.e., the linear correlation is weak but rather negative ($r=-0.25$) between January and the following July, whereas it is significantly positive ($r=0.60$, with the level of 0.1%) between July and the following January. That is to say, there is a reasonably strong persistence of the anomalies during the northern summer through the following winter and the transition of anomalies from positive to negative sign (and vice versa) occurs most frequently between winter and the following summer.

3. Indian monsoon and oceanic anomalies in the tropical Pacific

The QBO-like oscillation of the mixed-layer temperature in the tropical western Pacific as shown in Fig. 1 has also proved to be significantly correlated to the fluctuation of the Indian monsoon rainfall (IMR) index (Parthasarathy 1987), as shown in Fig. 3. Interestingly, the correlation appears to be more significant between the IMR and the following January SWT

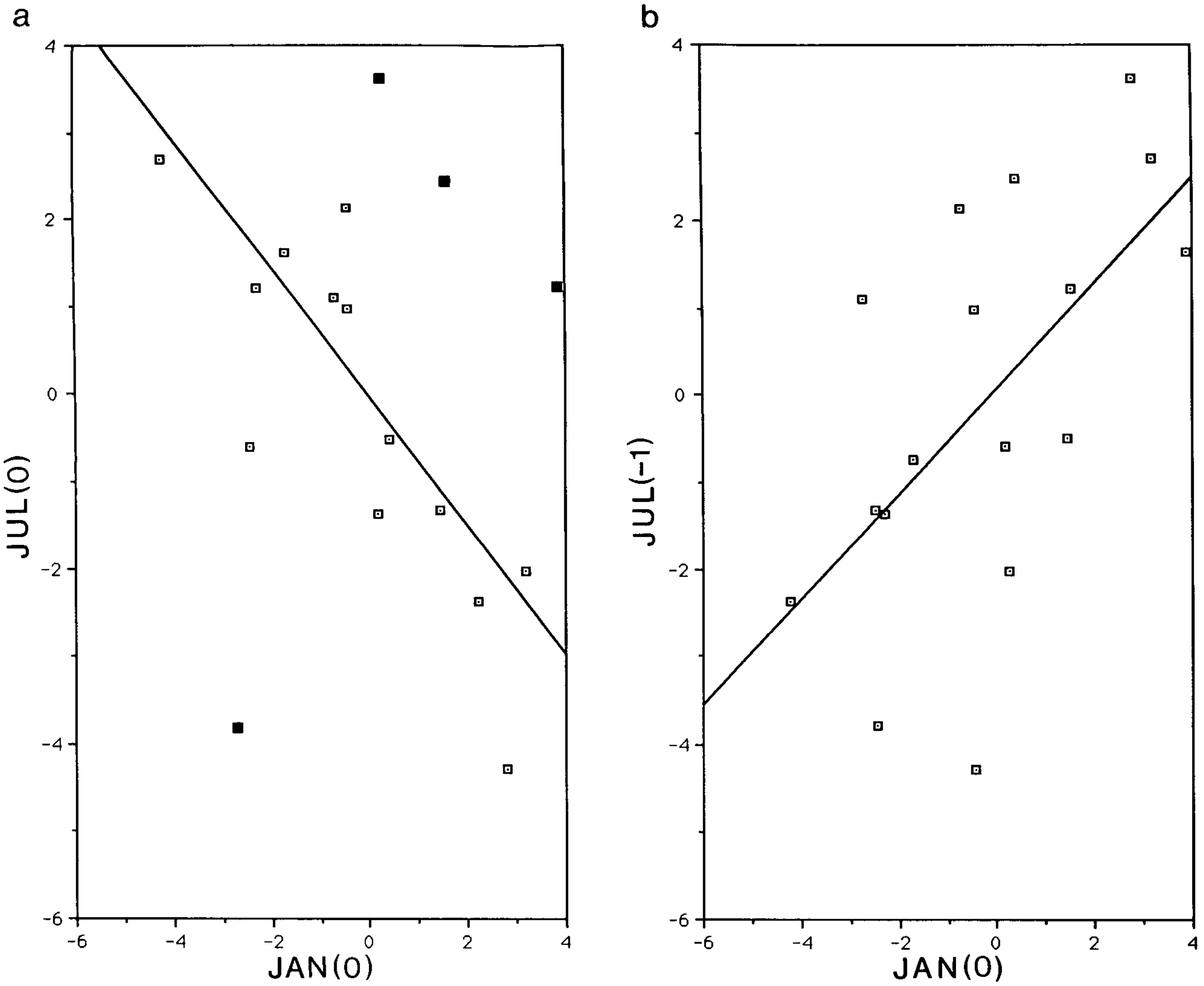

FIG. 2. Scatter diagram and linear regression for a) January SWT anomaly at 150 m and the succeeding July SWT anomaly and b) January SWT anomaly at 150 m and the preceding July SWT anomaly. Anomalies for the triennial cycle phase are plotted with black circles.

anomaly than that between the IMR and the concurrent July SWT anomaly. The correlation between IMR and January SWT anomaly at 20 m depth is 0.78, which far exceeds 0.01% significant level.

The lag correlations between the IMR and the SST anomalies in the equatorial western and eastern Pacific have also been investigated, as shown in Fig. 4. This diagram clearly demonstrates that the correlations of SST anomalies of the two regions to IMR gradually increase through the seasonal march from the concurrent summer monsoon season to the following winter, with the maximum absolute value in January or February. The secondary maximum correlations, but with the opposite signs to Y(0) (i.e., the concurrent monsoon year), are also noticeable in the latter half of Y(-1), due to the strong QBO nature of both IMR and SST anomalies.

The seasonal evolutions of SWT and SST anomalies mentioned above are physically consistent with the evolution of the zonal wind field anomaly over the tropical Pacific as shown in Fig. 5. This diagram shows the seasonal evolution of SST and zonal wind anomalies in the lower troposphere (700 mb) along the equatorial belt composited for two calendar years by using the six pair-years starting from the strong monsoon years (i.e., 1971, 1973, 1975, 1978, 1981, and 1983). Because of the strong biennial nature, we should note that the second years are mostly weak monsoon years including the ENSO years. It is noteworthy to state that the easterly anomaly starts to develop over the whole Pacific basin nearly at the same time that the strong Indian monsoon has started. The development of easterly anomaly in the western Pacific from summer to early winter is followed by significant negative SST anomaly in the central/eastern Pacific and positive SST anomaly in the western

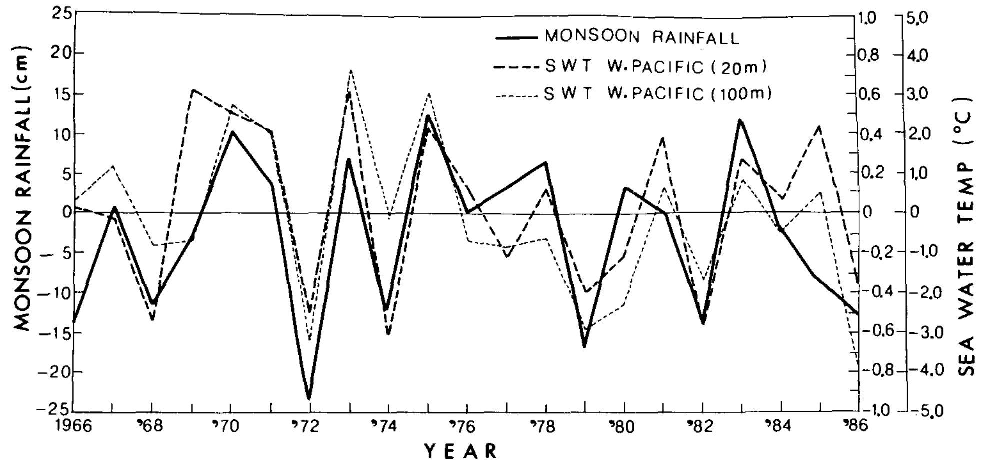

FIG. 3. Time series of Indian monsoon rainfall anomaly (thick solid line) and SWT anomaly at 20 m (thick dashed line) and 100 m (thin dashed line) depth averaged for the 137°E line (2°N–10°N) in the succeeding January (Yasunari 1990).

Pacific. The coupling of negative SST and easterly anomaly over the central/eastern Pacific persists through the winter and early spring, until the westerly anomaly appears over the western Pacific immediately before the (weak) Indian monsoon starts in the second year.

These characteristic features in the SST/SWT and zonal wind field are discussed in Yasunari (1990), suggesting that a strong (or weak) regime of the coupled ocean/atmosphere system with a tropical east–west (Walker) circulation in the Asian/Pacific sector (Krishnamurti et al. 1973) prevails about one year starting from the Indian monsoon season.

4. Proposal of "monsoon year" and its implication

We have now realized that the interannual variability of the climate system over the major part of the tropics (i.e., the Asian monsoon/Pacific sector) cannot be interpreted by using the ordinary unit year, i.e., the calendar year. Instead, it may be useful for us to introduce a new concept of the "monsoon year" as a unit year at least for the study of tropical climate, which may be defined as a year starting at some time between the northern spring and summer, or shortly before the summer monsoon season. Certainly, this concept seems to be valid for interpreting the year of one anomalous state in the tropics. For example, the interannual variability of the monsoon rainfall index over the Indonesian maritime continent (Yasunari 1981; Yasunari and Suppiah 1988) agrees well with this concept, as shown in Fig. 6. This index is adopted from the time coefficients of the first empirical orthogonal functions (EOFs) of the normalized rainfall anomalies of 54 stations over Java island, which explains about 50% of the total variance. This diagram clearly shows very high values of auto-correlation (with a strong persistency of more than a half year) in the period from May to December, and in contrast, very low persistency (of only one or two months) in January through April. In addition, the extremely asymmetric structure of the time-lag correlation, for May (or November) tells us that this predominant interannual mode seems to evolve rapidly in the early northern summer (April to June), persist during summer through early winter and rapidly decay in late winter through spring. It should be noted here that the mean seasonal

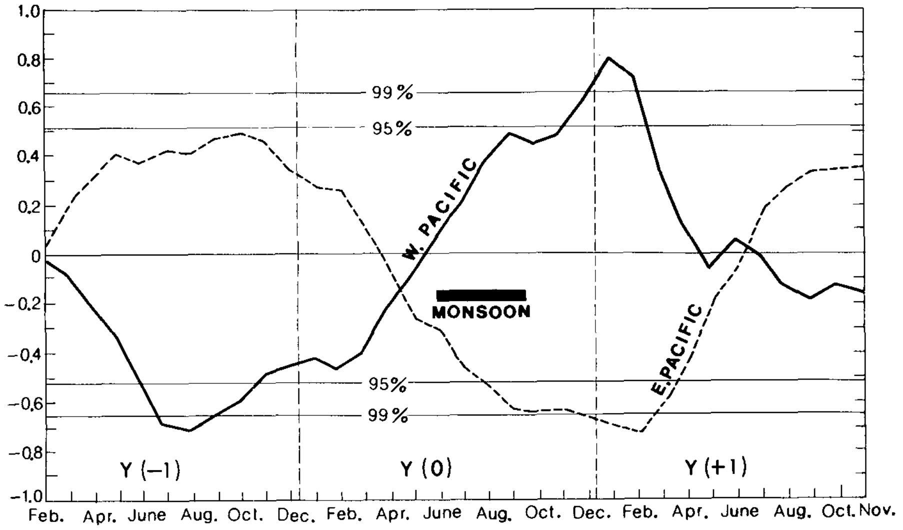

FIG. 4. Lag correlations between Indian monsoon rainfall anomaly and SST anomaly in the western (0°–8°N, 130°E–150°E) and the eastern (0°–8°N, 170°W–150°W) Pacific. The reference monsoon season is shown with thick black bar. Y(0) denotes the year of reference monsoon and Y(-1) [Y(+1)] denotes the year before (after) Y(0) (Yasunari 1990).

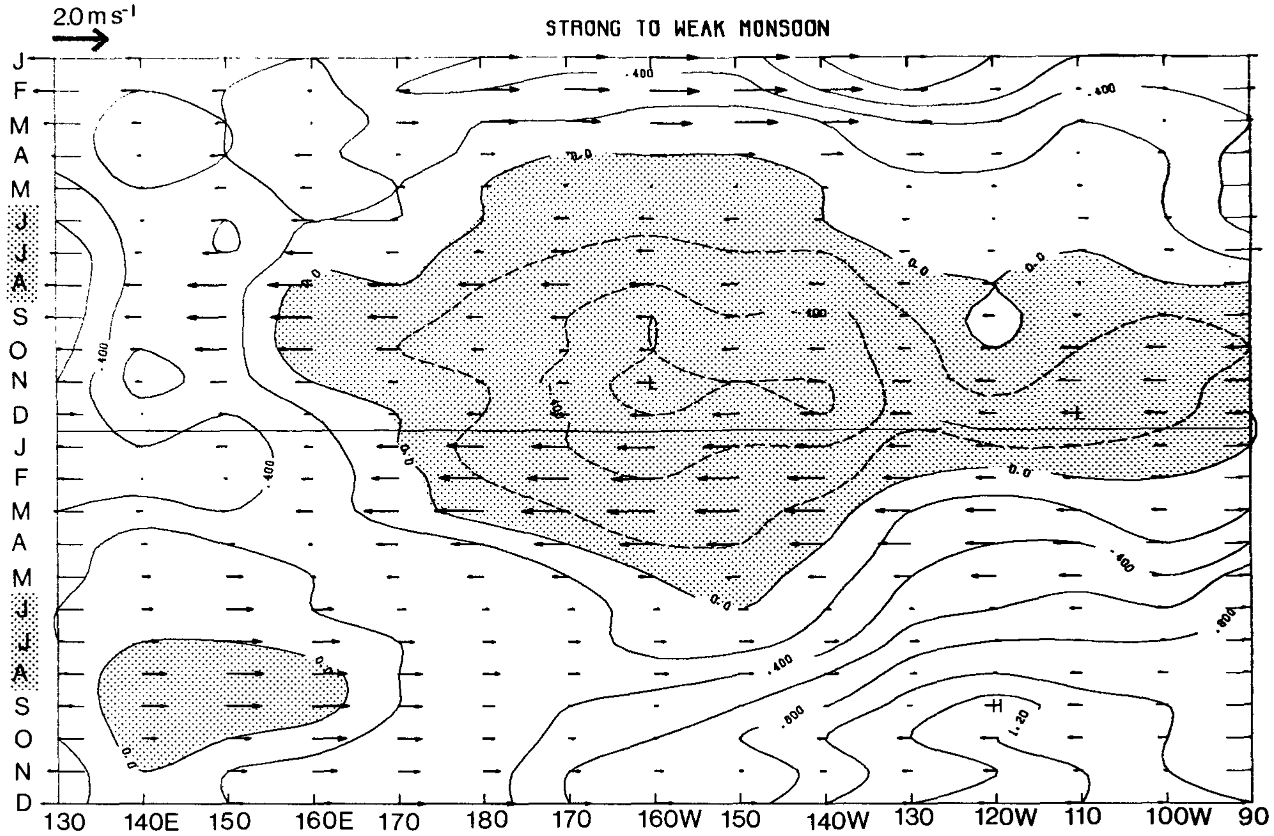

FIG. 5. Longitude–time section of SST anomaly and zonal wind anomaly vector at 700 mb along the equator composited for the two years from active to weak Indian monsoon year. Positive (negative) values in SST anomaly are shown with solid (dashed) lines (unit: 0.2°C) and negative values are shaded (Yasunari 1990).

rainfall variation in this area shows a quite different pattern, as shown in the lower panel. Roughly speaking, one monsoon year defined here may correspond to a dry season (May to September) plus the subsequent wet season (October to April). In other words, the anomalous condition in a dry season has a strong tendency to persist through the succeeding wet season with the same sign, while this anomalous condition is hardly correlated to that in the preceding wet season.

Another basis for this concept may exist in the southern oscillation index (SOI). Fig. 7 shows the lag-correlation of the SOI (defined as a normalized surface pressure difference between Tahiti and Darwin) in reference to some months of the year. The high persistency of the SOI is apparent from May to the following April, whichever month we may choose as a reference of correlation. This feature in the SOI had already been noticed by Walker and Bliss (1932) and was more comprehensively discussed by Troup (1965). Shukla and Paolino (1983) pointed out that the polarity (i.e., negative or positive sign) of this persistent anomaly of SOI is closely associated with the activity of Indian monsoon.

Ropelewski and Halpert (1989) comprehensively showed that the rainfall anomalies of most of the tropics and subtropics are linearly related to the phase of the SOI, particularly when the SOI is in either extreme. Their results are summarized in Fig. 8, which strongly suggests that the precipitation anomalies related to the Southern Oscillation in the entire tropics tend to appear within one unit of the "monsoon year," though the anomaly for each region shows a different seasonality from place to place. Thus, the concept of "monsoon year" seems to be valid for the description of interannual anomalies in almost all parts of the tropics.

5. Physical bases for the monsoon year

Undoubtedly, this monsoon year is closely associated with the characteristic nature of the coupled atmosphere/ocean system over the tropical Pacific. The strong persistency of the anomalies, particularly in the latter half of the calendar year, is directly related to the evolution of the coupling between SST, convection, and wind field over the equatorial eastern and western

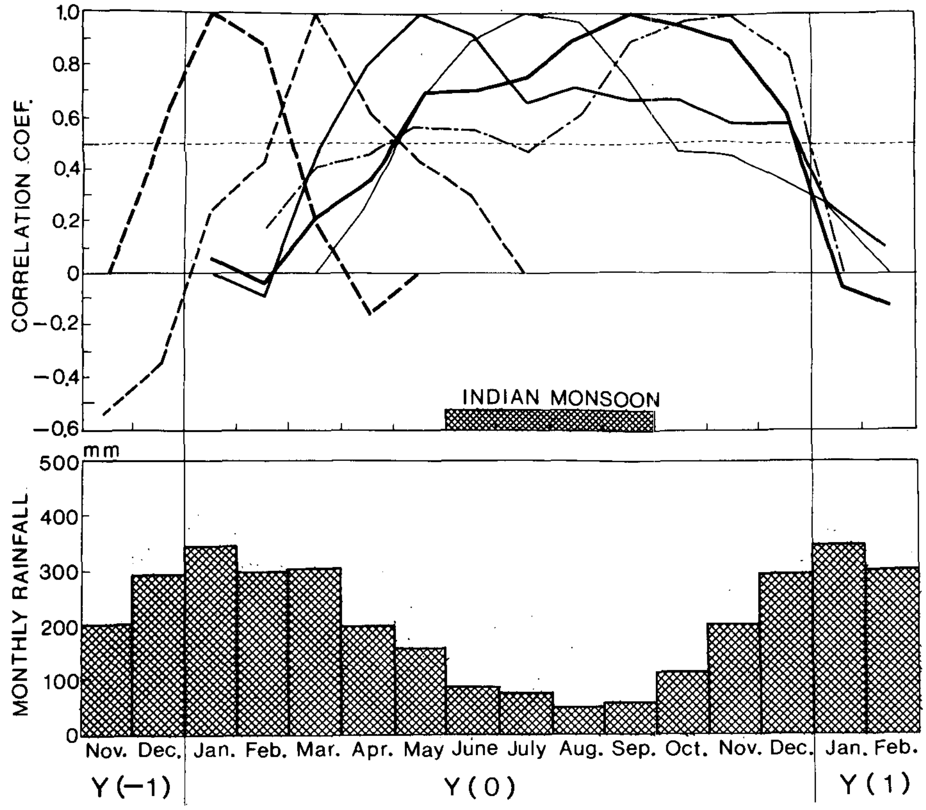

FIG. 6. (upper) Lag-correlations of Indonesian monthly rainfall anomaly with reference to January (thick dashed), March (dashed), May (solid), July (thin solid), September (thick solid), and November (dot-and-dash). Indian monsoon season is also shown with hatched bar. (lower) Mean seasonal rainfall for Java island (Yasunari and Suppiah 1988).

Pacific (Yasunari 1990). However, a key problem to be solved now may be why the anomaly is so transitional (i.e., so easy for changing signs) between the northern winter and summer. Meehl (1987) suggested the importance of atmosphere/ocean interaction over the equatorial Pacific through the SPCZ during the northern spring. On the other hand, some observational studies (Yasunari 1987, 1990; Barnett 1985, 1989) also suggest the possible important role of the Asian winter and summer monsoon on triggering the change of sign and the evolution of anomalies. The strong QBO signals, particularly over the Asian/Australian monsoon region and the warm tropical Indian and Pacific Oceans (Yasunari 1989; Rasmusson et al. 1990), may be evidence for these atmosphere/ocean model experiments with monsoonal heating (Yamagata and Masumoto 1989; Budin and Davey 1990) have prominently shown that the intensity of land (or monsoonal) heating to the west of the tropical Pacific strongly controls the state of the coupled system over there.

Although the exact answer for this question has been left for future studies, one important physical process involved may be the change of the seasonal basic state in the differential heating between the Eurasian continent and the two oceans. Because of the large heat storage of the tropical Pacific Ocean, the seasonal convection center is still located in the Southern Hemisphere for a while, even after the spring equinox (Sumi 1986). This condition

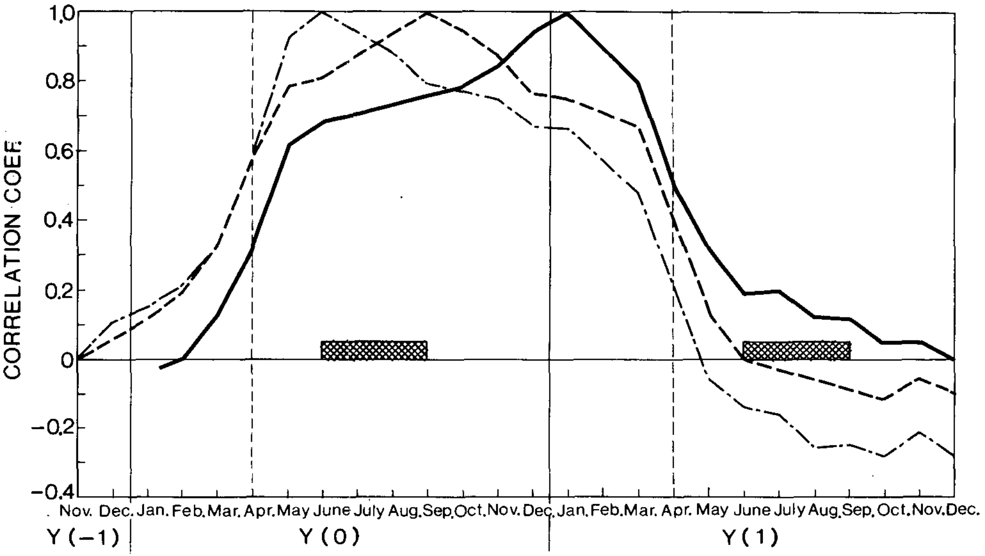

FIG. 7. Lag-correlations of SOI with reference to June (dot-and-dash), September (dashed), and January (solid). Indian monsoon season is also shown with hatched bar. Vertical dashed lines approximately show the limits of each monsoon year.

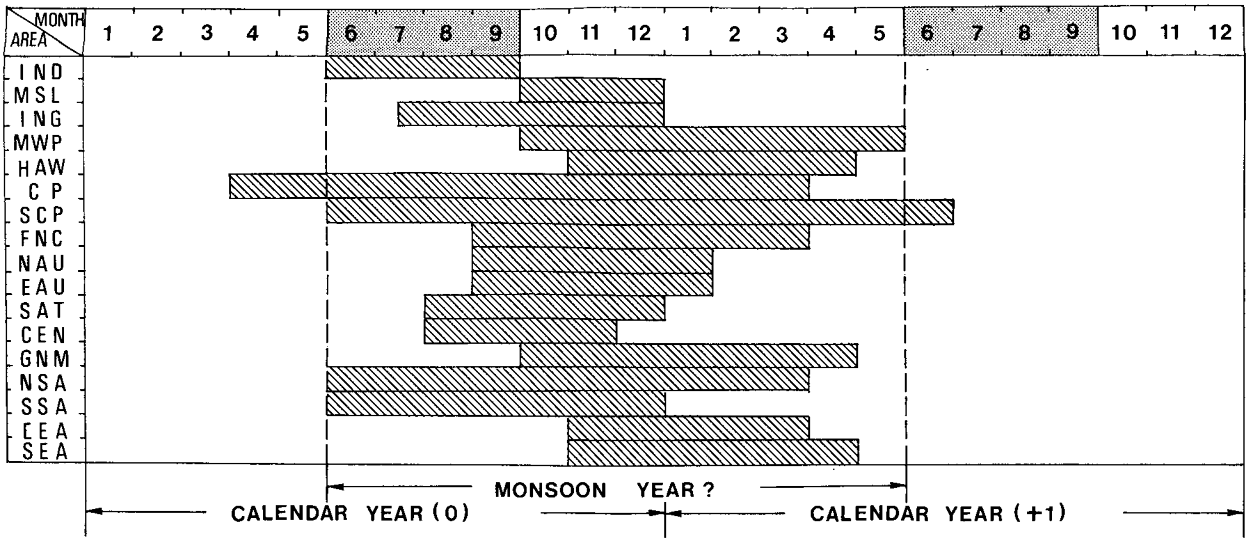

FIG. 8. Seasons of precipitation anomaly related to the extreme phases of SOI for the areas in the tropics and subtropics. Dashed vertical lines indicate the approximate extent of the "monsoon year." Abbreviated area names are as follows: IND, India; MSL, Minicoy/Sri Lanka; ING, Indonesia/New Guinea; MWP, Micronesia/West Pacific; HAW, Hawaiian; CP, Central Pacific; SCP, South Central Pacific; FNC, Fiji/New Caledonia; NAU, Northern Australia; EAU, Eastern Australia; SAT, Southern Australia/Tasmania; CEN, Central America/Caribbean; GNM, Gulf/North Mexico; NSA, Northeastern S. America; SSA, Southeastern S. America; EEA, Eastern Equatorial Africa; SEA, Southeastern Africa. (After Ropelewski and Halpert 1989.)

may be abruptly altered to the opposite condition just before the onset of the summer monsoon. This drastic change in the seasonal differential heating field may be plausibly responsible for "washing out" or "switching off" the interannual anomalies of the previous "monsoon year."

The anomalous differential heating in the northern spring through summer may be an important factor that may determine the anomalous state of the northern summer monsoon and, in turn, the coupled ocean/atmosphere system in the tropics in the following seasons of the "monsoon year." The relationship between the Eurasian snow cover in spring and the Asian monsoon in the following summer (e.g., Hahn and Shukla 1976) should be noted in this context.

A more microscopic view on the transitional phase of the interannual anomalies suggests the role of the synoptic-scale and intraseasonal-scale disturbances. Some observational and theoretical studies suggested that a single or group of eastward moving synoptic-scale or intraseasonal-scale disturbances over the western Pacific may have triggered the ENSO event (Lau and Chan 1986, 1988; Nitta 1989; Chu 1989). The problem may be whether this shorter time-scale variability plays a role merely as a background carrier wave for the interannual variability (i.e., as a "climatic noise"), or, otherwise, a more active role as part of the interannual signals. From this point of view, the activity of these disturbances particularly during the northern spring equinox season should be further investigated.

6. Concluding remarks

The interannual variability in the coupled ocean/atmosphere system or, rather, the coupled ocean/land/atmosphere system over the tropical Pacific and the Asian monsoon region prominently shows a quasi-biennial nature with the changes of signs during the northern spring through summer. The anomalous condition there rapidly evolves during the Asian summer monsoon season and persists through the succeeding winter. These remarkable features of the climate system in the tropics suggest that a concept of "the monsoon year" be proposed as a unit climatic year for the interannual anomalies over the tropics. This concept may also be valid for large parts of the subtropics and extratropics, since the role of this coupled ocean/land/atmosphere system on the global climate may be extremely large.

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