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Effect of the 30-50 day oscillation on the life cycle of the Indian monsoon

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सार - ई ओ एफ (EOF) विश्लेषणों का पालन करते हुए भारतीय मानसून से संबंधित भूमंडलीय परिचालन के निम्न आवृति प्रणाली का अध्ययन करने के लिए, मध्य परास मौसम पूर्वानुमान के लिए यूरोपीय केन्द्र से एफ जी जी ई (FGGE) III आंकड़ा सेट पर आधारित भूमंडलीय वेग विभव क्षेत्रों का प्रयोग किया गया है । वार्षिक चक्र से संबंधित मानसून के विकास का परीक्षण किया गया है ।

ABSTRACT. Global velocity potential fields based on the FGGE III data set from the ECMWF have been used to study the low frequency mode of the global circulation relevant to the Indian monsoon by performing EOF analyses. Development of monsoon in relation to the annual cycle is examined.

1. Introduction

Many recent studies have shown that the life cycle of the Indian monsoon includes a 30-50 day oscillation. The Indian monsoon only occurs during the northern summer, but the 30-50 day mode exists year round (*e.g.*, Lorenc 1984). Applying the simple harmonic analysis to the area-averged outgoing longwave radiation over the Bay of Bengal, Murakami *et al.* (1986) argued that the onset and withdrawal of the monsoon can be determined by the phase changes of the annual cycle and 30-50 day low-frequency mode. These studies suggest that the life cycle of the Indian monsoon is established by the annual cycle of the atmospheric circulation over the monsoon region and is modulated by the 30-50 day low-frequency mode.

Using the 30-50 day filtered 850-mb wind data over the Indian monsoon region, Krishnamurti and Subrahmanyam (1982) delineated synoptically the northward propagation of transient ridges and troughs associated with the 30-50 day mode. For convenience, we shall refer to them simply as KS ridges and troughs. Krishnamurti and Subrahmanyam found that when one of the KS trough or ridge lines arrives at roughly 15° N, the next line becomes distinct near the equator. The Somali jet's intensity reaches its peak (*i.e.*, a monsoon "active" condition occurs) when a trough line lies near 20° N. In contrast, the Somali jet weakens (*i.e.*, a monsoon "break" condition happens) when a ridge line is located around 20° N. Later, Chen and Yen (1986) showed that the 30-50 day variation of the Somali jet follows the deepening and filling of the Indian monsoon trough over central India when the KS troughs and ridges migrate to central India and coincide with the Indian monsoon trough.

Since the northward migration of KS troughs and ridges modulates the low-level Indian monsoon, how are the troughs and ridges related to the planetary-scale 30-50 day mode? It will be shown in this study that this coupling is accomplished through the transient local Hadley circulation induced by the planetary-scale 30-50 day mode over the Indian monsoon region. In this region this coupling is a key process in causing the modulation of the annual cycle of the atmospheric circulation.

2. Empirical orthogonal function analysis of the velocity potential

We derive the global velocity potential (X) fields with the wind fields generated by the FGGE IIIb analyses of the European Center for Medium Range Weather Forecasts (ECMWF) over the entire FGGE year. To extract out the annual cycle and the 30-50 day low-frequency mode from the fields, we adopt Lorenc's (1984) EOF analysis scheme by retaining the zonal mean and the first ten-wave components along latitudinal circles. This EOF analysis covers the global belt between 45° S and 45° N.

For 200 mb, the first three eigenmodes of the X-field departure from its yearly mean (not shown) explains, respectively, 36.2%, 23.3 % and 16.4 % of the total variance. The eigencoefficient time series of the first eigenmode show a clear annual cycle. The temporal phases of eigencoefficient time series of the second and third eigenmodes are in quadrature, and the spatial distributions of their eigenvectors are also about 90° out of phase. The eigenvectors of these two eigenmodes possess a wave number-one structure. The phase and structure of these two eigenmodes are similar to Lorenc's analysis. The temporal phase and spatial phase
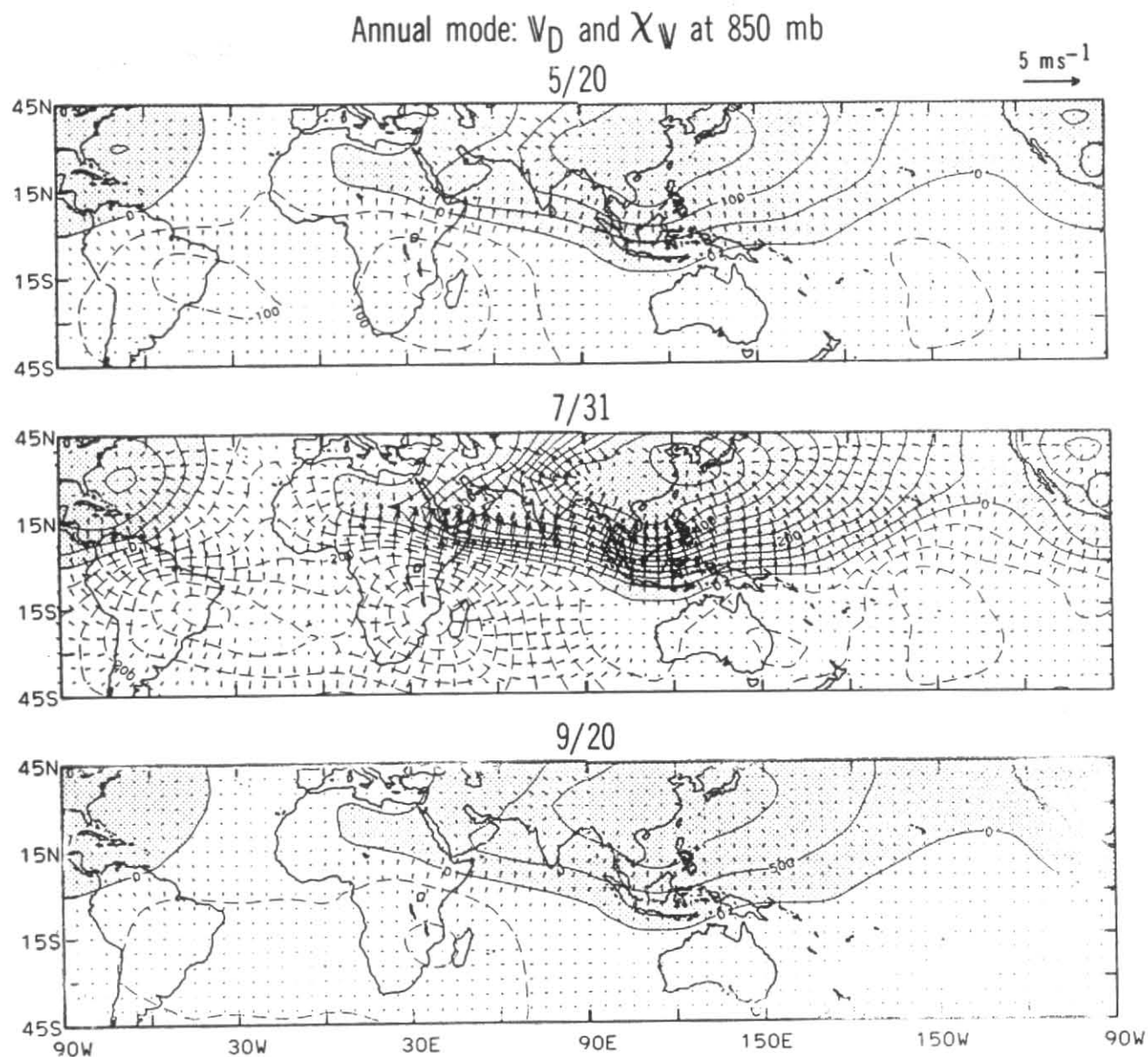
Annual mode: W_D and X_ψ at 850 mb

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Fig. 1. The annual cycle of the divergent circulation (v_D, χ) at 850 mb obtained by multiplying the annual cycle harmonic of eigencoefficient time series and eigenvector of the first eigenmode. The contours are the annual cycle anomaly field. The positive values of the χ anomaly field are shaded. The contour interval is 5×10^6 m^2 s^{-1}.

relationship between these two eigenmodes indicate that they constitute an eastward propagating 30-50 day oscillation.

For 850 mb, the first three principal eigenmodes of the χ field departure from its yearly mean (not shown) explain, respectively, 40.5, 16.1 and 12.2 % of the total variance. The first eigenmode is an annual cycle, and the next two eigenmodes form the 30-50 day mode. As expected, the structures of these three eigenmodes are similar to their counterparts of 200 mb, but they are in opposite phase.

### 3. Annual cycle and monsoon development

The direct atmospheric response to the diabatic heating is the intensification of divergent circulation as discussed by Chen and Wiin-Nielsen (1976). This response infers that the annual cycle of the divergent circulation is that to the seasonal march of the solar heating. To delineate the development of the Indian monsoon, three phases (20 May, 31 July, 20 September) of the annual cycle of the divergent circulation, both at 850 mb and 200 mb between May and September are displayed in Figs. 1 and 2 respectively.

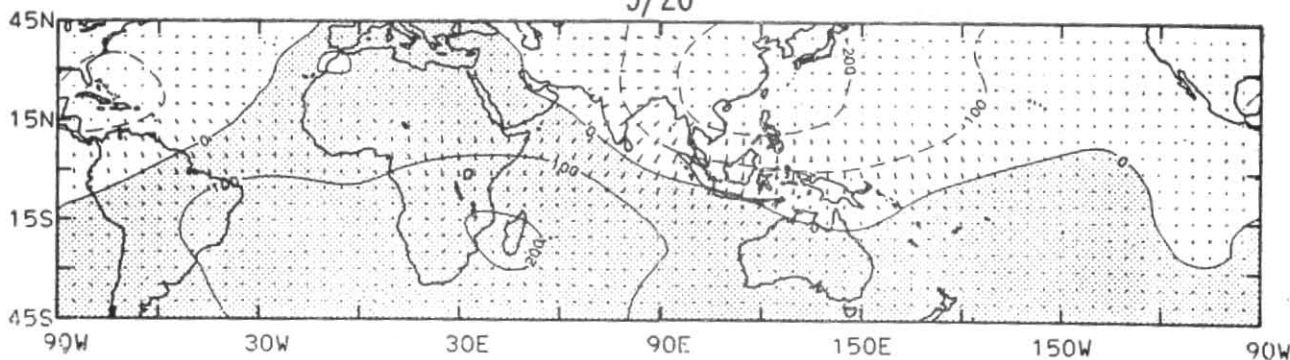## Annual mode: W_D and X_V at 200 mb
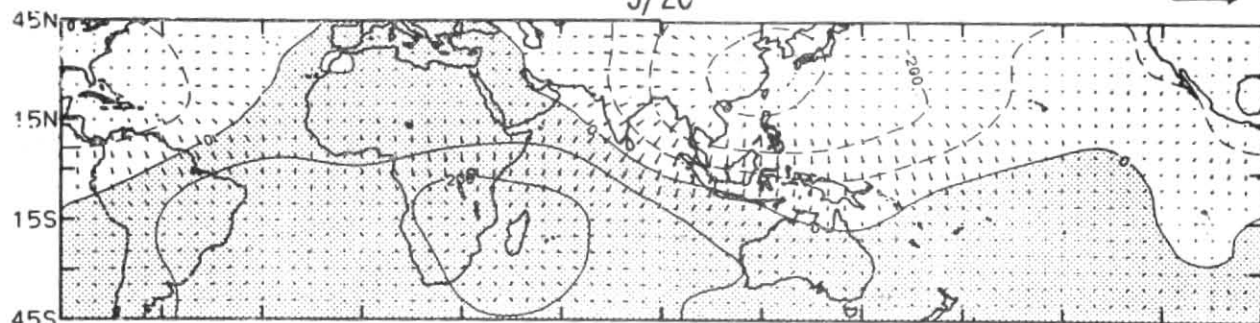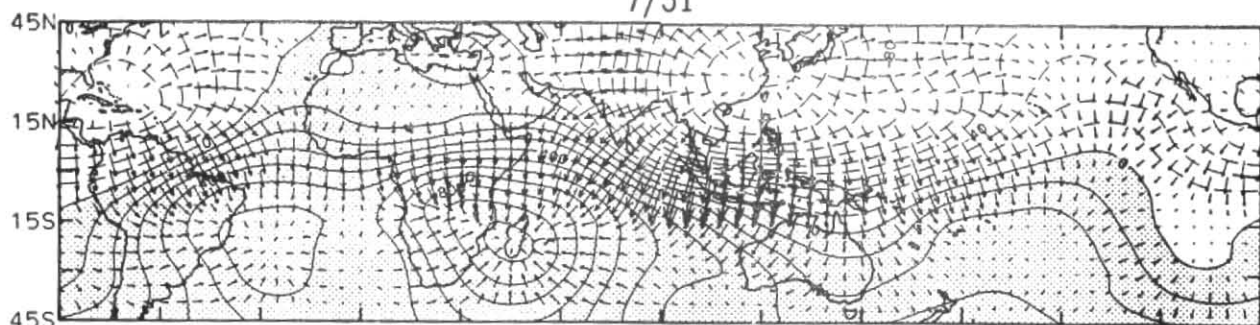
Fig. 2. Same as Fig. 3, except for 200 mb

Conventionally, the Indian monsoon is considered as a giant sea-breeze circulation. This classic view can be illustrated by the annual cycle of divergent circulation at 850 mb (Fig. 1) and 200 mb (Fig. 2) during the northern summer. The heated Asian landmass induces the upward motion. Therefore, the low-level airmass converges from the oceans over south and southeast Asia toward the Asian continent (Fig. 1). In the mean time, the airmass at 200 mb diverges away from the Asian continent toward the oceans to form a returning flow. Clearly, to establish a sea-breeze-like circulation, the land-ocean thermal contrast induces the annual cycle component of the divergent circulation over the Indian monsoon region.

As explained from the energetics viewpoint (Chen and Yen 1986), the northward divergent wind of the annual cycle component at 850 mb induces the coriolis force. This force, in turn, maintains the low-level Indian monsoon westerlies extending all the way from the east coast of Africa to Indochina. Since the low-level Indian monsoon westerlies belong to part of the Indian monsoon circulation, this annual cycle of the 850 mb divergent circulation maintains the low-level Indian monsoon. Like the northward divergent wind at 850 mb, the southward divergent wind of the annual-cycle component at 200 mb induces the coriolis force. This force, in turn, maintains the low-level Indian monsoon westerlies extending all the way from the east coast of Africa
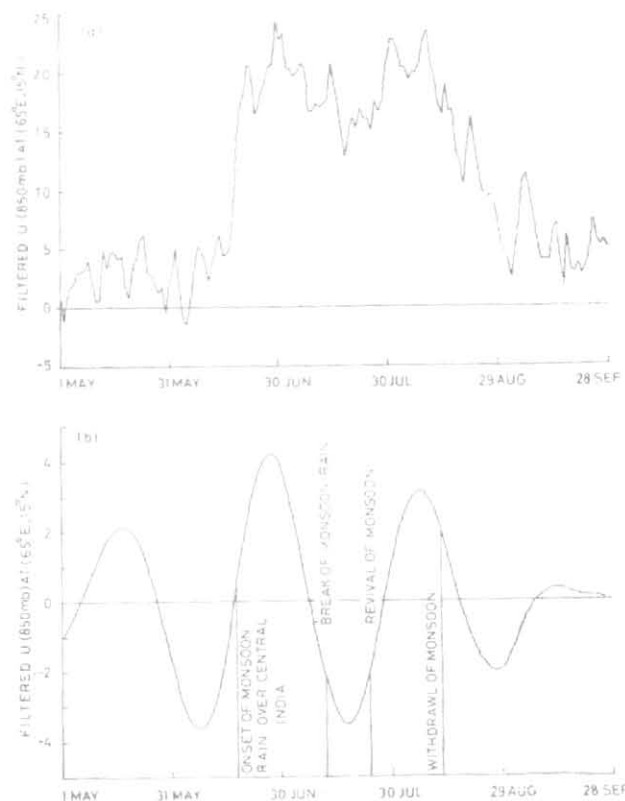
Fig. 3. The observed : (a) 30-50 day filtered & (b) zonal wind
at (65 E, 15 N) for a 120-day period from 28 April to
25 August 1979

(*After* Krishnamurti and Subrahmanyam 1982)

to Indochina. Since the low-level Indian monsoon west-
erlies belong to part of the Indian monsoon circulation,
this annual cycle of the 850 mb divergent circulation
maintains the low-level Indian monsoon. Like the north-
ward divergent wind at 850 mb, the southward
divergent wind of the annual-cycle component at 200
mb induces the coriolis force. This force, however,
supports the tropical easterly jet, which is located bet-
ween two upper-level monsoon anticyclones to the
north and south (*e.g.*, Krishnamurti 1979, Chen and
van Loon 1987).

4. Monsoon life cycle and 30-50 day mode

To examine how the eastward propagation of the
planetary-scale 30-50 day mode affects the Indian mon-
soon life cycle, let us use the intensity variation of
the Somali jet over the entire 1979 Indian monsoon
as an index. The time series of the 850-mb zonal wind
(u) at (65° E, 15° N), the core of this jet, is plotted in
Fig. 3(a) with the ECMWF FGGE III-b data. We apply
the second-order Butterworth bandpass filter (Murakami
1979) to this u (850 mb) time series to extract out the
30-50 day oscillation of the Somali jet (Fig. 3b).
Following Krishnamurti and Subrahmanyam (1982,

their Fig. 2), various phases of the 1979 Indian mon-
soon are labelled.

To show the overall relationship between the annual
cycle and the 30-50 day mode, we present a Hovmöller
diagram which was constructed with the 200 mb vel-
ocity-potential anomalies of these two components at the
equator (Fig. 4). Multiplying the first eigenvector of the
X field by the annual-cycle harmonic of its eigencoefficient
time series, we obtained the annual cycle of the velocity-
potential anomaly field. Based upon Fig. 3, dates
of weak monsoon conditions along 75 E (10 June,
20 July and 30 August) are marked by asterisks. The
phase relationship between the annual cycle and the
30-50 day mode suggests that the Indian monsoon life
cycle results from the modulation of the annual cycle
during northern summer by the 30-50 day mode.

The modulation process mentioned above is accom-
plished through the coupling between the planetary-
scale 30-50 day mode and the 30-50 day KS troughs
and ridges by the transient local Hadley circulation
induced by the former mode. To illustrate this
argument, we shall discuss only the second cycle
(9 June-20 July) of the 30-50 day oscillation (Fig. 3)
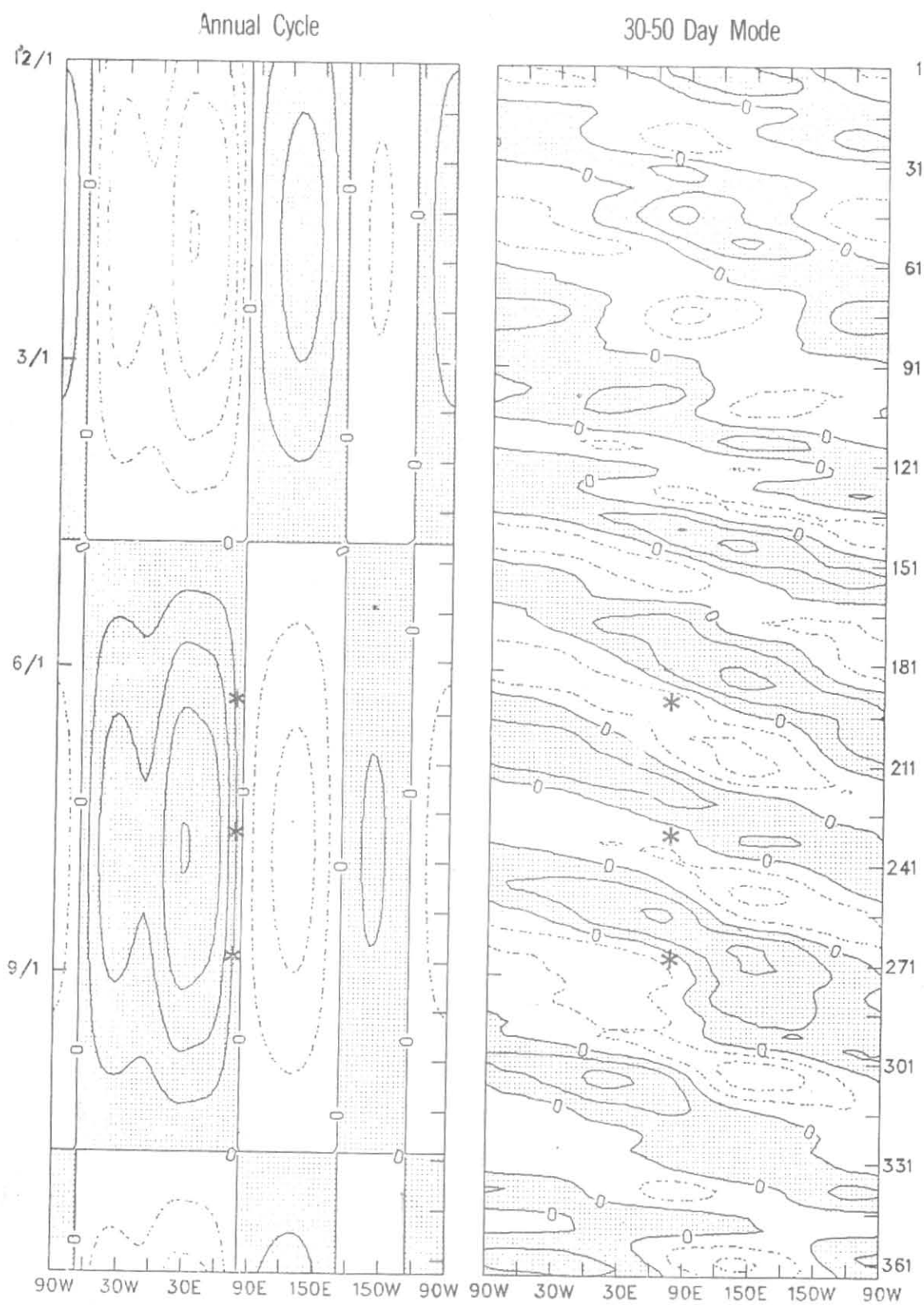to avoid redundancy.

Fig. 4. The Hovmöller diagrams of the annual cycle : (a) 30-50 day mode & (b) of the 200 mb X anomaly fields at the equator
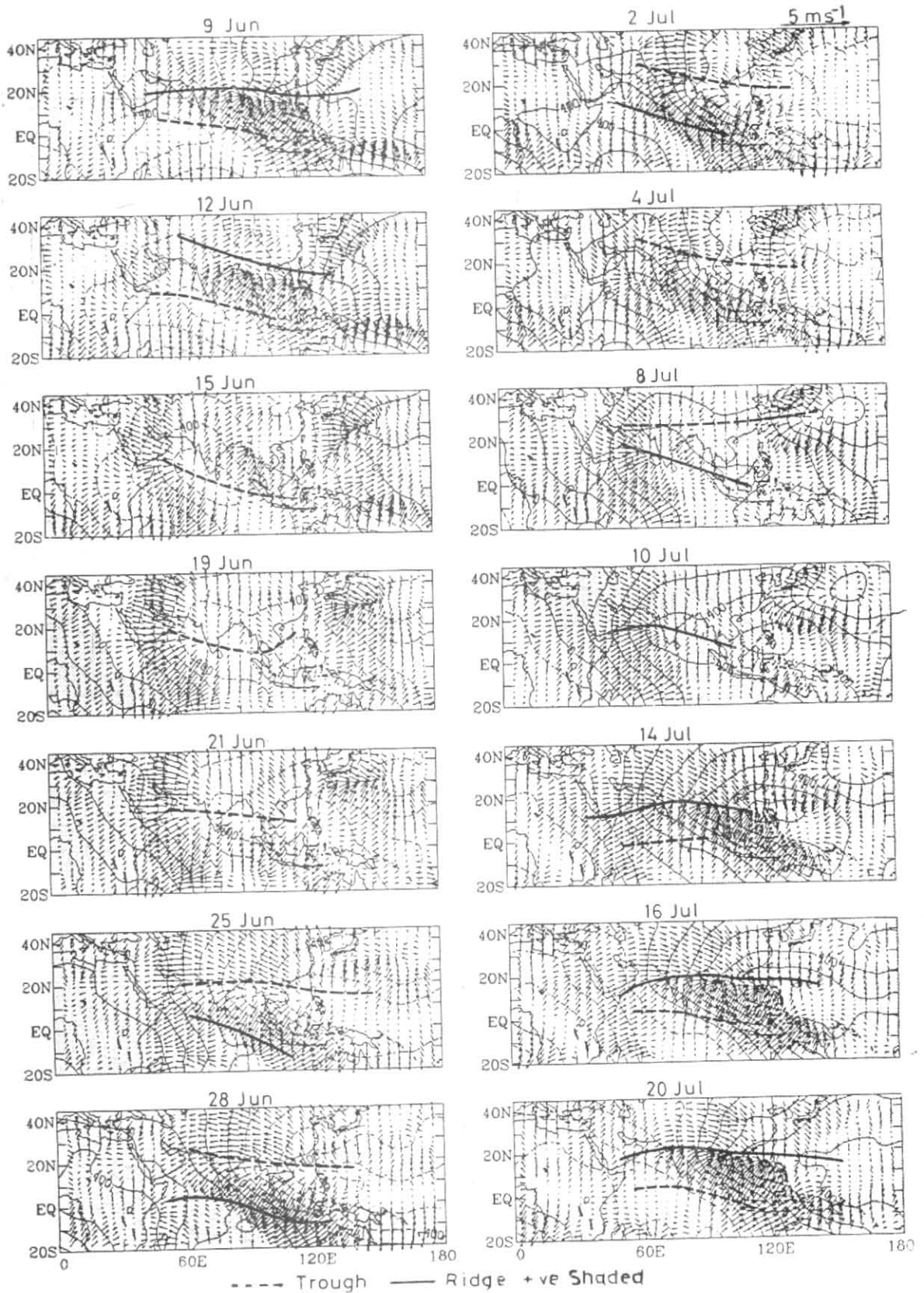
Fig. 5. The 30-50 day filtered 200 mb velocity potential (χ) and divergent wind vectors. The date of each panel is shown on the top right. The thick dashed and solid lines are trough and ridge lines respectively, depicted by Krishnamurti and Subrahmanyam (1982). The contour interval of the 30-50 day filtered is 10^6 m^2 s^{-1}. Positive values are shaded.
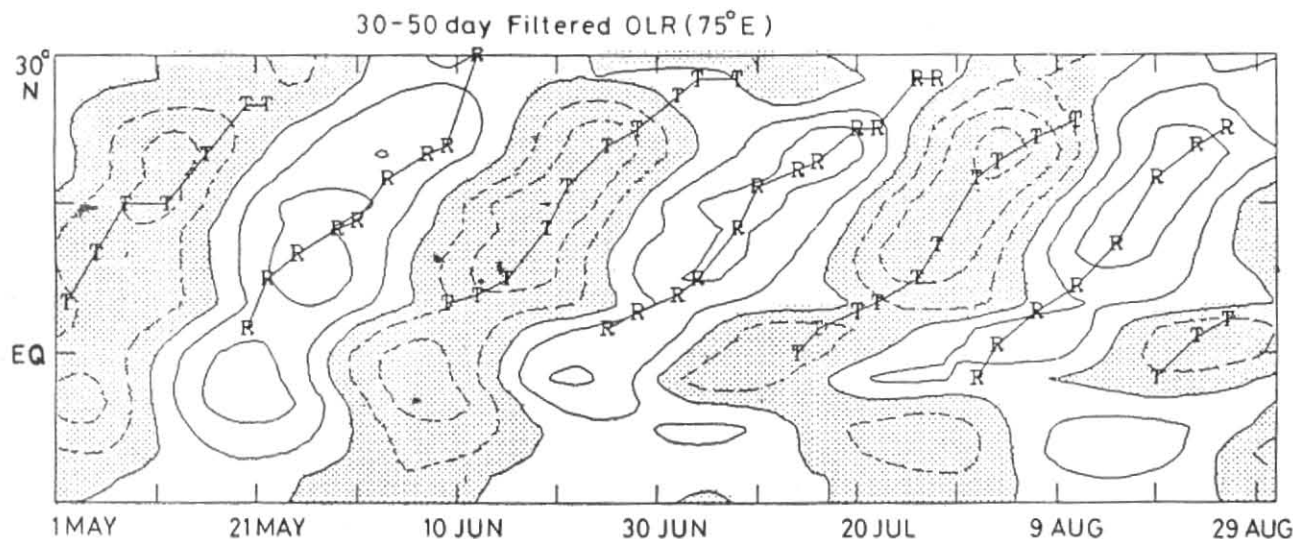
30-50 day Filtered OLR (75°E)

Fig. 6. The y-t (latitude-time) diagram of the 30-50 day filtered OLR superimposed with locations of the KS troughs (T) and ridges (R) along 75° E. The contour interval is 8 Wm⁻² and the negative values are shaded.

Using the same dates selected by Krishanamurti and Subrahmanyam (1982), the 30-50 day filtered, 200 mb divergent circulation (χ) for various phases of the second cycle (Fig. 3) are displayed in Fig. 5. The positive values are shaded. The eastward propagation of the 30-50 day divergent mode is clearly revealed in this figure. Note that the divergence or convergence centres usually appear over the western equatorial Indian Ocean. Then, they propagate to the western Pacific, around 20° N, in 20 days. The planetary-scale 30-50 day divergent mode at the upper level is synoptically related to the low-level 30-50 day mode over the Indian Ocean. To illustrate that relationship, the KS troughs (thick dashed lines) and ridges (thick sold lines) are shown in Fig. 5. We can see that these KS trough and ridge lines match well with the areas of 30-50 day filtered 200 mb divergence and convergence respectively. In other words, Fig. 5 depicts a possible coupling between the KS troughs and ridges and the planetary-scale 30-50 day divergent mode. The direct link between the low-level KS troughs and ridges and the planetary-scale divergent mode can be established through the construction of the transient local Hadley circulation. The locations of the KS troughs and ridges extracted from Fig. 5 are marked respectively by thick dashed and solid lines. The KS troughs and ridges are associated respectively with upward and downward branches of the 30-50 day transient local Hadley circulations. We notice that the coupling between the KS troughs and ridges and the planetary scale 30-50 day mode is achieved through the 30-50 day local Hadley circulation.

Note that the deep cumulus convection can be maintained and suppressed respectively by the upward and downward branches of the 30-50 day local Hadley circulation. To substantiate further the coincidence of the KS troughs (ridges) with the upward (downward) branches of this transient local Hadley circulation, we follow Sikka and Gadgil (1980) to construct a y-t diagram of the 30-50 day filtered OLR superimposed with locations of KS troughs (T) and ridges

(R) along 75° E (Fig. 6). The negative values of the 30-50 day filtered OLR indicate deep cumulus convection. Fig.6 shows clearly that the KS troughs are associated with cumulus convection, which is maintained by the upward motion of the 30-50 day local Hadley circulation.

The coherent propagation relationship between this low-frequency mode at 200 mb depicted in Fig. 5 and the KS troughs and ridges at 850 mb over the Indian Ocean and Indian subcontinent indicates that the northward propagation of the latter is steered by the former.

5. Concluding remarks

Many studies have observed that the life cycle of the Indian monsoon follows the 30-50 day oscillations. However, it does not seem possible that the Indian monsoon develops merely by the 30-50 day low-frequency mode. Murakami et al. (1986) suggested that the interaction between the annual cycle and the 30-50 day mode results in the monsoon life cycle. Applying the Empirical Orthogonal Function (EOF) analysis to the entire FGGE-year velocity potential fields, we are able to isolate the annual cycle and the 30-50 day mode of the divergent circulation. This study showed that the Indian monsoon circulation is portrayed by the annual cycle of the divergent circulation and develops as the classic model of a giant sea breeze between the ocean to the south and the Asian continent to the north. The northwestward propagation of the planetary-scale 30-50 day mode over the Indian monsoon region induces the transient local Hadley circulation. Through this circulation, the planetary-scale 30-50 day mode couples with the low-level 30-50 day troughs and ridges, and it steers them northward. These northward travelling 30-50 day troughs and ridges interact with the Indian monsoon trough situated over central India to cause its deepening and filling as shown in Figs. 7 & 8. This modulation process results in the intensification and the weakening of the Indian monsoon and establishes the life cycle (onset-active-break-revival-retreat) of this monsoon,

HEIGHT (850 mb)

(a) seasonal mean (JJA)   (d) phase 3

(b) phase 1   (e) phase 4
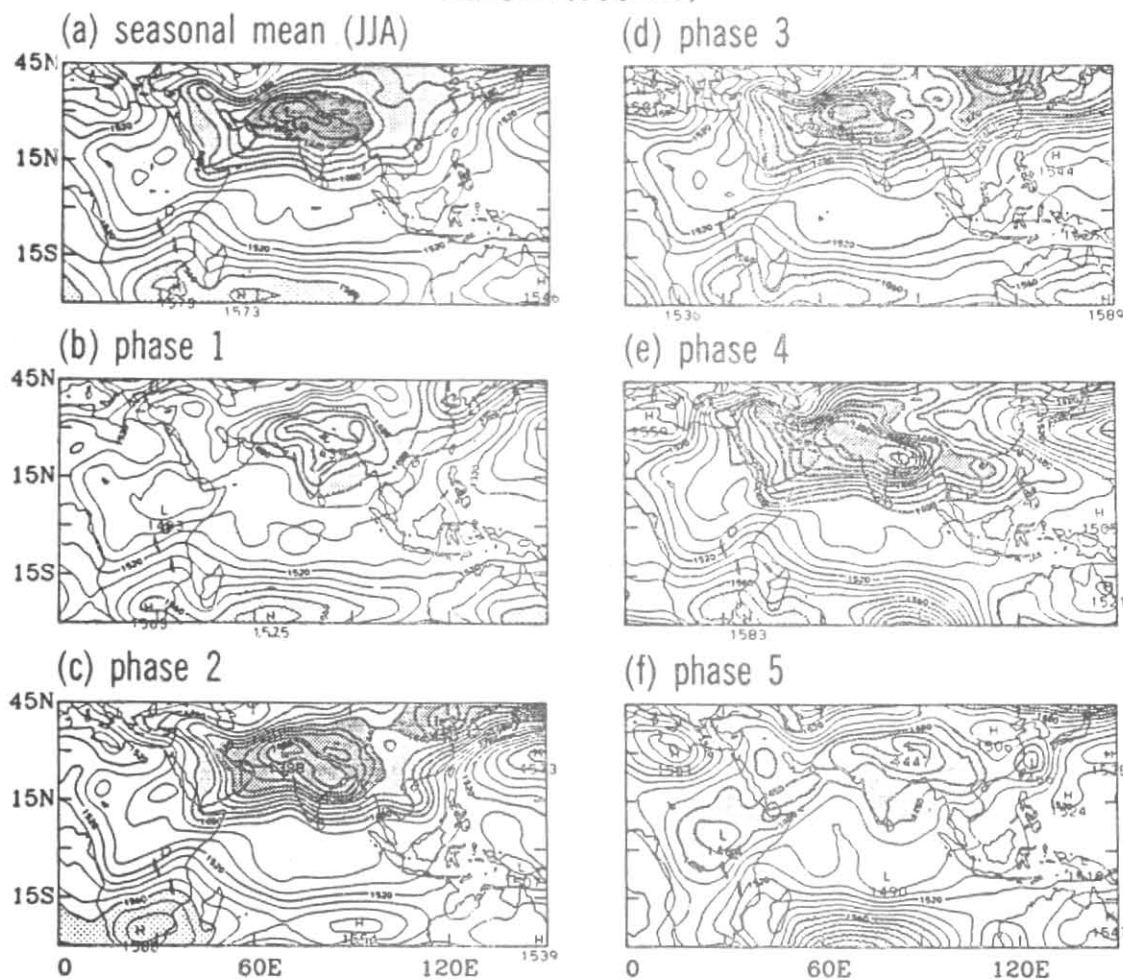
(c) phase 2   (f) phase 5

Fig. 7. The 850 mb height fields for seasonal mean (a), five phases (b)-(f) ; 3-13 June, 19-29 June, 8-18 July, 27 July-8 August and 17-27 August
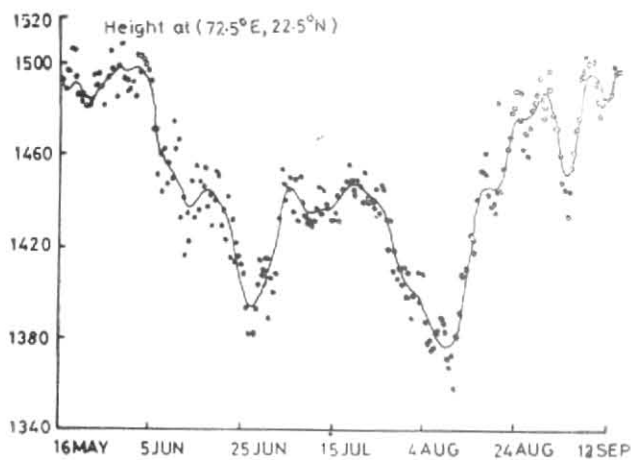
Fig. 8. Time series of height at 72.5 E, 22.5° N from 16 May to 15 September 1979

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