LARGE SIGNALS OF CLIMATIC VARIATION OVER THE OCEAN IN THE ASIAN MONSOON REGION

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Received August 3, 1987

ABSTRACT

The aim of this paper is to identify and delineate large signals of climatic variation in the Asian monsoon region and try to understand the nature of transformation from one climate regime to another.

It is found that the summer monsoon over the Indian and western Pacific oceans shows distinct climatic regimes with changes occurring in the years around 1875, 1900, 1940 and 1960. The change of about 1900 is the largest one, which occurs in step with the variation of global oceanic climate pointed out by Fletcher, et al. (1982).

The main characteristics of the transformation from one regime to another is an alternation of meridionality of monsoon current. The transformation occurs most strongly in the western Pacific convergence zone, where monsoon has strong interaction with the trade wind systems.

The variability of monsoon rainfall over India and East China also exhibits some large signals which are synchronous with those of wind field over the ocean: the monsoon rainfall increases (decreases) during the "meridional monsoon period" (zonal monsoon period) over the ocean.

It should be noted that the apparent decreasing of plum rains in East China since 1958 which is well known in China would be linked mainly with the sudden increasing of U-component of SW monsoon over the South China Sea.

Finally a kind of seesaw between Indian monsoon and East China monsoon with somewhat time-lag is discussed.

I. INTRODUCTION

Some large signals in the long-term variation of global climatic system of last century were pointed out firstly by Fletcher, et al. (1982). He found that these signals also displayed as the alternation of wind direction in the surface wind field in the ITCZ region of western Pacific in northern winter, which reflects the interannual variation of seasonal transformation between summer monsoon and winter monsoon.

Now we focus on monsoon itself in more detail to look at the large signals in the Asian monsoon region and the characteristics of transformation from one regime to another.

In the first part of this work (Fu, Fletcher and Slutz, 1983), the climatological characters of summer monsoon over the ocean and the branching phenomenon of SW monsoon have been explored. There are three branches of SW monsoon located at western Arabian Sea, Bay of Bengal and South China Sea respectively and the SE monsoon in western Pacific,

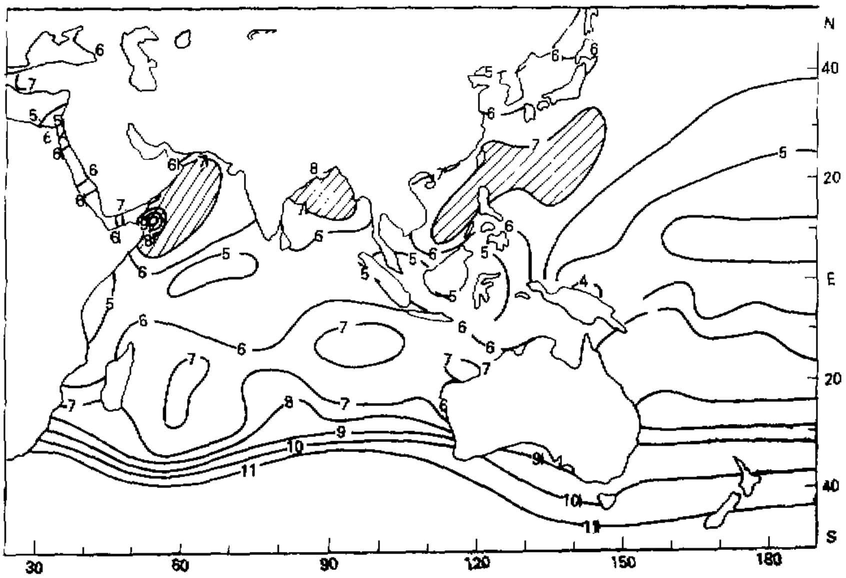

Fig. 1. The standard deviations of surface wind in July (kts) (from U. S. Navy, marine climatic atlas of the world, Vol. IX, world-wide means and standard deviation).

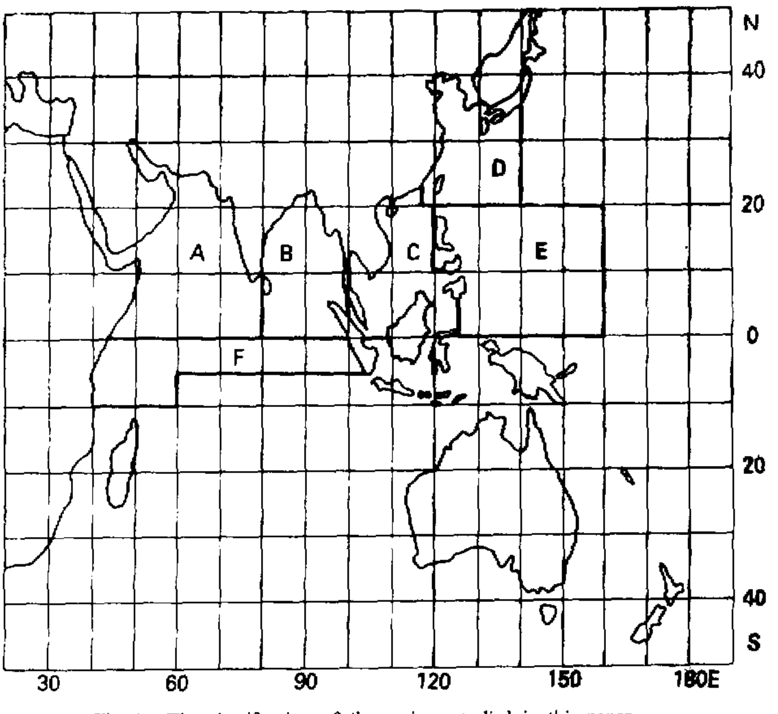

Fig 2. The classification of the regions studied in this paper.
A: monsoon in Arabian Sea;
B: monsoon in Bay of Bengal;
C: monsoon in South China Sea;
D: SE-monsoon in China Sea;
E: tropical convergence zone in western Pacific;
F: equatorial buffer zone in Indian Ocean.

Fig. 1, the map of standard deviation of surface wind in July shows that the most active summer monsoon regions mentioned above are just the regions with the largest interannual variability in the surface wind field. Therefore the emphasis of this paper is put on these regions. Considering the sensitivity of some transient regions between different wind systems and also the interaction between monsoon and other wind systems, some transient zones, for example, ITCZ region, the equatorial buffer zone, etc. were chosen to reveal the general features of monsoon's activities. Fig. 2 gives the six regions representing three branches of SW monsoon, SE monsoon, ITCZ in western Pacific and cross-equatorial flow in the Indian Ocean respectively.

II. DATA

The surface wind data over the ocean are not well-distributed in space and time. In order to study its interannual variability and especially to search for the climatic signals, we should first define the periods and regions when and where the number of observations of wind are qualified for certain statistical test.

Generally, there are not enough records in some boxes in earlier periods, so the mean value calculated by such spacing data cannot be used to represent their real conditions. For example, if there are less than 10 observations in a box of $5°\times5°$ per month, the mean value of these records does not represent the real monthly mean. According to the statistical test, the number of the observation in a $5°\times5°$ box should be 15 to 30 per month at least for qualifying the statistical confidence of mean value.

Table 1. Number of Observations for Surface Wind in July for Each Decade*

	before 1880	1881–1890	1891–1900	after 1900
Equatorial Indian Ocean	<10	15–30	>30	>30
Tropical Indian & Pacific Ocean	<10	<10	15–30	>30

*number of observations for monthly mean

For this purpose, the number of wind observations in July in Indian and western Pacific oceans for each decade have been calculated. Table 1 gives the result. Before 1880, over most of this area the number of observations (NWB) was less than 10 per month. During 1881–1890, in most of boxes in equatorial Indian Ocean the NWB was in the range of 15–30. Only in few boxes, the NWB was about 30. In the period of 1891–1900, NWB was about 30 in most of the equatorial Indian Ocean. Since 1900, NWB has been beyond 30 in the region of 10°N–10°S, 50°E–120°E. After that the observational conditions stay at same level (see Fig. 3).

From above analyses, it is believed that the wind data in the Indian and western Pacific ocean have been qualified for statistical confidence since 1881. The period with more confidence started from 1891 for tropical Indian Ocean. Since 1900, the wind observations have been available in most of northern part of ocean. Therefore the signals appearing before 1881 need some collateral evidences from other data sources.

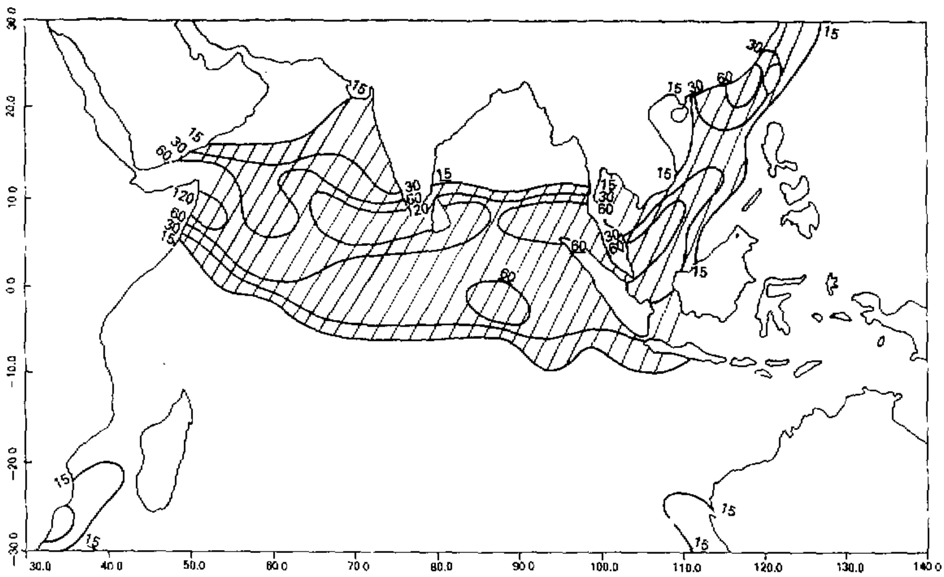

Fig. 3. Number of wind observation for the period 1901–1910.

III. CLIMATE REGIMES OF SUMMER MONSOON OVER THE OCEAN

1. *Stability of SW-Monsoon and Its Climate Regimes*

By using the vector sum of surface wind which describes the direction change of monsoon current, Fig. 4 shows the sequential plots of vector wind for each season (each season vector is added to the sum of the previous vectors) in the regions A, B, C defined in Fig. 2. The end of each decade is labeled. The century vector mean is shown as a dashed line arrow with the modulus divided by the number of years. It can be seen from this figure that three branches of SW-monsoon over the ocean are rather stable and almost have the same mean direction of 230° (SW). The wind steadiness of monsoons are: Arabian Sea −99%, Bay of Bengal −85% and South China Sea −95%. Nevertheless the wind direction of basic current of three branches of monsoon do show apparent variations. Three signals in 1875, 1900 and 1940 occurred in Indian Ocean and two signals in about 1875 and 1960 occurred in South China Sea, among which, the variation in Bay of Bengal appeared more clearly than the others.

Although the large-scale area-averaged results can reserve strong signals; it has two shortcomings: Some big signals might be filtered because the transformation of wind system sometime occurs in a rather narrow regions; some signals in area-averaged are not correct for it includes some boxes which have very few observation records and some individual records may bring about false signal.

In order to get more sensitive signals and more trustworthy information, we choose the section along 5° N in Indian Ocean, where we have more observational data as mentioned

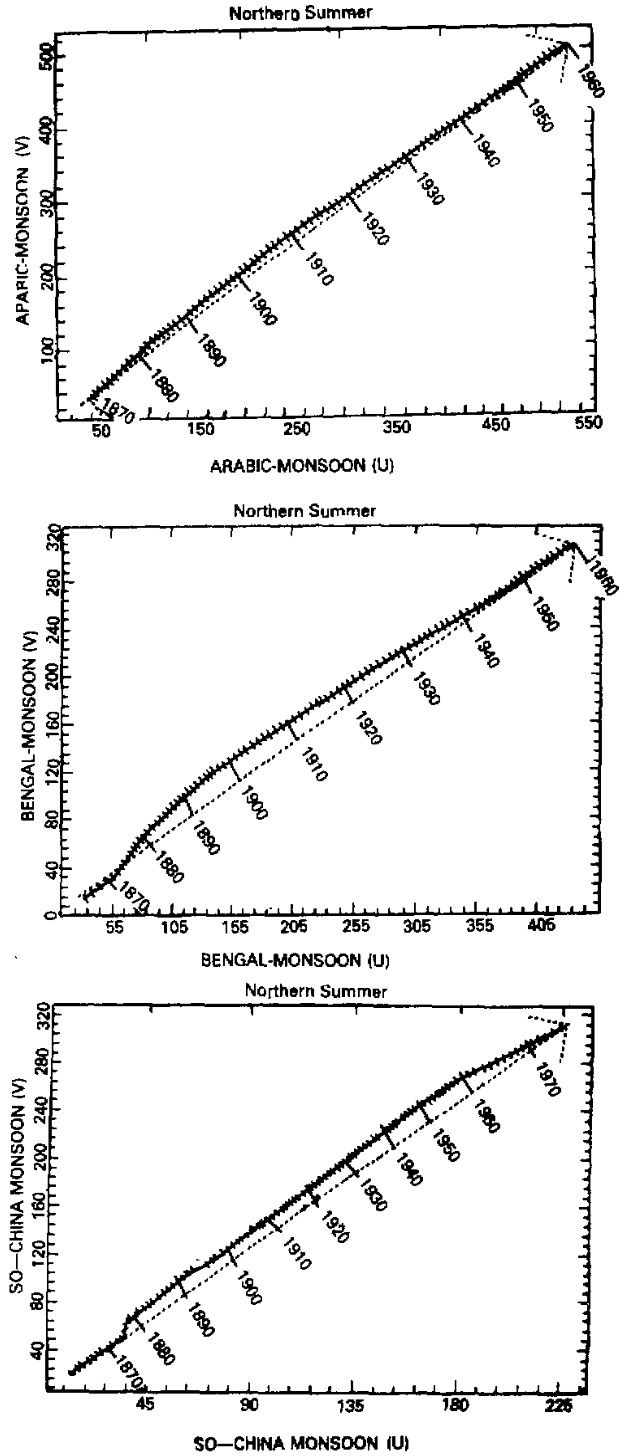

Fig. 4. Vector sum of surface wind for three branches of SW-monsoon over Indian and Pacific ocean.

in section 1 and also which is a boundary region from SE-trade to SW-monsoon, to describe the general characteristics of SW monsoon in Indian Ocean.

From Figure 5, three big signals of about 1870, 1900 and 1945 can be found clearly in SW-monsoon over the equatorial Indian Ocean, particularly the big signal of about 1900. The main features of variation are as follows: 1860–1875, normal condition; 1875–1900, turned into more southerly and more meridionally; 1900–1945, turned into more westerly or more zonally and 1945–1960, returned to normal. The wind direction changed about 25° from the period 1875–1900 to the period 1900–1945. Such kind of variation, i.e. the changes of basic monsoon current persisting for about 45 years should be a large signal of climatic system.

As for signal of 1875, we do remember that the data in this period would not be qualified for statistical confidence, but as seen in section 4, the rainfall data from the observation of weather stations in India, subcontinent, provide more reliable collateral evidence for this signal.

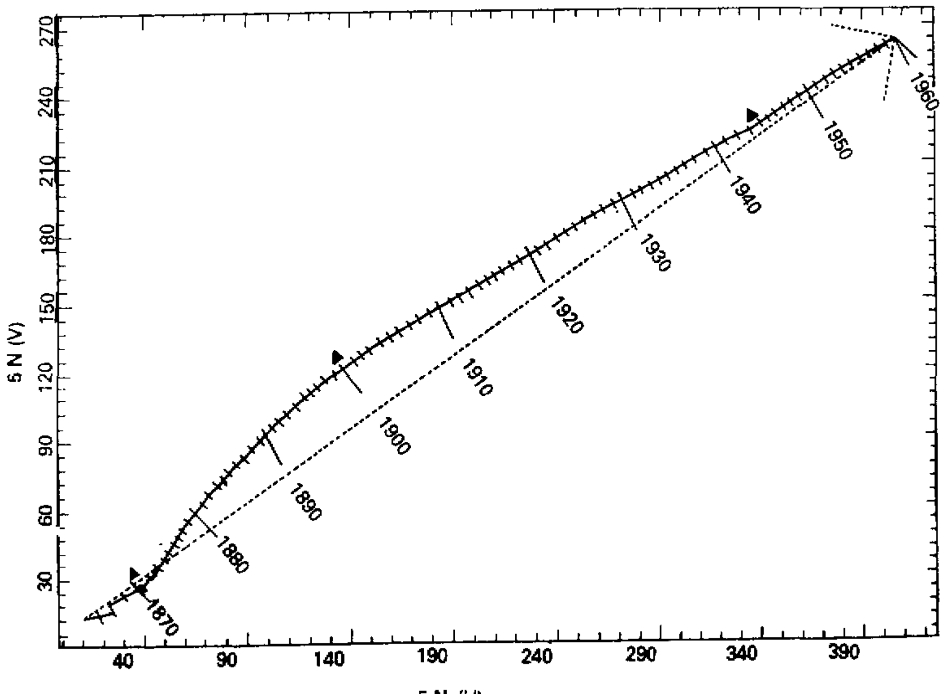

Fig. 5. Vector sum of wind in the equatorial Indian ocean (average at 5°N).

Large signals of SW-monsoon also demonstrate in the time series of its two components, especially in U-component. Figs. 6 (A) and (B) are the time series of U and V components of summer monsoon (June, July, August) in Bay of Bengal. Three signals shown in Fig, 5 appear in U-component of monsoon in Bay of Bengal. While in V-component only the signal in about 1900 still exist, but other two disappear. On the whole, 1870–1900: U component decrease and V component increased; 1900–1949: U component increased and V component decreased. These are coincided with the variation of the vector sum of wind in this area.

So we believe that the long term variation of SW-monsoon over the Indian is mainly

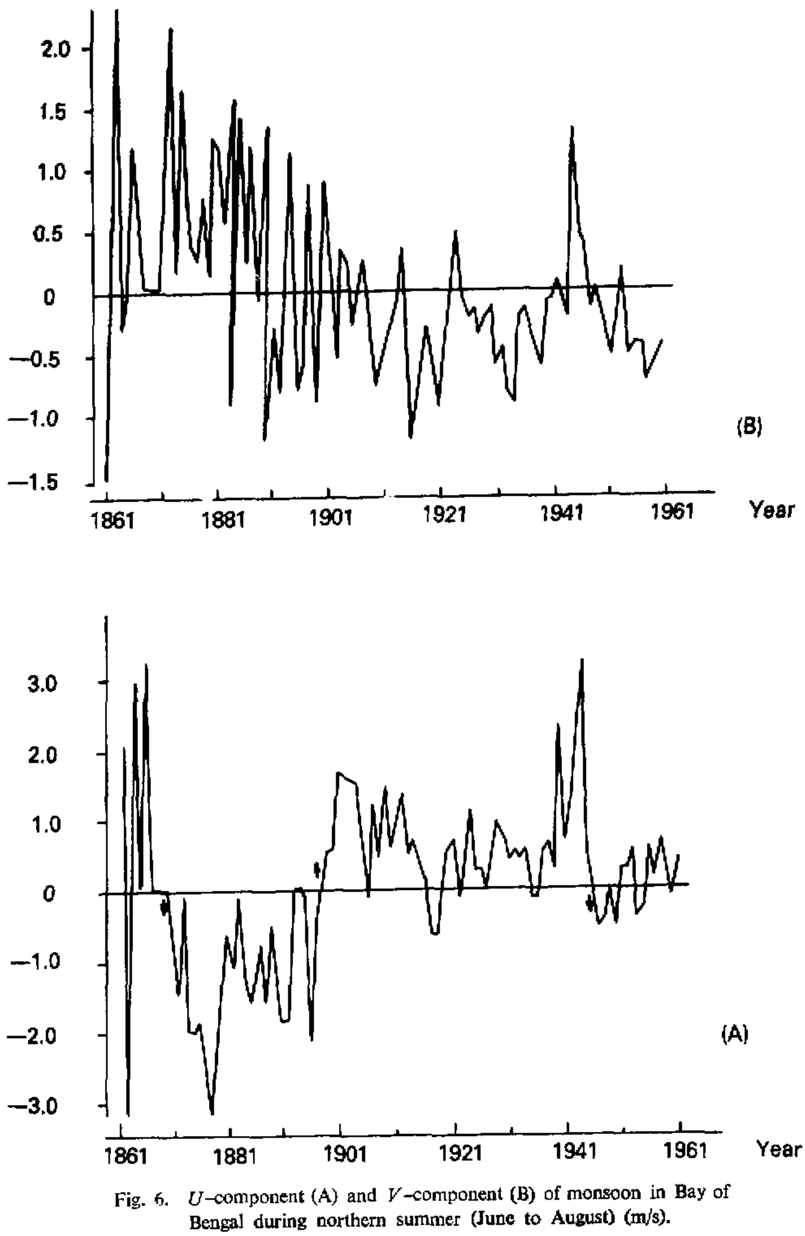

Fig. 6. U–component (A) and V–component (B) of monsoon in Bay of Bengal during northern summer (June to August) (m/s).

displayed as the alternation of "zonal monsoon period" and "meridional monsoon period". In last century, the period from 1875–1900 was a major "meridional monsoon period" and the period from 1900–1940 was the major "zonal monsoon period". The transform from "meridional monsoon" to "zonal monsoon" happened in about 1900. It is the strongest signal in last century.

2. *The Changeable SE-Monsoon and Its Climatic Regimes*

Fig. 7 is the vector sum of the surface wind in the region D, representing the variation of SW-monsoon in western Pacific and China Sea. Rather different from SW-monsoon, the SW-monsoon was more changeable in last century with the wind steadiness of about 68%, much less than SW-monsoon. There also appears three large signals in about 1875, 1898 and 1930. The first two are about the same as those in SW-monsoon, excluding the third one. The main features of wind transformation are: 1860–1875, SW-current, instead of SE-monsoon in this region; 1875–1898, SE-monsoon became a little bit southerly (meridionally); 1898–1930, it turned more easterly. The wind direction changed about 30° from the period of 1875–1898 to the period of 1898–1930. So the year of 1898, two years before 1900, was also a big signal of climatic variation in SW-monsoon area. After that it returned to its normal condition again.

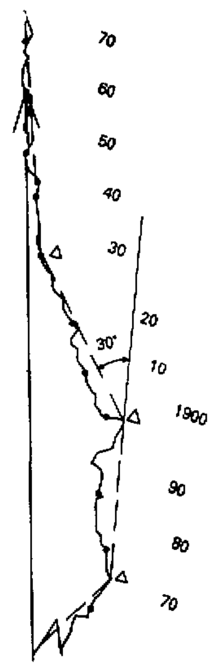

Fig. 7. The vector sum of wind in SE-monsoon area (D).

In comparing variations of SW-monsoon in Indian Ocean with those of SE-monsoon in western Pacific, it seems to be an inphase oscillation between these two wind systems, except the earliest period (1860–1875) During 1875–1900, both SE-monsoon and SW-monsoon became more meridionally which would decrease the convergence between them, but increase their convergence with polar air mass. Its influence on the variation of rainfall in India and East China will be seen in next section. During most of the period from 1900 to 1940, both the SW-monsoon and SE-monsoon became more zonally but with opposite direction. In that case, the convergence between them strengthens, and also influences the distribution of rainfall in Asia. It coincides with the wet period of plum rains in East China (see Fig. 9). By 1960, both the SW-monsoon and SE-monsoon had returned to their normal condition.

3. *The Alternation of Wind Direction around the ITCZ of Western Pacific and Its Relation to Transformation of SW-Monsoon*

The sensitivity of wind direction in ITCZ region of western Pacific in northern winter has already been pointed out by Fletcher (1982). Here we concentrate on the variation in the northern summer and its relations to summer monsoon over the ocean.

Fugure 8 is the vector sum of surface wind in the region E, western Pacific tropical convergence zone. Usually it is a boundary region of SW-monsoon, SE-monsoon, SE-

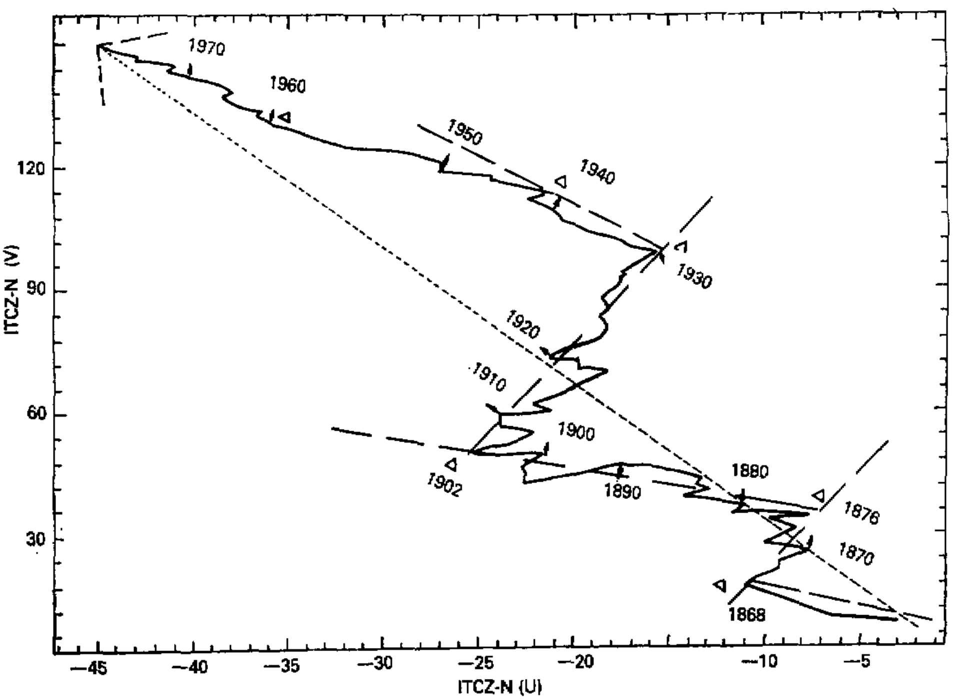

Fig. 8. Vector sum of wind in the tropical convergence zone in western Pacific (area E).

trade and NE-trade wind systems, so the wind direction is more changeable in this area. It can be seen from this figure that its mean direction is southeasterly (125°) and there were about 6 apparent changes in 1868, 1876, 1902, 1930, 1940 and 1960, among which there are four times when the wind direction occurs alternatively from SE to SW or SW to SE. The directions of basic currents in each period are: 1860–1868, SE; 1868–1876, SW; 1876–1902, SEE; 1902–1930, SSW; 1930–1940, SE; 1940–1960, SEE; 1960–1976, SE; The changes of wind direction in 1876, 1902 and 1930 are larger than 90°.

In addition, two regimes in 1876–1902 and 1902–1930, divided by the strongest singal of 1902, have the longest persistence and are closely linked with the variation of SW-monsoon. During the period of 1876–1902, the "meridional monsoon period" in Indian Ocean, the southeast current dominated this area. That means the ITCZ moves westward. While in the period of 1902–1930, the part of "zonal monsoon period" in Indian Ocean, the southwest current dominated this area. This means the strengthened SW-monsoon advanced eastward and pushed the ITCZ to move northeastward. The mean wind direction in this area changed about 130° between these two periods.

It can be seen that the alternation of wind direction is much stronger in ITCZ region compared with the dominant monsoon regions.

So the alternation of wind direction in ITCZ region is not only an index of movement of ITCZ, but also an indication of the transformation of atmospheric circulation patterns and climatic regimes.

IV. LARGE SIGNALS IN THE LONG-TERM VARIATION OF MONSOON RAINFALL IN ASIA AND ITS SYNCHRONISM WITH MONSOON OVER THE OCEAN

In order to describe the large-scale feature of monsoon rainfall variation in India, the Indian Monsoon Rainfall Index (IMRI) developed by Fu and Fletcher (1985) is used in this paper. The IMRI is the number of the regions with excess rainfall subtracting the number of the regions with deficit rainfall. The original data are taken from the paper presented by Banerjee and Raman (1976). The whole India is divided into 31 regions in their paper. The regions are defined as three catalogues: excessive, normal and deficit according to the percentage ratio of rainfall anomalies for the monsoon rain season (May to September) for each year.

Fig. 9 (a) gives the accumulative curve of IMRI from 1875 to 1975. Generally, there was no trend during last century, but existed several obvious transitions with large signals at about 1878, 1898, 1940 and 1964. The monsoon rainfall of India can be divided into four regimes. A wet monsoon lasted for 20 years for the period from 80's of last century to the beginning of this century (1878–1898). and then it entered into a relative dry monsoon period for about 42 years (1898–1940), with some short periods of wet monsoon in 1907–1910, 1915–1917 and 1930–1933. After that a wet monsoon occurred again for 25 years (1940–1964). By 1974 there had been another dry monsoon period which seems to last for 20 years. It is not clear for the last few years.

It is interesting that the variations of Indian monsoon rainfall are synchronous with the variations of summer monsoon over the ocean. Fig. 9 also gives the accumulative curve of the anomalies of U-component of surface wind in Bay of Bengal in northern summer from 1860–1960 (unfortunately the data after 1960 in India Ocean are still not available in hand). There are three signals in this curve occurring at about 1870, 1898 and 1944 which divide the whole curve into three periods: 1870–1898, U-component of monsoon in Bay of Bengal decreases, that is the "meridional monsoon period"; 1898–1944, U-component of monsoon in Bay of Bengal increases, that is the "zonal monsoon period". After 1944, it returned into its normal condition.

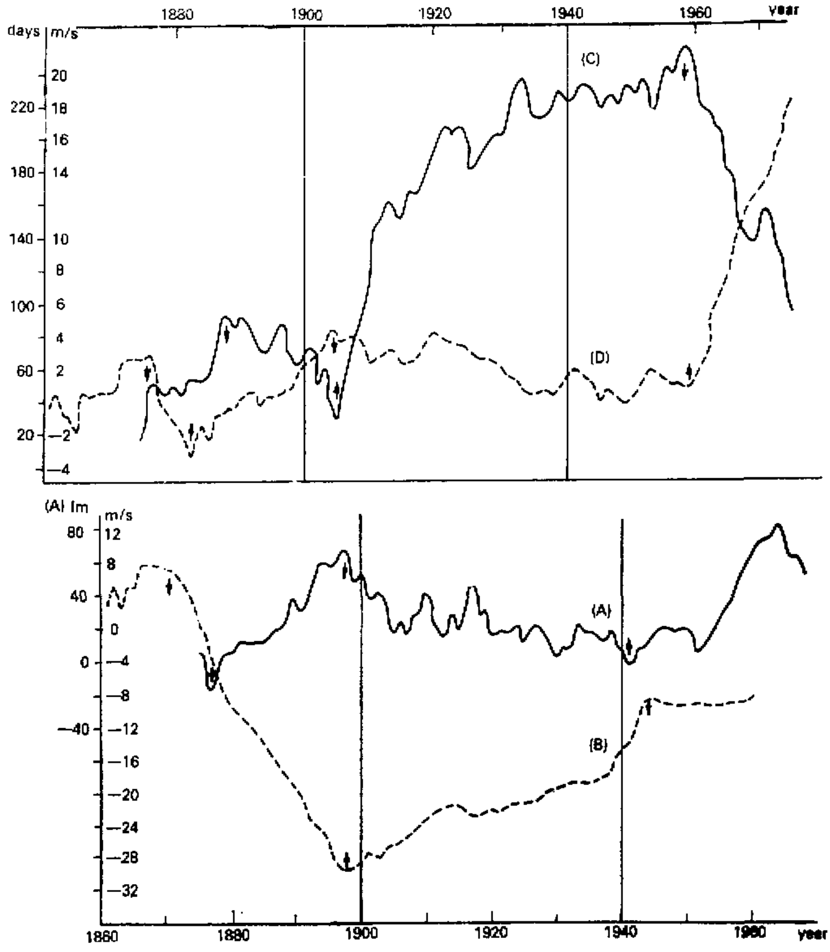

Fig. 9. The accumulative curves of Indian monsoon rainfall index (A), U-component of monsoon in Bay of Bengal (June to August) (B), Plum rains index in East China (C), and U-component of monsoon in South China Sea (June to August) (D).

In comparing with the curve of IMRI, it is observed that the monsoon rainfall in India increased during the "meridional monsoon period" (1878–1898), when the meridional monsoon current mainly converged with polar air mass over the Indian peninsula and the monsoon rainfall in India decreased during the "zonal monsoon period" (1898–1940), when zonal monsoon current advanced eastward and converges in East Asia.

One more thing should be pointed out that the variation of Indian monsoon rainfall is mainly related to the monsoon current in Bay of Bengal located at its downstream rather than to the monsoon in Arabian Sea, because the current converging into monsoon low mainly comes from the Bay of Bengal, but not from the Arabian Sea (see the streamline field in July, not given here).

Now let's look at the variation of monsoon rainfall in East Asia.

Fig. 9(b) gives the accumulative curve of the length of plum rains (days of pluviosity for each year) in Changjiang-Huai river valley (Yangtze and Huai River) from 1875 to 1975, which is used to be an index of summer monsoon in East Asia. This curve shows rather different features from curve of IMRI in Fig. 9 (a). The monsoon rainfall in East Asia during last century can be divided into 4 regimes: 1875–1887, wet monsoon; 1887–1905, dry monsoon: then suddenly the monsoon rainfall increased rapidly until about 1958 for a period about 53 years. After 1958, it decreased rapidly and entered a dry monsoon period. Two big signals in about 1905 and 1958 are somewhat different from two big signals of IMRI in about 1898 and 1940. There seems to be a certain degree of time-lag between the variation in East Asia and the variation in South Asia.

However, it is shown that the variation of plum rains in East China is closely linked with that of the summer monsoon in South China Sea. The accumulative curve of U-component of surface wind in South China Sea in northern summer in Fig. 9(b) shows four signals in about 1875, 1882, 1905, and 1958. The variation of this curve is almost out of phase with that of the plum rains. When the U-component of summer monsoon in South China Sea increases, i.e, it becomes more zonally, the plum rains in East China decrease and when it becomes more meridionally (U-component decrease), the plum rains increase.

It is interesting that the apparent decreasing of plum rains since 1958 which is well known in China was coincided with the sudden increasing of U-com onent of summer monsoon in South China Sea. That may indicate that the SW-monsoon from South China Sea is probably a major moisture source of plum rains in Yangtze valley: the more meridional the monsoon in South China Sea, the more stronger the moisture convergence in Yangtze valley and vice versa.

In the mean time the signal in about 1875 occurring in the rainfall data in Indian and China also provides more reliable collateral evidence for it occurring over the ocean. Because the rainfall data are from the weather stations which were not related to the observational method over the ocean and the changes of merchant ship route, which may indicate the reality of the existence of above signals.

The changes of monsoon circulation pattern mentioned above seem to be closely linked with the changes of cross-equatorial flow over the Indian and Pacific Oceans. Fig. 10 gives the departure of V component along the equator for the epoches of 1875–1895 and 1905–1925, showing the big changes of crossequatorial flow before and after the large signal of 1900. Before 1900. there was an enhanced cross-equatorial flow in the Indian Ocean which is reasonably related to the meridional monsoon over there, while it was weakened in most part of South China Sea and western Pacific related to the zonal monsoon over there. After 1900, however, the cross-equatorial flow was weaker in the Indian Ocean, which is related to the zonal monsoon over there, while it was stronger in the western Pacific, related to the meridional current over there and pushed the ITCZ to move northeastward as showing in Fig. 8.

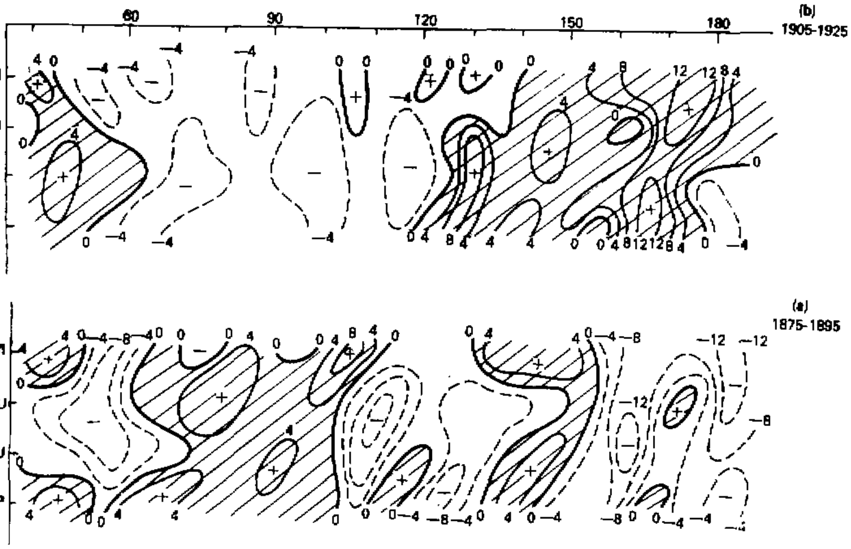

Fig. 10. Seasonal variation of ΔV along the equator for two epoches (a) 1875-1895; (b) 1905-1925.

V. A TIME-LAG SEESAW BETWEEN INDIAN MONSOON AND CHINA MONSOON

In the previous section, the relationship between summer monsoon over the continent and the summer monsoon over the ocean is explored. It shows the effects of the orientation of monsoon current over the ocean, i.e. the changes of major convergence channel of moisture, on the monsoon rainfall.

Since both Indian monsoon and China monsoon are part of the Asian monsoon, their variations should also link with each other in a general picture.

In putting Fig. 9 (a) and Fig. 9 (b) together with the time lag of China monsoon behind Indian monsoon for about 10 years, an out-of-phase variation between them displays rather clearly. The increasing Indian monsoon rainfall (1878–1898)is followed by the decreasing plum rains (1888–1905) and the decreasing Indian rainfall (1898–1940) is followed by the increasing plum rains (1905–1958).

The U-component of summer monsoon in South China Sea also appears as an out-of-phase oscillation with that in Bay of Bengal. The meridional summer monsoon in Bay of Bengal is followed by the zonal monsoon on South China Sea and the zonal summer monsoon in Bay of Bengal is followed by a meridional monsoon in South China Sea.

Combining the variation of monsoon rainfall both in India and East China and the variation of monsoon currents both in Bay of Bengal and in South China Sea and the SE-monsoon in western Pacific, we propose a general picture of monsoon oscillation in Asia.

It seems to be two types of monsoon circulations and rainfall patterns appearing before and after the large signal of about 1900 (see Fig. 11).

One pattern is characterized by the meridional SW-monsoon in Bay of Bengal and SE-monsoon in western Pacific and the zonal monsoon in South China Sea. In that case, the moisture over the ocean mainly converges to Indian Peninsula and meets with the polar air mass over there, leading to a large amount of monsoon rainfall over India. In the

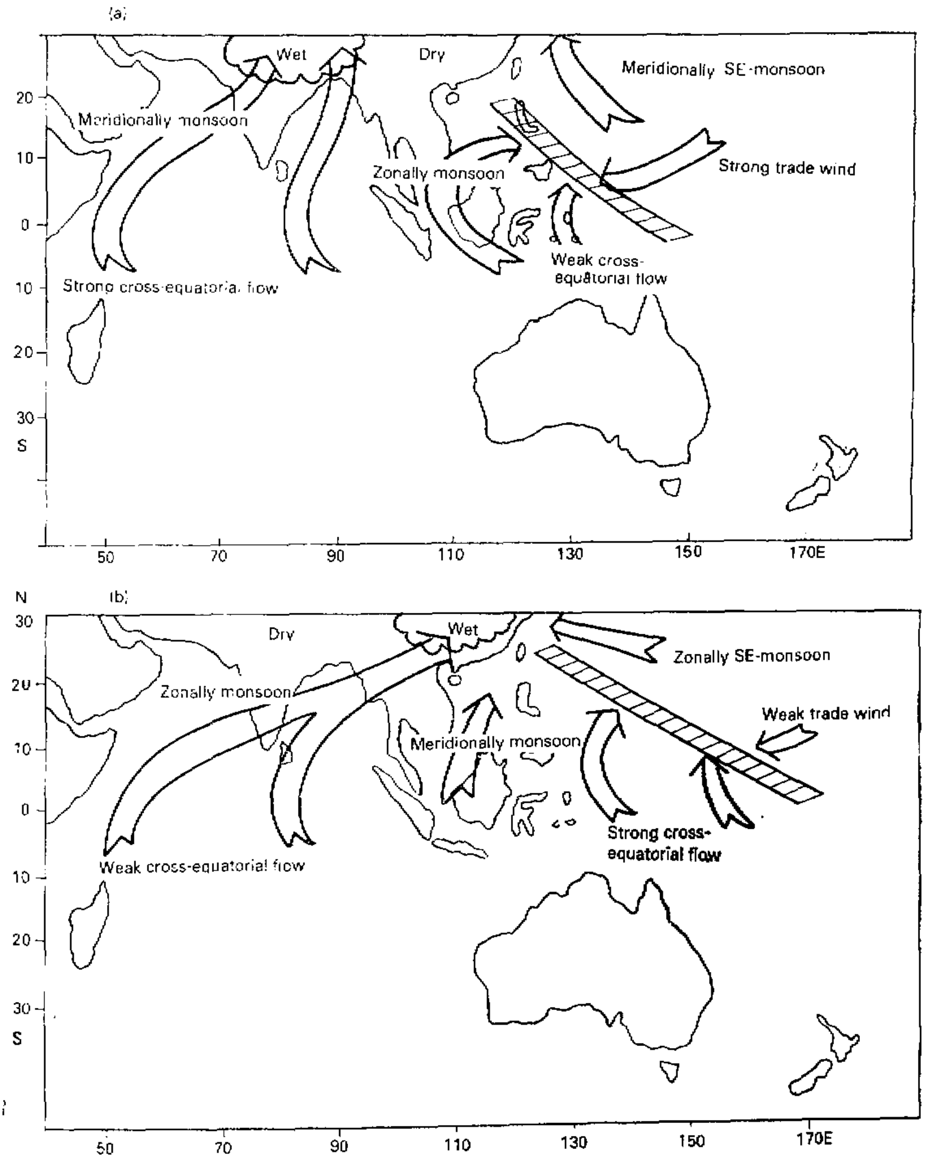

Fig. 11. Schematic maps of two patterns of Asian monsoon (a) before 1900; (b) after 1900.

mean time, the zonal monsoon over South China Sea does not converge to East China, but advances eastward and meets with SE-monsoon and SE trade in western Pacific. On the other hand, the SE-monsoon in China Sea also becomes more meridionally (see section 3(b)) and meets with polar air in North China instead of in Yangtze River valley. As a result, the dry plum rains are dominant in Yangtze River valley (see Fig. 11 (a)).

Another pattern has more zonally SW-monsoon in Bay of Bengal (also in Arabian Sea). It goes through India Peninsula and Indo-China Peninsula and enters into South China. While the meridional monsoon over South China Sea advances northward directly. Under such condition, the moisture over both Indian Ocean and South China Sea mainly converges over the southeast China. At that time, the SE-monsoon in western Pacific also becomes more zonally and brings the moisture from the Pacific into East China. Three branches of summer monsoon meet in Yangtze valley and cause the strong convergence of moisture. These are the main factors causing wet plum rains for this period. On the contrary, there is no strong convergence over India Peninsula and there will be dry monsoon over there (see Fig. 11(b)).

Based upon above analyses, it is suggested that the long-term variation of Asia monsoon, especially the transformation between two types of monsoon circulations and monsoon rainfall distributions mostly depend on which channel the moisture over the ocean prefers to enter into, Bay of Bengal or South China Sea. During the meridional Indian monsoon period, the moisture enters mostly in India Peninsula through the Bay of Bengal and causes the wet Indian monsoon. But during the zonal Indian monsoon periods, South China Sea monsoon becomes meridionally. At that time, the moisture over the ocean enters mainly into East China through South China Sea and meet with zonal SE-monsoon from western Pacific. In that case, dry India monsoon and wet plum rains would dominate the whole period. Such a phenomenon may be called the time-lag seasaw between Indian monsoon and China monsoon.

The out-of-phase oscillation between China monsoon and Indian monsoon within Asian monsoon system on interannual scale has also been observed recently (Fu and Fan, 1983).

VI. CONCLUSIONS

(1) From data of both the surface wind over the ocean and the rainfall over the continent, the large signals of climatic variation in the Asia monsoon region occurred in about 1900, 1940 and 1960 (perhaps also 1875). The one of about 1900 is the strongest and well documented, when sudden change happened also in global climatic system as pointed out by Fletcher (1983).

(2) The variations of summer monsoon over the ocean are mainly characterized by the alternation between "meridional monsoon" and "zonal monsoon". The SW-monsoon in Indian Ocean oscillates in-phase with the SW-monsoon in western Pacific, but out of phase with the SW-monsoon in South China Sea.

(3) The meridionalities of SW-monsoon in Bay of Bengal and in South China Sea are closely linked with the monsoon rainfall in India and plum rains in East China respectively: the more meridional the monsoon current, the heavier the monsoon rainfall and vice versa.

(4) The combination of oscillations of these major monsoon currents produces two different patterns of moisture convergence and then an out-of-phase oscillation between Indian monsoon rainfall and plum rains in East China with certain degree of time lag, which may be called seesaw between Indian monsoon and China monsoon.

However the correlation between Indian monsoon and China monsoon with the time lag of about one decade is not easy to understand like some other questions in the studies of long term climatic variation, because we know little about its physical mechanism.

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