Significance of the normalized seasonality of wind field and its rationality for characterizing the monsoon

LI Jianping (李建平) & ZENG Qingcun (曾庆存)

State Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

Correspondence should be addressed to Li Jianping (email: ljp@lasgsgi4.iap.ac.cn)

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Abstract The significance of the normalized seasonality of wind field is theoretically studied and the intrinsic relationship between its critical value and the definition of the monsoon region is revealed. As a result, the rationality which the monsoon region is characterized by the significant normalized seasonality is proved. Based on this, by use of the NECP/NCAR reanalysis data during 1958—1997, the spatial structure of the significant normalized seasonality of wind field is investigated, and the significant baroclinity of the seasonal variation of the atmospheric general circulation in the vertical direction is verified. Moreover, in the tropics there exists an anti-symmetric distribution between the significant seasonality in the eastern hemisphere and that in the western hemisphere, and the monsoon is linked closely to some important systems such as the subtropical highs, the night jet and the west wind channels.

Keywords: normalized seasonality, monsoon, monsoon region, significance baroclinity, western hemisphere tropical monsoon.

Monsoon is a seasonal wind and an important member of the global climate system[1—3]. Traditionally, it is a regional concept in climatology[1−3] and has the principal effect on the seasonal and interannual changes of the global atmospheric general circulation in the tropics[1−9]. The monsoon variation influences seriously the occurrence of disastrous weather and climate such as dry damage and waterlogging in monsoon regions, and brings serious economic loss[7]. The monsoon research is therefore undoubtedly very important. To study quantitatively the monsoon, some objective indexes which can characterize the main features of the monsoon must be given; otherwise we are in no position to discuss it. The (classical) monsoon summarizes all drastic seasonal variations over some regions in the tropics and the associated midlatitudes[1−3], so it is a natural idea with clear physical meaning that the monsoon is characterized by use of the seasonal variation magnitude of wind field. Based on the idea, Zeng et al.[1,2] presented a new concept, the normalized seasonality, to study the seasonal variation of the atmospheric general circulation and monsoon, and obtained some very bright three-dimensional pictures of the seasonal variation and some new discoveries. Their results show that: in the lower troposphere all the classical monsoon regions (i.e. the tropical monsoon regions) are the regions with maximum seasonal variability, and besides them there exist some regions with large seasonality in the subtropics and in the middle and high latitudes, which are called the subtropical monsoon region and the temperate-frigid monsoon region respectively; in the upper troposphere and in the lower stratosphere, apart from the known planetary monsoon region in South Asia-Africa, there exists another planetary monsoon region in the central and eastern Pacific-north and south America-Atlantic in the tropics (here it is called the western hemisphere tropical monsoon for short); in the middle stratosphere, there exists one planetary monsoon region around a whole parallel in each hemisphere, i.e. the stratosphere monsoon. Furthermore, they extended the concept of monsoon; namely, the (general) monsoon region may be defined as a region with significant seasonal variation. These investigations from Zeng et al. indicate that the normalized seasonal variability is an objective index for characterizing monsoon. However, there is still an important problem awaiting a solution. That is the inherent relationship in quantity between the significance of the normalized seasonality and the monsoon. (Clearly, the quantitative criterion is somewhat subjective. Thus, we use the criteria in ref. [8] as the standard.) In this paper, we establish the relationship between the normalized seasonality and the usual method in defining the monsoon region, and carry out some analyses with the observed data.

1 Normalized seasonality

Before our discussion, it is very necessary to explain some basic concepts. The normalized seasonality presented by Zeng et al.[1,2] is defined as follows:

$$d = \frac{\left\| F_{\mathrm{s}} - F_{\mathrm{w}} \right\|}{\left\| \overline{F} \right\|}, \tag{1}$$

where F is a characteristic quantity of meteorological element, F_{s} and F_{w} are the typical values in summer and winter, respectively (e.g. F_{s} is the monthly mean in July, F_{w} the monthly mean in January), $\overline{F}$ is the annual mean or two-seasonal mean of summer and winter (i.e. $\overline{F} = (F_{\mathrm{s}} + F_{\mathrm{w}})/2$), $\|A\|$ is the norm of A, i.e.

$$\|A\| = \left(\iint_S |A|^2 \,\mathrm{d}S \right)^{1/2}, \tag{2}$$

where S represents the computational domain. Obviously, the normalized seasonality d is a relative measure for characterizing the seasonal variation of F. Over most regions of the globe, on the mean state, January or July is truly the extreme month, so the normalized seasonality d can also be considered as the normalized amplitude of seasonal cycle[1,2]. This paper only discusses the case where F is wind field, i.e. $F \equiv \boldsymbol{V}$. Hence, $\boldsymbol{V}_{\mathrm{s}}$ and $\boldsymbol{V}_{\mathrm{w}}$ can be regarded as prevailing wind in summer and in winter, respectively. Additionally, according to the meteorological practice, hereafter consider the number field K as the real field.

2 Significance of seasonality and monsoon

Let the angle between the wind vectors $\boldsymbol{V}_{\mathrm{s}}$ and $\boldsymbol{V}_{\mathrm{w}}$ be a, $a \in [0, \pi]$. Then one has

$$\cos a = \frac{(\boldsymbol{V}_{\rm s}, \boldsymbol{V}_{\rm w})}{\|\boldsymbol{V}_{\rm s}\|\|\boldsymbol{V}_{\rm w}\|}. \quad (3)$$

Theorem 1. When the norms $\|\boldsymbol{V}_{\rm s}\|$ and $\|\boldsymbol{V}_{\rm w}\|$ are fixed, the angle a ($a \in [0, \pi]$) between $\boldsymbol{V}_{\rm s}$ and $\boldsymbol{V}_{\rm w}$ is a strictly increasing function of the normalized seasonality ***d***.

Proof. For the real field K one has

$$\|\boldsymbol{V}_{\rm s} - \boldsymbol{V}_{\rm w}\|^2 = \|\boldsymbol{V}_{\rm s}\|^2 + \|\boldsymbol{V}_{\rm w}\|^2 - 2(\boldsymbol{V}_{\rm s}, \boldsymbol{V}_{\rm w}),$$
$$\|\boldsymbol{V}_{\rm s} + \boldsymbol{V}_{\rm w}\|^2 = \|\boldsymbol{V}_{\rm s}\|^2 + \|\boldsymbol{V}_{\rm w}\|^2 + 2(\boldsymbol{V}_{\rm s}, \boldsymbol{V}_{\rm w}).$$

Therefore

$$d = 2\sqrt{\frac{\|\boldsymbol{V}_{\rm s}\|^2 + \|\boldsymbol{V}_{\rm w}\|^2 - 2(\boldsymbol{V}_{\rm s}, \boldsymbol{V}_{\rm w})}{\|\boldsymbol{V}_{\rm s}\|^2 + \|\boldsymbol{V}_{\rm w}\|^2 + 2(\boldsymbol{V}_{\rm s}, \boldsymbol{V}_{\rm w})}}$$
$$= 2\sqrt{\frac{\|\boldsymbol{V}_{\rm s}\|^2 + \|\boldsymbol{V}_{\rm w}\|^2 - 2\|\boldsymbol{V}_{\rm s}\|\|\boldsymbol{V}_{\rm w}\|\cos a}{\|\boldsymbol{V}_{\rm s}\|^2 + \|\boldsymbol{V}_{\rm w}\|^2 + 2\|\boldsymbol{V}_{\rm s}\|\|\boldsymbol{V}_{\rm w}\|\cos a}}. \quad (4)$$

Since

$$\cos a = \frac{\left(\|\boldsymbol{V}_{\rm s}\|^2 + \|\boldsymbol{V}_{\rm w}\|^2\right)(4 - d^2)}{2\|\boldsymbol{V}_{\rm s}\|\|\boldsymbol{V}_{\rm w}\|(4 + d^2)}, \quad (5)$$

let f=cos$a$, $c = \left(\|\boldsymbol{V}_{\rm s}\|^2 + \|\boldsymbol{V}_{\rm w}\|^2\right) / 2\|\boldsymbol{V}_{\rm s}\|\|\boldsymbol{V}_{\rm w}\|$. Then while $\|\boldsymbol{V}_{\rm s}\|$ and $\|\boldsymbol{V}_{\rm w}\|$ are fixed, c is fixed,

$$f_d' = -\frac{16cd}{(4+d^2)^2} < 0, \quad d > 0. \quad (6)$$

Thus, cos$a$ is a strictly increasing function of d. In other words, a is a strictly increasing function of d. The proof is complete.

From (4) we easily obtain:

Theorem 2. Let the angle between $\boldsymbol{V}_{\rm s}$ and $\boldsymbol{V}_{\rm w}$ be a. Then

(i) $d < 2$ for $0 \leqslant a < 90°$;

(ii) $d = 2$ for $a = 90°$;

(iii) $d > 2$ for $90° < \alpha \leqslant 180°$.

Theorem 1 reveals the inherent relationship between d and the seasonal variation of wind field. It suggests that the normalized seasonality d is truly an index which can characterize the degree of monsoon, and that the region with large d is certainly the region with large variation of wind direction. Theorem 2 indicates that if the monsoon region is defined as the region which the prevailing wind direction shifts by at least 90° between winter and summer (the angle is slightly smaller than that in the definition from Ramage[8]), it corresponds to the region where the normalized seasonality $d > 2$, and $d = 2$ is simply the critical value of significant normalized seasonality (If we use the definition given by Ramage, i.e. one of the conditions of the monsoon region is the prevailing wind direciton $a \geqslant 120^\circ$ between January and July[8], the monsoon region corresponds to the region where $d > d_c$, here d_c is corresponding to 120°; but d_c is a space function and is disadvantageous to application). As for the difference between the region determined by d =2 and that determined by d_c, we make a comparison (here taking S as an area of 5° latitude by 5° longitude) by use of the climatological mean wind field (with 17 levels from 1 000 hPa to 10 hPa in the vertical direction) from the NECP/NCAR 1958—1997 reanalysis data. Fig. 1 is the result at 850 hPa. As is shown, the two regions are very close (the conclusion holds for other levels). Therefore, it is reasonable and convenient that 2 is regarded as the critical d value. In a word, the above results suggest that the significant normalized seasonality is able to characterize the main characteristic of monsoon which the prevailing wind direction has a significant alteration, so characterizing monsoon by it is objective and rational. Since the definition of the normalized seasonality is not limited to the tropics, it is true that the concept of monsoon was extended in refs. [1,2], i.e. the monsoon region is defined as the region with significant seasonal variation. The distribution of significant normalized seasonality d is therefore the geographical distribution of monsoon in the world.

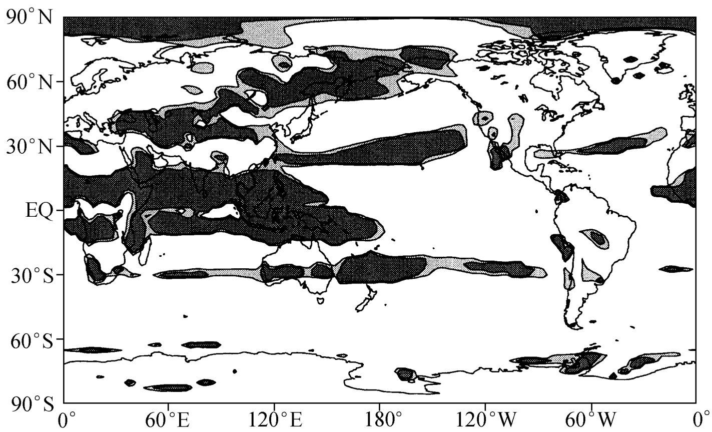

Fig. 1. The normalized seasonality of wind field d =2 and $d = d_c$ at 850 hPa (where the wind field is the climatological mean data during 1958—1997, the light shaded area and the dark shaded area represent the regions with d =2 and $d = d_c$, respectively).

Broadly speaking, the monsoon region determined in fig. 1 is divided into three large regions: the tropical, subtropical and temperate-frigid monsoon regions[3]. All the classical monsoon regions such as the Asia-Australia monsoon region (including the Indian monsoon region), the tropical Africa monsoon region, are contained in them, and the so-called North Africa, North America, South Africa and Australia monsoon regions and Europe monsoon tendency region are also shown in the figure. Different from the classical monsoon regions, however, fig. 1 indicates that in the subtropics there exist obviously monsoon regions in the Pacific, the North Atlantic and the South Indian Ocean, and that there are also monsoon regions in central Asia along the northern edge of the Iran and Tibetan Plateau (The significant region of normalized seasonality in the Iran and Tibetan Plateau is false since the earth's surface there is higher than 850 hPa), the Far East and northern Alaska, and north polar region.

3 Vertical distribution of significant seasonality

To display briefly and clearly the vertical structure of significant seasonality and the interactions and relationships between it and some important synoptic and climatic systems, fig. 2 gives the zonal mean distribution of the normalized seasonality, and the distributions of westerly-easterly zero lines (WEZLs) of zonal mean fields of January and July and those of the mean of the two months. The figure shows that: (i) Though the distributions of seasonality in the Northern and Southern Hemispheres are similar, the differences between them are quite distinct. One is that at every level the seasonal variations in the Northern Hemisphere are stronger than those in the Southern Hemisphere. In other words, the monsoons in the Northern Hemisphere are stronger than those in the Southern Hemisphere. This is associated with the property which the land-sea distribution in the Northern Hemisphere is more complete than that in the Southern Hemisphere. Another is that the seasonality of the middle and high latitudes in the Southern Hemisphere in the lower troposphere is very small, but there is temperate-frigid monsoon in the Northern Hemisphere. (ii) The seasonal variation of the atmospheric general circulation possesses significant baroclinity[2]. In the lower troposphere under 500 hPa, there exist four regions with significant seasonality, i.e. the tropical, subtropical and Northern Hemisphere temperate-frigid monsoon regions. In the troposphere (under 200 hPa), two regions with significant ***d*** in the subtropics slope to the equator as altitude increases; and the intensity of the Northern Hemisphere one increases as altitude increases, contrary to the Southern Hemisphere one. From the upper troposphere to the bottom of the stratosphere (about 350—400 hPa), the Southern Hemisphere one disappears, and there remains only the Northern Hemisphere one. Its intensity reaches a maximum value, and extends to the tropics so that the tropical and subtropical monsoons combine together into a nonseparable system. In the stratosphere, the Southern Hemisphere one appears again, and two subtropical regions with significant ***d*** slope to the middle and higher latitudes as altitude increases, as opposite to the case in the troposphere. The two stratospheric monsoons around the whole parallel are associated with the form, maintenance and breakdown of the night jet[2]. (iii) The significant seasonality is closely related to the subtropical highs. From fig. 2, the mean WEZLs of January and July are roughly coincident with the axes of the significant seasonality ***d***, and the ranges between the WEZLs of January and those of July are approximately coincident with the regions with significant seasonality. The subtropical monsoons are closely linked to the seasonal migration of the subtropical highs[1,2] since the subtropical ridge line lies on the WEZL. The main physical reasons causing the vertical structure of seasonality mentioned above may be the seasonal variation of the solar radiation, the vertical distribution of the atmosphere composition and land-sea contrast, etc.

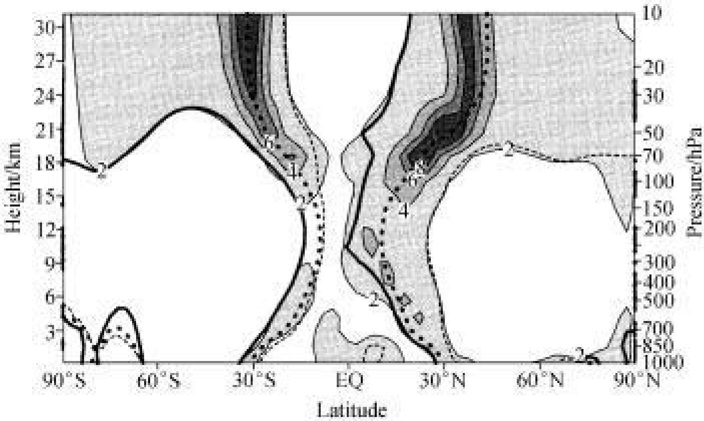

Fig. 2. The zonal mean distribution of the normalized seasonality of wind field. The thick, thin and dotted lines denote the WEZLs of January and July and the mean WEZL of the two months, respectively.

Seasonality is not purely zonal distribution, and it has some distinct regional differences which shows the zonal non-symmetrical characteristics. Fig. 3(a) and (b) show the mean

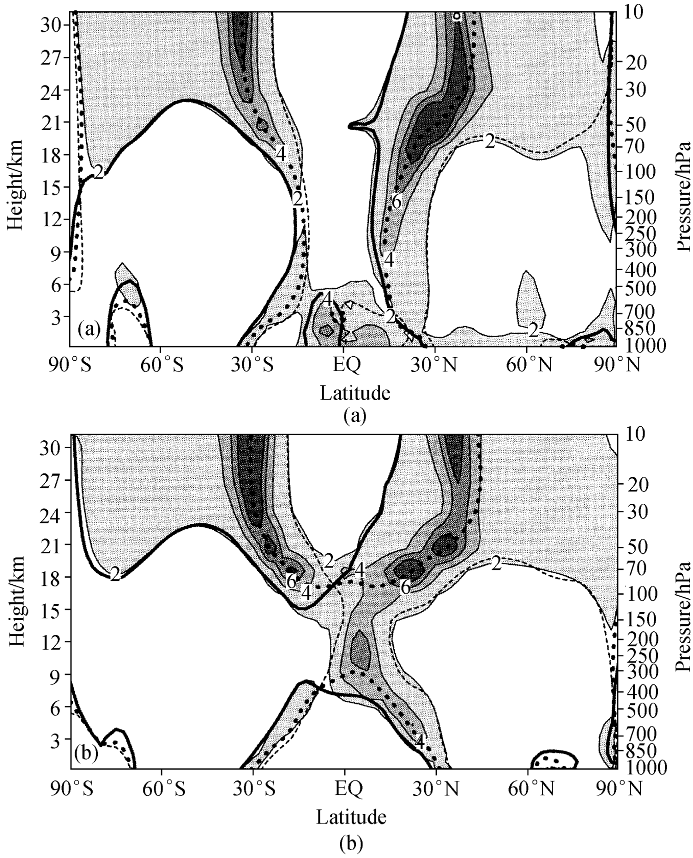

Fig. 3. The Mean meridional distributions of the normalized seasonality of wind field in the eastern hemisphere and in the western hemisphere. Otherwise the same as in fig. 2.

meridional distributions of ***d*** in the east and west hemispheres, respectively. They suggest that the distributions of the normalized seasonality of wind field in two hemispheres are different, especially under 50 hPa. The differences are as follows: (i) The eastern hemisphere includes the classical tropical monsoons (i.e. the Asian-Australian monsoon, the African monsoon). The significant ***d*** region in it presents approximately “U” pattern, and the significant ***d*** in the western hemisphere appears in roughly “X” pattern. (ii) In the lower troposphere (under 500 hPa), in the east hemisphere the tropical, subtropical and temperate-frigid monsoons coexist, and the tropical monsoon is strongest; in the western hemisphere, however, there only exists a subtropical monsoon but no tropical monsoon. Above the middle troposphere, the eastern hemisphere is chiefly characterized by subtropical monsoon and has no tropical monsoon; the western hemisphere is quite distinct with this. Two subtropical monsoons above 500—100 hPa combine together into one and transform into the monsoon which is mainly characterized by the tropical monsoon, and this is the central and eastern Pacific-north and south America-Atlantic planetary monsoon found by Zeng et al.[1,2]. Here it is called the western hemisphere tropical monsoon. It again branches two subtropical monsoons in higher levels. The western hemisphere tropical monsoon is situated in the corresponding position with the west wind channels over the central and east Pacific and the Atlantic. It is closely associated to the seasonal variation of the west wind channels over the two areas. (iii) The slope of significant ***d*** region in the eastern hemisphere subtropics is obviously weaker than that in the western hemisphere. Additionally, the above analyses point out that in the tropics under 50 hPa the regions with significant seasonality in the eastern hemisphere and in the western hemisphere possess anti-symmetrical characteristics. This is clearly shown in the mean zonal distribution of ***d*** in the topics (15° S—15N°) (fig. 4). In the tropics, the lower troposphere in the eastern hemisphere is the tropical monsoon region. There does not exist significant seasonality in the higher troposphere and in the stratosphere; but in the western hemisphere, vice versa. The International Date Line and 500 hPa level are the lines of

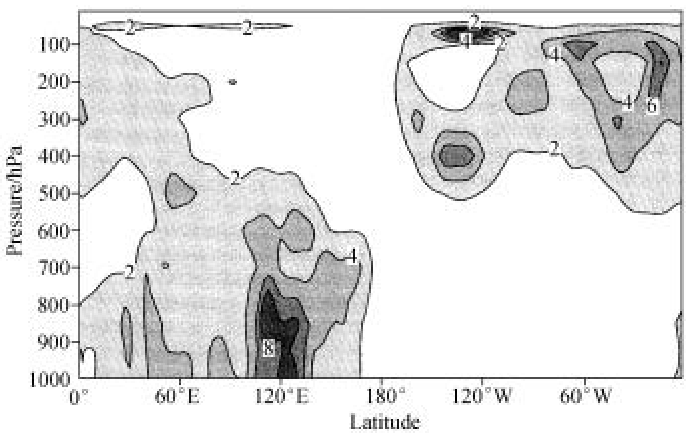

Fig. 4. The mean zonal-vertical distribution of the normalized seasonality of wind field in the tropics (15° S—15N°).

demarcation of this anti-symmetrical structure which is an important characteristic of the tropical monsoon vertical distribution. Besides, the above results also indicate that the zonal non-symmetrical characteristic appears mainly under 50 hPa.

4 Discussion

Monsoon is an important global atmospheric general circulation system. It is shown by the significant seasonal variation of circulation. This paper reveals theoretically the relationship between the normalized seasonality of wind field and the monsoon, studies the significance of seasonality, and states the rationality which monsoon is characterized by the seasonality. The theoretical results show that the distribution of the significant normalized seasonality *d* is simply the geographical distribution of monsoon in the world. Using the NECP/NCAR 1958—1997 reanalysis data, the space structure of the significant normalized seasonality of wind field is investigated, and the significant baroclinity of the seasonal variation of the atmospheric general circulation in the vertical direction is verified. Moreover, we find that there exists an anti-symmetric distribution between the significant seasonality of the eastern hemisphere and that of the western hemisphere in the tropics, and point out that the monsoon is associated closely to some important systems such as the subtropical highs, the night jet and the west wind channels. Based on our results, all the following directions are worth studying deeply in the future: this anti-symmetrical structure in the tropics, the profound physical mechanisms of the interactions and relationships between different monsoon systems and between the monsoons and the subtropical highs, the night jet and the west channels etc., and their important effects on interannual climatic variation.

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