Identifying the northernmost summer monsoon location in East Asia*

Hu Haoran[1] and Qian Weihong[2]**

(1. Institute of Plateau Meteorology, CMA, Chengdu 610071, China; 2. Monsoon and Environment Research Group, School of Physics, Peking University, Beijing 100871, China)

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Abstract An integrated index which can be used to indicate the advance of subtropical summer monsoon in East Asia has been proposed in this paper. The index was combined by three variables including precipitation, wind and pseudo-equivalent potential temperature. The northernmost summer monsoon location (NSML) was identified by using this index annually. It was found that the NSML experienced an interdecadal shift in the period 1977—1979 based on the annual index analysis from 1961 to 2001. A comparison of the NSML with other four summer monsoon indices has also been made. The result showed that the NSML could well represent the interannual and interdecadal variability of summer monsoon precipitation in North China (beyond 35°N), while other four indices could well indicate the precipitation anomalies of East Asian summer monsoon along the Yangtze River valley (around 30°N).

Keywords: subtropical summer monsoon, northernmost location, index, interdecadal variability, East Asia.

It is well known that the climate of monsoon has a wide coverage for about one fourth in the world land and a huge impact on nearly one third of the world population as well as an impact on local culture, religion, and economy. China is located within the famous region of East Asian monsoon. In eastern China, drought or flood is directly linked to the intensity and location (advance and retreat) of the East Asian summer monsoon annually.

In previous studies, the work[1,2] was focused on the region of southern China, such as South China and Jiang-Huai River valley because the subtropical summer monsoon can directly affect these regions annually. In northern China, however, similar studies were relatively few because it is located in the arid or semi-arid regions and along or near the northernmost location of East Asian summer monsoon. Climatologically, the long-term mean annual precipitation in northern China is so small but the interannual variability of summer rainfall is larger. This large variability of summer rainfall from interannual and interdecadal scales in northern China is directly associated with the intensity and advance of East Asian summer monsoon. Some studies[3,4] showed that many natural disasters, specially the occurrence of flood or drought events, are related to the variation of the northernmost summer monsoon location (NSML).

In general, there are two types of definition on the NSML. The first is based on the air mass's feature from both temperature and moisture. The NSML is the result of the interaction between the warm-moist air mass of summer monsoon from the tropical low latitude and cold-dry air mass of westerly flow from the mid-high latitude. In the 1940s, Tu and Huang[5] proposed a combined variable, based on a fact that the wet bulb potential temperature of the warm-moist air mass is higher than that of the cold-dry air mass, to identify the advance and retreat of the subtropical summer monsoon in eastern China. The basic idea illustrated the fact that the NSML is a crossing section of warm-wet air mass and cold-dry air mass when they meet each other in eastern China. Shi et al.[6] applied the pentad-mean pseudo-equivalent potential temperature at the 850 hPa level in summer (June, July, August, September) as a variable for the period 1971—1981 to judge the influence of summer monsoon. He confirmed that the θ_{se} isotherm of 332 K is the critical value to find that the climatological northernmost latitude of summer monsoon in North China is located at around 40°N. Tang

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** To whom correspondence should be addressed. E-mail: qianwh@pku.edu.cn

et al.[7] chose the θ_{se} isotherms of 344 K—348 K at the 1000 hPa level and 336 K—340 K at the 850 hPa level as indices of the advance and retreat of the subtropical summer monsoon. Considering the higher temperature and moisture in the subtropical monsoon air mass, Zhu et al.[8] suggested that it would be better to use the isodrosotherm instead of the isotherm, such as the 14℃ isodrosotherm at the 850 hPa level. By using the pentad mean NCEP reanalysis data from 1983 to 1996, Wang et al.[9] proposed a new definition of summer monsoon advance, including the intensity of the southwest wind and temperature-moisture conditions. By using the Wang et al.'s definition[9], Wu et al.[10] found that there was an interdecadal transition for the northernmost location of East Asian summer monsoon in China according to the analysis of the last 50-year NCEP pentad mean data.

The second type of the NSML definition is mainly based on the advance of precipitation. The rainy season in eastern China generally begins with the onset of the summer monsoon in the South China Sea and ends with its withdrawal. The major seasonal rain belt over East Asia moves from low to middle and high latitudes as the summer monsoon develops and advances northward. Thereafter the summer monsoon retreats southward rapidly, thus leading to the end of the rainy season in summer in eastern China. Each year, there should be the northernmost limit of this seasonal rainfall if a criterion of rainfall is given first. The rainfall criterion or index is widely used in the study of monsoon onset and its intensity. Synthesized indices to determine the NSML in China have been carried out by Gao et al. using the data in the 1950s[11]. They identified the northernmost limit of East Asian summer monsoon where the highest frequency of the polar front activity occurred, the mean trough of the sea level pressure, the largest pentad rainfall belt, and the maximum dry-wet transition zone from summer to winter seasons. Finally, they drew a line that the climatological mean line of the NSML is basically at the north of 40°N and its latitude gradually extends northeastward to the 50°N at the 120°E longitude. Tao and Chen[1] concluded a marching sketch of East Asia summer monsoon seasonally on the basis of previous studies and it was improved by Lau and Yang[12] using satellite observation. Wang and Lin[13] regarded the rainfall as an index to study the onset, marching and withdrawing of Asian-Northwest Pacific summer monsoon and clearly revealed the integrated feature of summer monsoon in these regions.

Reviewing the study process, most of indices and conceptional models about the advance and withdrawal of East Asian summer monsoon have been defined through air mass and precipitation. The compositive and exhaustive study began from Wu et al.[10]. A series of study shows that the advance and withdrawal of summer monsoon can be well illustrated through air mass, but the NSML is not very accurate only by air mass[5—10]. The physical meaning of the relationship between the location of summer monsoon advance and summer rainfall in North China is very clear. Warm and damp air coming from Indian Ocean and South China Sea to North China results in the increase of summer rainfall when summer monsoon reaches North China. On the contrary, when the advance northward of summer monsoon is slow or its strength is weaker, the summer rainfall will decrease in North China. Recently, Wu et al.[10] found that the correlation between summer rainfall in North China and the limit location of summer monsoon defined by wind and θ_{se} fields was very low. The difference between monsoon rainfall and non-monsoon rainfall is difficult to identify when only considering the rainfall in some regions such as in South China, lower reaches of Yangtze River and Northeast China. This can largely influence the definition of the advance and withdrawal of summer monsoon as well as the determination of the NSML.

Through those analyses mentioned above, this paper defines a new criterion by synthesizing both air mass and rainfall, hoping this can better reflect the advance and withdrawal of summer monsoon as well as accurately identify the NSML. In this paper, we focus on the applicability of the new criterion in the longitude scale from 110°E to 120°E. The NSML and four indices of summer monsoon are chosen to identify and compare their capacity in indicating the summer rainfall regionally in interannual scales.

1 Data and method

In this study, two data sets were used. The first is the pentad-mean data including wind and pseudo-equivalent potential temperature calculated by using the daily NCEP-NCAR reanalysis data with a spatial resolution of 2.5° × 2.5° for the period of 1961—2001. The second data is the original precipitation data including 726 stations provided from China Meteorological Administration. The data actually used in the study are dealt with interpolation with a spatial resolution of $1^{\circ}\times 1^{\circ}$ in the period of 1961—2001[14]. The main methods included correlation and comparison analyses as well as the running t-test.

2 Seasonal advance of summer monsoon

Through repeating experiments, we finally confirmed a new criterion to describe the advance and withdrawal of summer monsoon as well as to determine the NSML. To reach this description, three conditions should be satisfied at the same time including (i) southwest wind averaged for five-day mean at the 850 hPa level, i.e., $U>0$ m/s and $V>0$ m/s; (ii) $\theta_{se}\geqslant 335$ K averaged for five-day mean at the 850 hPa level; and (iii) precipitation $P\geqslant 4$ mm·d^{-1} averaged for five-day mean. By using this compositive criterion, the advance and withdrawal of summer monsoon can be well described in South China and lower reaches of the Yangtze River while the NSML can be well identified in North China.

According to the new criterion, Fig. 1 presents the climatic normal advance process of East Asian summer monsoon averaged for the 41 years from 1961 to 2001. In Fig. 1, the summer monsoon first reaches South China (around 25°N) at the 27.5th pentad, then lower reaches of the Yangtze River (30°N) at the 33th pentad, the lower reaches of the Yellow River (35°N) at the 37th pentad, and North China (beyond 40°N) at the 39th pentad. Finally, it reaches the northernmost location (41.6°N) at the 42th pentad and stays there for about three pentads. Its southward retreat starts from the 45th pentad. From South China to lower reaches of the Yellow River the advance keeps the same speed and retreat is rapid. In the advance northward process, four stages are associated with the rainfall periods in South China, lower reaches of the Yangtze River, the Yellow River, and North China, respectively. It was noted that two curves of 335 K θ_{se} isotherm and 4 mm·d^{-1} precipitation isoline have a cross point at the 39th pentad. Before the pentad, the 335 K θ_{se} isotherm is always lower than the 4 mm·d^{-1} isoline. In northern China (north of 35°N), two curves have a same tendency with pentads basically.

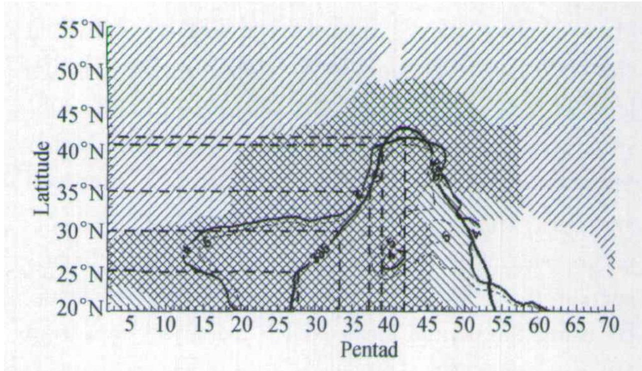

Fig. 1. The climatic normal advance process of East Asian summer monsoon averaged for the 41 years from 1961 to 2001. The regions covered by left-downward diagonal denote west wind, the regions covered by right-downward diagonal denote south wind, so the regions covered by reticulation pattern denote southwest wind; thick solid lines denote the 335 K θ_{se} isotherm; thin solid lines denote the 4 mm·d^{-1} precipitation isoline; and thin dashed lines denote the 5 mm·d^{-1} isoline.

3 Interannual and interdecadal variability of the NSML

The yearly zonal-mean latitudes averaged from 110°E to 120°E for the NSML were calculated based on the new criterion and are shown in Fig. 2. In the total 41 years, the annual deviation was changed from a decade to another. A relatively small interannual variability was observed in the 1970s while large interannual variability appeared in the 1980s and 1990s. In the total 41 years, nine years with the latitude of the NSML were lower than 40°N and concentrated mostly after 1979. The northernmost latitude of the NSML was observed in 1963 (44°N) and the southernmost latitude of the NSML found in 1999 (33°N). The running t-test method has been used to identify its interdecadal shift. Its result shown in Fig. 3 indicates that an interdecadal shift of its northernmost location happening in a 2 to 3-year period (1977—1979) was detected with the 99% significance level. Abnormal years of the NSML have been chosen out according to the criterion with the value that should be greater or equal to a standard deviation

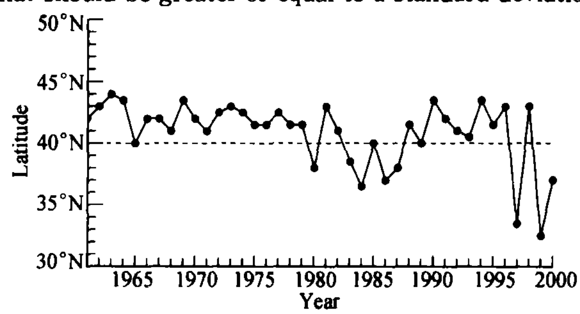

Fig. 2. The yearly zonal-mean latitudes averaged from 110°E to 120°E for the NSML.

from the series. During the 41 years, seven years after 1979 with the lower latitudes and five years with higher latitudes were detected out. Two years with the southernmost latitudes were observed in 1979 and 1999, respectively.

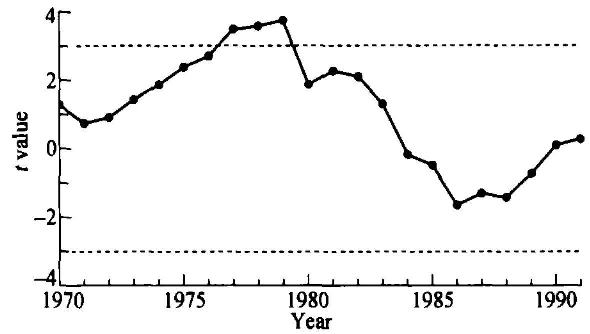

Fig. 3. Running t-test from the yearly series in Fig. 2. The dashed lines denote the 99% significance level.

According to the interdecadal shift of the NSML, two periods of 1961—1979 and 1980—2001 were separated to show their advance processes (Fig. 4). For the period of 1961—1979 (Fig. 4(a)), the southwest wind was prevailing, the controlling range was wider, and the lasting period was longer than the period 1980—2001 (Fig. 4(b)). For the daily-mean 4 mm precipitation, it appeared around 27°N from the 13th to the 14th pentads in the first period that was later than the second period around at the 9th pentad. For the 335 K θ_{se} isotherm, it originally appeared around 24°N at the 27th pentad in the first period and was later for almost four pentads than the second period. In the first period, the daily-mean 4 mm precipitation and the 335 K θ_{se} isotherm reached a higher latitude than that in the second period. A comparison could be clearly observed that the speed of advance northward in the first period was faster than the second period. Another feature was also found that staying pentads were longer in the first period than that in the second period when these isolines reached their northernmost locations.

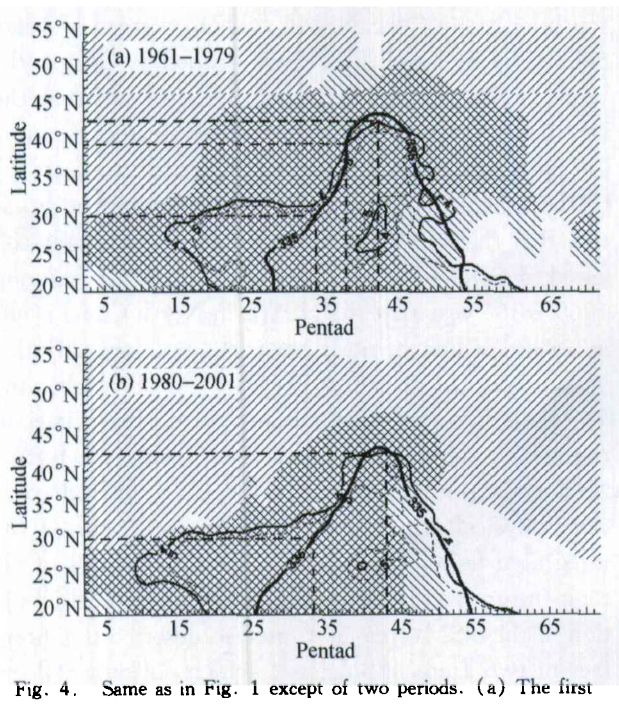

Fig. 4. Same as in Fig. 1 except of two periods. (a) The first period 1961—1979 and (b) the second period 1980—2001.

4 Comparison of various monsoon indices

There are various indices for indicating summer monsoon's intensity in East Asia or eastern China. The basic features of summer monsoon in eastern China, such as summer precipitation in the basin of the Yangtze River can be well indicated by these indices. However, our results indicated that these indices are difficult to depict the precipitation feature in North China. In order to describe possible differences, in the following we give the comparison result of precipitation with various indices.

4.1 HY index

According to the conceptual model of East-Asia-Pacific (EAP) from an atmospheric teleconnection, Huang and Yan[15] propounded a circulation index that can be used to indicate the monsoon intensity in East Asia. We refer to this index as HY index. Its definition is written as

$$\begin{aligned}\mathrm{HYI} = Nor(&-0.25Z_s'(20°\mathrm{N}, 125°\mathrm{E}) \\ &+ 0.50Z_s'(40°\mathrm{N}, 125°\mathrm{E}) \\ &- 0.25Z_s'(60°\mathrm{N}, 125°\mathrm{E}))\end{aligned}$$

where, $Z' = Z - \bar{Z}$, Z denotes the geopotential height at the 500 hPa level for the summer and $\bar{Z}$ is its climatic mean height, $Z_s' = Z' \sin 45°/\sin\varphi$, φ denotes latitude. $Nor(X)$ indicates the standardized X. The relationship describes that if the HY index is higher, the summer monsoon in that year will be stronger.

4.2 ZH index

There is an opposite relationship from their intensity variation between the tropical convergence zone (tropical monsoon trough) and subtropical convergence zone (Meiyu trough) in East Asian summer monsoon system. According to this circulation character, Zhang et al.[16] defined the difference of zonal wind anomaly at the 850 hPa level from the regions of tropical monsoon trough and the Meiyu trough. This index (ZHI) is written as

$$ZHI = u_{850\ hPa}(10°N—20°N, 100°E—150°E) - u_{850\ hPa}(25°N—35°N, 100°E—150°E)$$

The larger ZHI is associated with the stronger summer monsoon.

4.3 SU index

Monsoon is atmospheric circulation phenomena mainly caused by the seasonal thermal difference between sea and land. The unsymmetrical sea-land heating induced by solar radiation is the main reason why monsoon shows the geographical difference. Sun et al.[17] applied the difference of the ground temperature (T_{EC}) and the surface sea temperature (SST_{STNWP}) in four regions to construct a monsoon thermal index. The longitudinal difference was constructed by the ground temperature (T_{EC}) in the region of East Asia monsoon (27°N—35°N, ≥105°E) and the surface sea temperature (SST_{STNWP}) in the region of the subtropical northwest Pacific Ocean (15°N—30°N, 120°E—150°E). The meridional difference came from the ground temperature (T_{SC}) in the region of South China (≤27°N, ≥105°E) and the surface sea temperature (SST_{SCS}) in the region of the South China Sea (5°N—18°N, 105°E—120°E). This index (SUI) is expressed as

$$SUI = (T_{EC} - SST_{STNWP}) \times 4/5 + (T_{SC} - SST_{SCS}) \times 1/5$$

The larger SUI is associated with the stronger summer monsoon.

4.4 GU index

Zonal difference of summer sea-level pressure (SSP) was used by Guo et al.[18] to represent the intensity of summer monsoon. The detailed definition is the sum of the summer SSP difference between two longitudes 110° E and 160° E with the condition $P_{110°E-160°E} \leqslant -5$ hPa and those points of 10-degree latitude interval from 10°N to 50°N. Considering the fact that land pressure is low and sea pressure is high in summer, the larger GU index is associated with the weaker summer monsoon. For conveniently comparing with other indices, the GU index is multiplied by −1.

The relationships among these five indices including four summer monsoon indices and the NSML index are listed in Table 1. The remarkable correlations can be found from those indices of HYI, ZHI and SUI. The correlation coefficient between HYI and ZHI is 0.51 and the correlation coefficient between HYI and SUI is 0.68, reaching the 99% significance level. There is litter correlation between SUI and GUI. These high linear correlations indicate that there are internal and cooperative variations from those fields of sea-level pressure, geopotential height, lower layer wind and temperature. Correlations between GUI and the NSML as well as between SUI and the NSML are 0.4 and 0.37, reaching the 99% and 95% significance levels, respectively.

Table 1. Correlations from four monsoon indices and latitude series of the NSML

Index	HYI	ZHI	SUI	GUI	NSML
HYI	1.00	0.51a)	0.68a)	0.48a)	0.34b)
ZHI		1.00	0.40a)	0.11	0.06
SUI			1.00	0.47a)	0.37b)
GUI				1.00	0.40a)
NSML					1.00

Notes: a) and b) reach 99% and 95% significance levels, respectively

Table 2 lists those anomalous years when one standard deviation should be reached for these five indices. Remarkable differences can be observed from these anomalous years of various indices indicated, such as the stronger monsoon years 1972, 1978, and 1994 as well as those weaker monsoon years 1980, 1983, and 1991. A possible relation should be a weaker monsoon in intensity associating to a relatively south location of the NSML. There were four years defined by SUI and three years defined by GUI in the weak monsoon years matching the situation that the NSML in North China is abnormally located in southern part, and only one year for SUI and two years for GUI in the strong monsoon years matching the situation that the NSML in North China is abnormally situated in northern part. According to the definition, 1969 is the year that the NSML in North China is abnormally located in northern part, but for HYI this year is the weak monsoon year. As a result, the NSML is not always abnormally in northern part in the strong summer monsoon years, and *vice versa*. As a good summer monsoon index, it must have a clear physical description, and can well express the integrated feature and explain the abnormities of air temperature and precipitation in summer. The definition of the NSML has been used to describe the interface of two kinds of air mass, which not only reflects the advance process from low latitude to mid-high latitude, but also confirms the northernmost location, then directly represents flood or drought condition in North China. Difference can be understood that summer monsoon indices need to well indicate the principle character of summer monsoon in East Asia, but the NSML should be a good indicator to indicate the marginal character of summer monsoon.

Table 2. Strong and weak monsoon years derived from four monsoon indices and latitude series of the NSML

Index	Strong summer monsoon year	Weak summer monsoon year
HYI	1961, 1972, 1975, 1978, **1994**, 1997	1969, **1980**, 1983, **1986**, **1987**, 1991, 1992, 1993
ZHI	1967, 1972, 1974, 1978, 1981, 1984, 1985, 1986, **1994**, 1997	**1980**, 1983, 1995, 1998
SUI	1961, **1964**, 1966, 1967, 1971, 1978	**1980**, 1982, **1983**, **1987**, 1989, 1993, **1999**
GUI	1961, 1962, **1963**, **1964**, 1966	**1980**, **1986**, 1991, 1996, **1997**
NSML	**1963**, **1964**, 1969, **1990**, **1994**	**1980**, 1984, **1986**, **1987**, **1997**, **1999**, 2000

Notes: The underlined denote the strong monsoon years matching the situation that the NSML in North China is abnormally located in northern part. The framed denote the weak monsoon years matching the situation that NSML in North China is abnormally located in Southern part.

5 Monsoon indices and summer precipitation

In application, monsoon index should well reflect regional precipitation variability. This section analyzes the correlation between these four indices (HYI, ZHI, SUI and GUI) and summer rainfall over eastern China. Their distributions of correlation are given in Fig. 5(a)—(d), respectively. A feature is found that the correlation pattern is like the positive and negative signs " + - + " crossing in eastern China from south to north. It means that in the strong (weak) monsoon year above (below) normal rainfall is located in South China and North China while the below (above) normal rainfall appears along the Yangtze River. Although there are some differences in correlation distributions between various summer monsoon indices and summer rainfall, they have a common feature that the region where the highest correlation lays is located in the Yangtze River valley. The highest correlation is found from the SUI and summer precipitation. In Fig. 5(d), the first three indices have no significant correlation with summer precipitation in North China. The index GUI is calculated on the basis of the sea-level pressure difference between sea and land so that this definition could partly reflect the advance of summer monsoon. The fact shows that positive and significant correlation between the index GUI and summer precipitation covers the region over 110°E—120°E, 35°N—40°N, reaching the 95% significance level. It is easy to understand that the summer monsoon indices depict well the main body feature of summer monsoon, centering along the 30°N in the Yangtze River valley. Each year summer monsoon must march to the Yangtze River valley (the east of 110°E and the south of 35°N) with various intensity variations but it cannot confirm whether the different conditions of summer monsoon meet in anywhere of North China. That is the reason why the NSML as an index can well express the summer rainfall in North China.

After testing the correlation coefficient distributions of summer rainfall over eastern China with various indices, the relationships between the summer rainfall in eastern China with the NSML should also be given. Fig. 6 shows the correlation distributions between the NSML and precipitation in June, July, August, and two months (July, August). In June, a pattern " + - + " of correlation is noted but there is no significant distribution. The reason is that in June the summer monsoon has not reached northern China. In July (Fig. 6(b)), a region of significant correlation is found in North China, marking the relationship between the NSML and monsoon rainfall and expressing whether it was active in northern China. In late July or early August of some years the strong monsoon rainfall can be observed in North China. This correlation can also be found from Fig. 6(c) with a higher center in North China. Combining July and August, the correlation coefficient in North China has increased from 0.5 to 0.6 (Fig. 6(d)).

Results show that the higher correlation which passes the degree of confidence test is concentrated in the marginal region of summer monsoon. The physical meaning of the relationship between the location of summer monsoon advance and summer rainfall in North China is very clear. Warm and damp air coming from low-latitude oceans to North China results in increase of the summer rainfall when summer monsoon reaches North China. On the contrary, when the advance northward of summer monsoon is slow or its strength is weaker, the summer rainfall will decrease in North China.

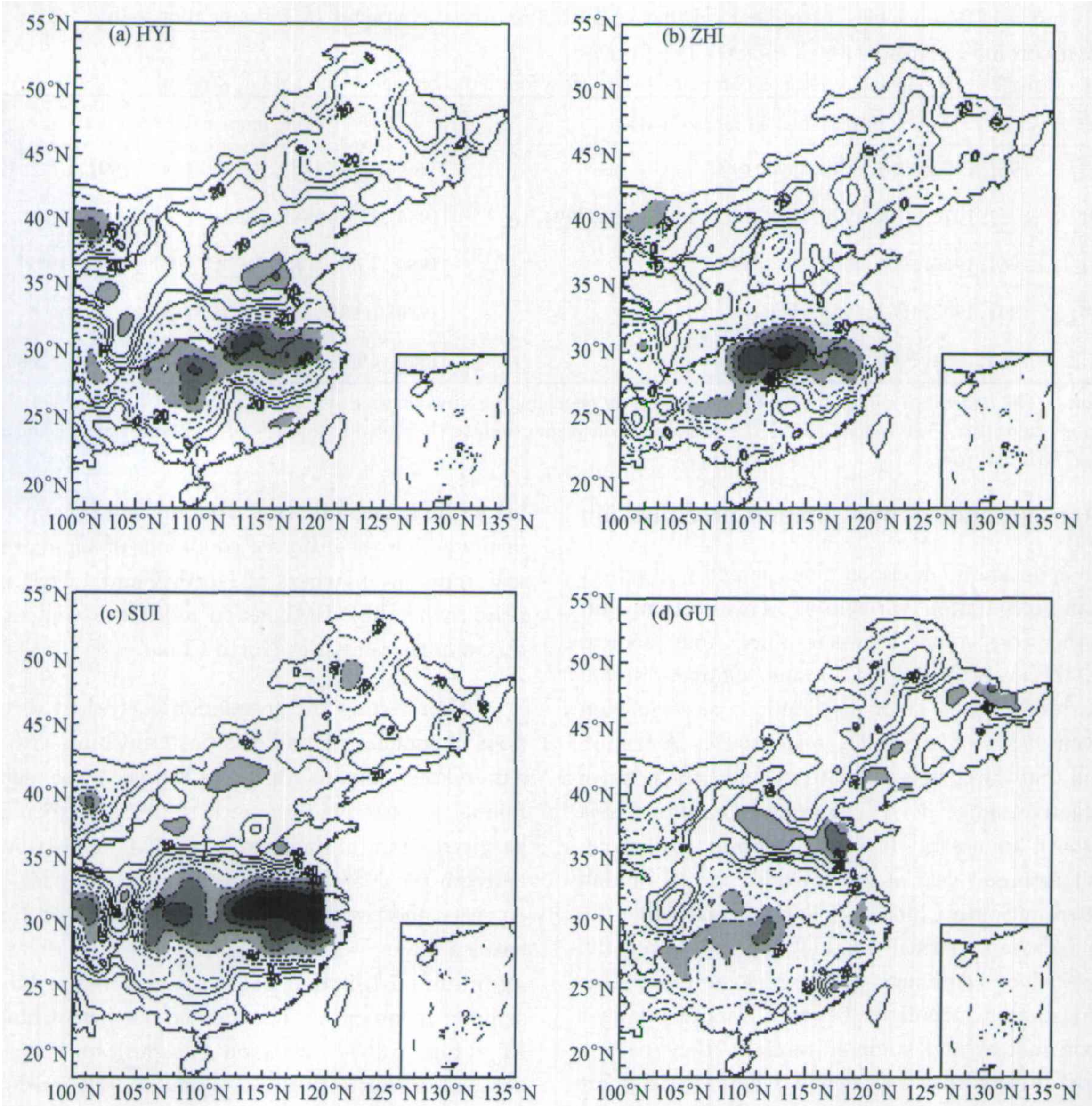

Fig. 5. The correlation coefficient distributions of summer rainfall over eastern China with various indices (a) HYI, (b) ZHI, (c) SUI and (d) GUI. The shaded regions from light to dark represent the 95%, 99%, and 99.9% significance levels, respectively.

6 Conclusions and discussion

(1) An integrated index which can be used to indicate the advance of subtropical summer monsoon in East Asia has been proposed in this paper. The index was combined by three variables including precipitation, wind and pseudo-equivalent potential temperature. The northernmost summer monsoon location was identified by using this index annually and it can be used to indicate the rainfall anomaly in North China.

(2) There was a significant interannual variability of the NSML in the last 41 years. The northernmost latitude of the NSML happened in 1963 (44°N) and the southernmost latitude occurred in 1999 (33°N). A significant interdecadal shift of the NSML is also noted in the period 1977—1979 from the NSML series. During the last 41 years, most events with its advances to the southern part of its ordinary location appeared after 1979 for seven years.

(3) A comparison of the NSML with other four summer monsoon indices indicates that the NSML could well represent the interannual and interdecadal variability of summer monsoon precipitation in North China (beyond 35°N), while other four indices could well indicate the precipitation anomalies of East Asian summer monsoon along the Yangtze River valley (around 30°N).

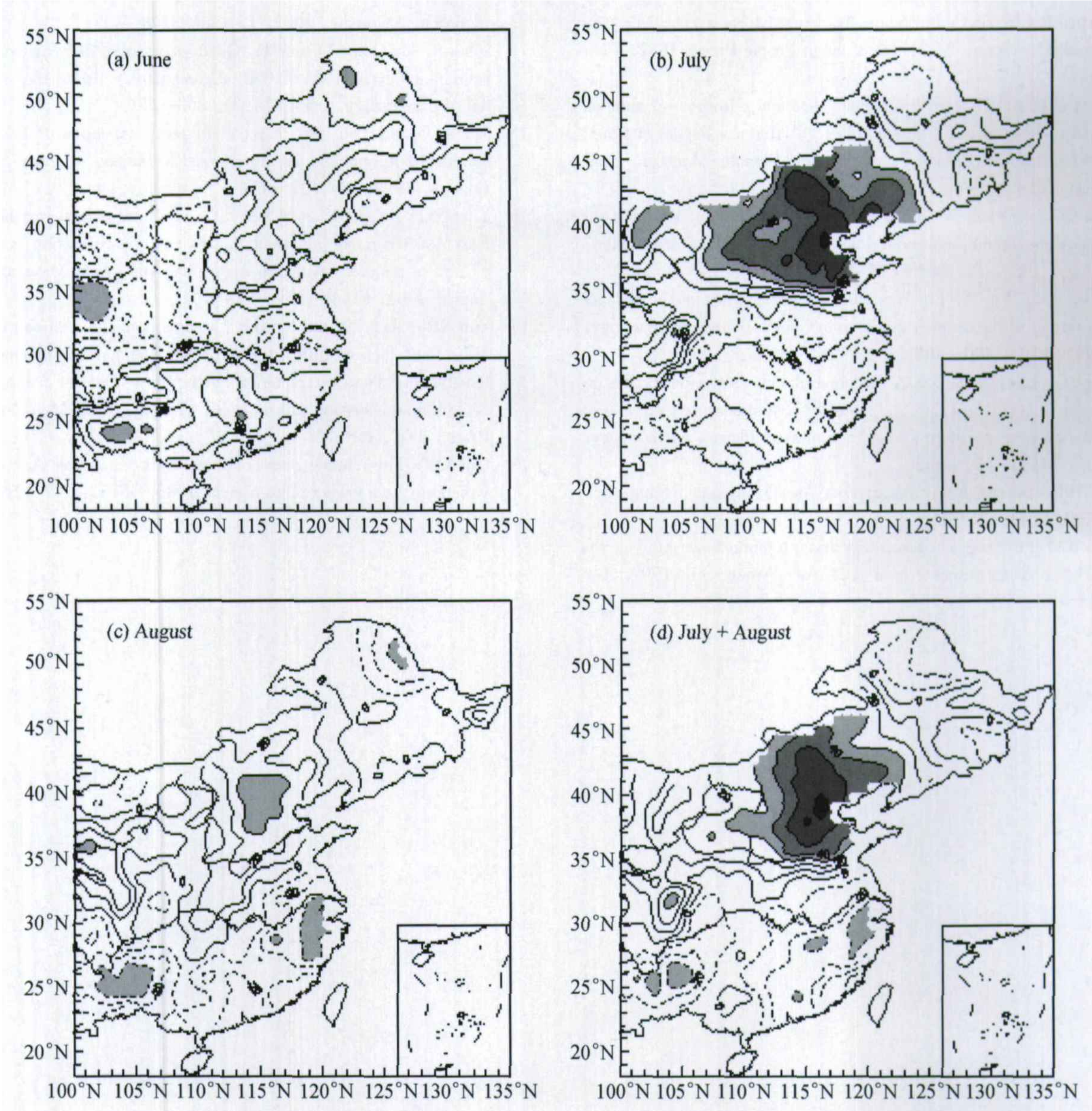

Fig. 6. The correlation coefficient distribution between the NSML and summer rainfall over eastern China for (a) June, (b) July, (c) August, and (d) July + August. The shaded regions from light to dark represent the 95%, 99%, and 99.9% significance levels, respectively.

According to the above-mentioned analysis, the significance in determining the northernmost location of East Asian summer monsoon is a fact that the advance process and location change decide the precipitation distribution in eastern China, especially in North China. It is well known that many factors can influence the location, including westerly flow and the Qinghai-Tibet Plateau. The study on the location variability is more complicated, especially for the reason and effect of the significant interdecadal variability, which need to be deeply investigated in the future.

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