A Unified Monsoon Index for South China

ER LU AND JOHNNY C. L. CHAN

Department of Physics and Materials Science, City University of Hong Kong, Hong Kong, China

(Manuscript received 1 June 1998, in final form 26 August 1998)

ABSTRACT

A unified index for both the summer and winter monsoons over south China (SC) is proposed for the purpose of studying their interannual variability. By examining the monthly distribution of the meridional flow v over the Asia–Pacific region from 20 yr (1976–95) of the reanalysis data of the National Centers for Environmental Prediction, the area of the South China Sea (SCS) is identified as an important segment of the planetary-scale east Asia monsoon circulation. The monthly v fields at 1000 and 200 hPa over the SCS show the most significant reversal in direction between summer and winter. The summer rainfall over SC is found to correlate well with these two fields as well as their differences averaged over the northern part of the SCS (7.5°–20°N, 107.5°–120°E). Winter temperatures over SC are, however, only related to the v field at 1000 hPa within the same region. It is therefore proposed to define a unified monsoon index for SC as the value of v at 1000 hPa averaged over this region within the period of June through August for summer and November through February for winter.

1. Introduction

It is generally recognized that the east Asia monsoon and the south Asia monsoon are two different subsystems of the entire Asia monsoon system, each having its own characteristics due to the different combinations of land and sea, and the different relative positions of the Tibetan Plateau (e.g., Ding et al. 1988; Chen et al. 1991). One common method to represent the intensity of the monsoon system is to use a monsoon index. Such an index is useful in studying the interannual variability of monsoon activities.

For the south Asia monsoon (i.e., the Indian monsoon), which generally emphasizes entirely the summer monsoon rainfall, at least two indices have been put forward to identify strong and weak monsoons. One is the so-called all-India summer rainfall of June through September (see, e.g., Krishnamurti 1985). The other is the zonal wind shear defined by the zonal wind difference between 850 and 200 hPa over south Asia introduced by Webster and Yang (1992). Utilizing these indices, Shukla (1987a,b), Meehl (1987), Krishnamurti et al. (1989a,b), Yasunari (1990), and Li and Yanai (1996), among many others, have studied several aspects of the variability of south Asia monsoon.

The situation is more complicated in the case of the east Asia monsoon. Generally, the summer monsoon over east Asia consists of three airflows: southwesterly flow (part of the Indian monsoon), southeasterly flow (from the southwestern edge of the western Pacific subtropical high), and cross-equatorial flow over the southern part of the South China Sea (SCS). Summer rainfall results from the interaction among not only the tropical and subtropical air masses, but also the cold air mass from the mid- to high latitudes (Ding 1994; Chang and Chen 1995). Such a complexity in the monsoon behavior and the associated rainfall processes makes it difficult to put forward a single but representative monsoon index. For the intraseasonal variation of the east Asia summer monsoon, different monsoon indices have been proposed (e.g., Shi and Chao 1982) to describe the advance and retreat of the summer monsoon in a particular year. However, for the interannual variability of the east Asia monsoon, only few studies have been made (e.g., Guo 1983; Li and Yanai 1996).

A characteristic of the east Asia monsoon is its particularly strong winter monsoon component. The north to northeasterly flow affects China and the SCS, then crosses the equator to the Southern Hemisphere and becomes the northwest monsoon over northern Australia. The cold air from the mainland of China can also migrate off the east coast of the continent to the East China Sea before surging south toward the equator, again producing strong northeasterlies (Boyle and Chen 1987; Wu and Chan 1995).

Therefore, over the east Asia region, the winds in the summer (winter) have a southerly (northerly) component. However, the zonal component in the two seasons can be the same (southeasterly in summer and north-

Corresponding author address: Dr. J. C. L. Chan, Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China.
E-mail: Johnny.Chan@cityu.edu.hk

easterly in winter). Although the meridional wind direction is completely reversed between summer and winter, both monsoons should be driven primarily by the same mechanism: the meridional thermal contrast, which is opposite between the two seasons. Because the fundamental physical mechanism appears to be identical, it should be possible to use only one index to describe both monsoons. This study is therefore an attempt to develop a unified index that may be used to indicate the intensity of both components. A basic requirement is that this index should be able to reflect physically the main features of the planetary-scale circulation. Because the entire summer monsoon begins over south China (SC; Tao and Chen 1987) and the winter monsoon winds over this region can become quite strong (Wu and Chan 1995), the index to be developed here focuses on the monsoonal conditions over the SCS.

A brief description of data is given in section 2. To provide a background for choosing a suitable index, a simple method is described in section 3 to map out the areas within the Asia–Pacific region where both summer and winter monsoons prevail. In section 4, the seasonal variations of the meridional circulation of the east Asia monsoon are described. Based on these variations, a unified monsoon index is proposed in section 5. Its usefulness is demonstrated by relating it to the summer rainfall and winter temperatures over SC. A summary and discussion are given in section 6.

2. Data

In the study, two datasets are used.

1) The National Centers for Environmental Prediction (NCEP) reanalysis pressure-level data for the 20-yr period (1 January 1976–31 December 1995). The original 6-h data are first daily averaged. Monthly mean data for the zonal and meridional wind components, temperature, and geopotential height at 1000 and 200 hPa are then computed.
2) Monthly rainfall data of 43 stations over eastern and southern China for the same 20 yr. The distribution of the stations can be found in Fig. 8.

3. Areas of active summer and winter monsoons

If the summer and winter monsoons develop from the same physical mechanism, it is useful to identify those regions where both components prevail. For the east Asia monsoon problem, the meridional component v is considered to be a more representative variable since on a planetary scale, the monsoon may be primarily considered to result from a north–south temperature gradient. (Analyses of the zonal component have also been made, but the results do not present the strong signal that can be identified from the v component.) The following method is used to locate the regions where the monsoons prevail.

The averages of the meridional wind component at 1000 hPa for each of the 12 months over the 20-yr period (1976–95) are calculated (denoted as $v_{\rm Jan}$, $v_{\rm Feb}$, . . . , and $v_{\rm Dec}$). Let v_p and v_n denote, respectively, the summations of all the positive and negative values of v_m [m = January (Jan), February (Feb), . . . , December (Dec)], that is,

$$v_p = \sum_{m={\rm Jan}}^{\rm Dec} v_m|_{v_m>0}$$

and

$$v_n = \sum_{m={\rm Jan}}^{\rm Dec} v_m|_{v_m<0}.$$

The value of v_p (v_n) at each grid point may be regarded as a measure of the total annual northward (southward) airmass transport. For marked summer (winter) monsoon areas, the values of v in a year should be positive (negative) continuously for several months. From another point of view. the concept of v_p and v_n in a monsoon area may also be a reflection of the intensity and duration of the summer and winter monsoons, respectively.

Over the Asia–Pacific region, the distribution of v_p and v_n at 1000 hPa shows several areas with large values of both v_p and v_n (Fig. 1). These are the monsoon regions. In other locations, only v_p or v_n is dominant. These generally correspond to the trade wind regions where the northward or southward component persists throughout most of the year.

To provide a better identification of the monsoon regions, the function

$$Z_v = \min(v_p, -v_n)$$

is defined to map out areas where v_p and v_n both have similar magnitudes. In regions where both summer and winter monsoons prevail, v_p and v_n should both be large and so should the value of Z_v. On the other hand, in the nonmonsoon regions, either v_p or v_n will be small so that Z_v will have a small magnitude. It can be seen from Fig. 2 that the significant areas with active summer and winter monsoons include the Arabian Sea, the Bay of Bengal, the SCS, off the coast of the Asian continent, and northern Australia.

These results are generally consistent with the monsoon regions sketched out by Krishnamurti (1982). The distribution of Z_v given in Fig. 2 further quantifies the intensity of the monsoon and can therefore be used as an index for the monsoon. However, the flow at 1000 hPa only reflects the response of the atmosphere to the thermal forcing at the lower boundary. To relate changes in the planetary circulation to this forcing, the upper-level flow is also examined in the next section. Since the main focus of this study is on a monsoon index over SC, only the flow over this area will be analyzed. However, this methodology may also be applicable to other regions shown in Fig. 2 as well.

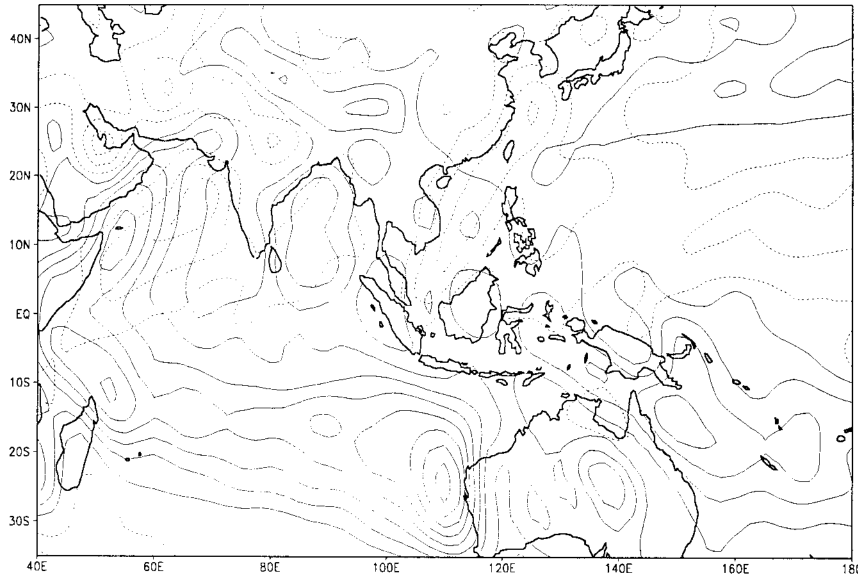

FIG. 1. Contours of v_p (solid) and v_n (dashed) at 1000 hPa for the Asia–Pacific region. See text for definition. Contour interval: 10 m s^{-1}. The zero contour is omitted.

A possible drawback to using the 1000-hPa flow to represent the low-level component of the meridional circulation rather than that at 850 hPa is the bias between land and ocean. A large portion of the land area over the Asia continent is near or above the 1000-hPa surface so that over land the flow at this level obtained from the NCEP reanalysis is weak compared with that over water, or even fictitious. This might explain why the largest values of Z_v are mostly over the ocean. However, since the flow at this level is closest to the lower boundary where the forcing is the strongest, it is considered to be more representative of the low-level component of the monsoon circulation. This is especially true in the case of the winter monsoon in which the 1000-hPa flow appears more prominently than that at 850 hPa (Wu and Chan 1995, 1997a).

4. Monsoons over the SCS and the meridional circulation over east Asia

a. Seasonal variation of the monsoons over the SCS

The 20-yr monthly mean 1000-hPa wind fields over east Asia show that the flows over the SCS are very

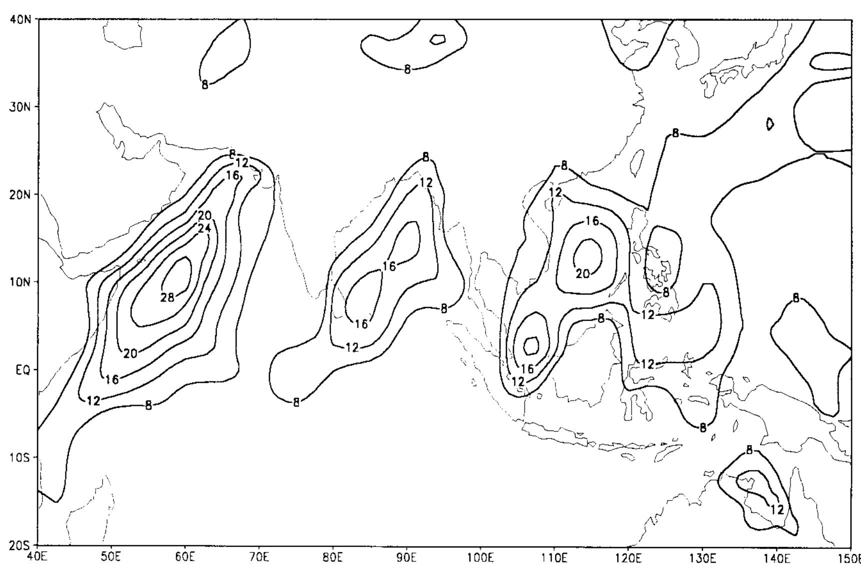

FIG. 2. Contours of Z_v at 1000 hPa over the Asia–Pacific region. Contours with values <8 m s^{-1} are omitted.

similar in June, July, and August (Fig. 3). The distributions of v in these three months have nearly the same pattern as that of Z_v shown in Fig. 2. During autumn (September–October), the flow over the SCS changes from southerly to northerly. The winter monsoon may include the four months of November, December, January, and February, in which similar v values exist over the SCS. Among them, the strongest northerly flow occurs in December and January. During spring (March–May), the circulation changes from the winter to the summer monsoon regime, with the magnitude of v being a minimum in April.

The components and activities of the summer monsoon over east Asia are not as simple as those in India. The monsoonal flow over the northern part of the SCS for the months of June–August has two origins: the southwesterly flow from the Indian monsoon and the cross-equatorial southerly flow in the southern part of the SCS. The combination of the two flows results in a strong v over the SCS, while the zonal component here appears to be not as important as in the Indian monsoon. In July, the northward monsoonal flow over the SCS, in addition to affecting SC, combines with the southeasterly flow associated with the western Pacific subtropical high to give a maximum v over the East China Sea. Along the coastal regions from the southern and northern parts of the SCS to the East China Sea, where three v maxima occur in July, the northerly wind in January also shows a maximum band. Therefore, the east Asia monsoon may be considered as consisting of two parts: the South China Sea monsoon and the East China Sea monsoon. They have different flow origins in summer and the situation in the latter is probably more complicated. However, the intensity of the East China Sea monsoon in both summer and winter is generally weaker than that of the SCS monsoon. The duration of the winter monsoon over the East China Sea is particularly long (from September to April, totaling 8 months), while the summer monsoon is very short (only from June to August).

b. Seasonal variation of the meridional circulation over east Asia

Figures 4a and 4b show the 20-yr mean monthly variation of v along the longitude band (107.5°–120°E) that crosses the northern part of SCS where a maximum in Z_v is found (see Fig. 2). At the low level (Fig. 4a), the monthly mean value of v in the Southern Hemisphere does not change sign south of ~10°S, with southerly flow throughout the year. In the Northern Hemisphere, however, the directions of v for summer and winter are always opposite at almost all latitudes within this longitude band. At latitudes south of 45°N, the wind switches from southerly in the summer to northerly in the winter. The most dramatic change occurs over the northern part of the SCS (~10°–20°N).

A similar figure for the upper-level flow (Fig. 4b) illustrates that the direction of the 200-hPa v in the mid- to low latitudes is opposite to that at 1000 hPa, with northerly wind in summer and southerly wind in winter. Such a feature implies that a closed meridional circulation must be maintained during summer and winter, and the direction of the circulation is opposite for the two seasons. The strong winter circulation is the typical Hadley circulation, and results from the meridional thermal contrast induced by solar radiation as well as the land–ocean distribution. This contrast reverses in summer, the consequence of which is a northward migration of the Hadley circulation so that the low-level flow is southerly all the way to ~40°N.

c. Seasonal variation of the thermodynamic fields over east Asia

Opposite features between summer and winter can also be found in the low-level temperature field of east Asia (Fig. 5a). At the mid- to low latitudes of both hemispheres, the temperature in summer increases on the whole from the Southern to the Northern Hemisphere, while it decreases in winter from south to north. Note, however, the asymmetry between the two hemispheres. The heating over the Northern Hemisphere during summer encompasses a much larger area, with the maximum temperature occurring around 40°N in July. The 300 K isotherm covers the northern part of the SCS from about May to September. The boreal winter also displays much lower temperatures than the austral one. Over the SCS, the temperature is quite uniform between November and February.

The heating/cooling patterns are also reflected in the 1000–200-hPa thickness (Fig. 5b). The largest thickness is within the 20°–30°N latitude band between June and August, which suggests that over this region heights are lower (higher) at the lower (upper) levels. However, the situation is just the reverse over the SCS. This north–south thickness gradient then reverses from about November. Such a thermal structure therefore favors ascending (descending) motion over the SCS and descending (ascending) motion in the Southern Hemisphere during the boreal summer (winter). Coupled with the results for the meridional flow from the last section, it may be concluded that the ''classic'' Hadley circulation must occur over this longitude band during the winter (i.e., rising motion over the equatorial region and sinking motion in the 20°–30°N band). On the other hand, in summer, the entire Hadley circulation is displaced northward with rising motion over the land areas from SC to ~40°N and sinking motion near the equator.

The thermal contrast between the south and north is thus the primary cause of both monsoons. Through the geostrophic adjustment process, this contrast forces the atmosphere to adjust to form the monsoonal flow. The prominence in the reversal of the meridional flow between winter and summer suggests its possible use as

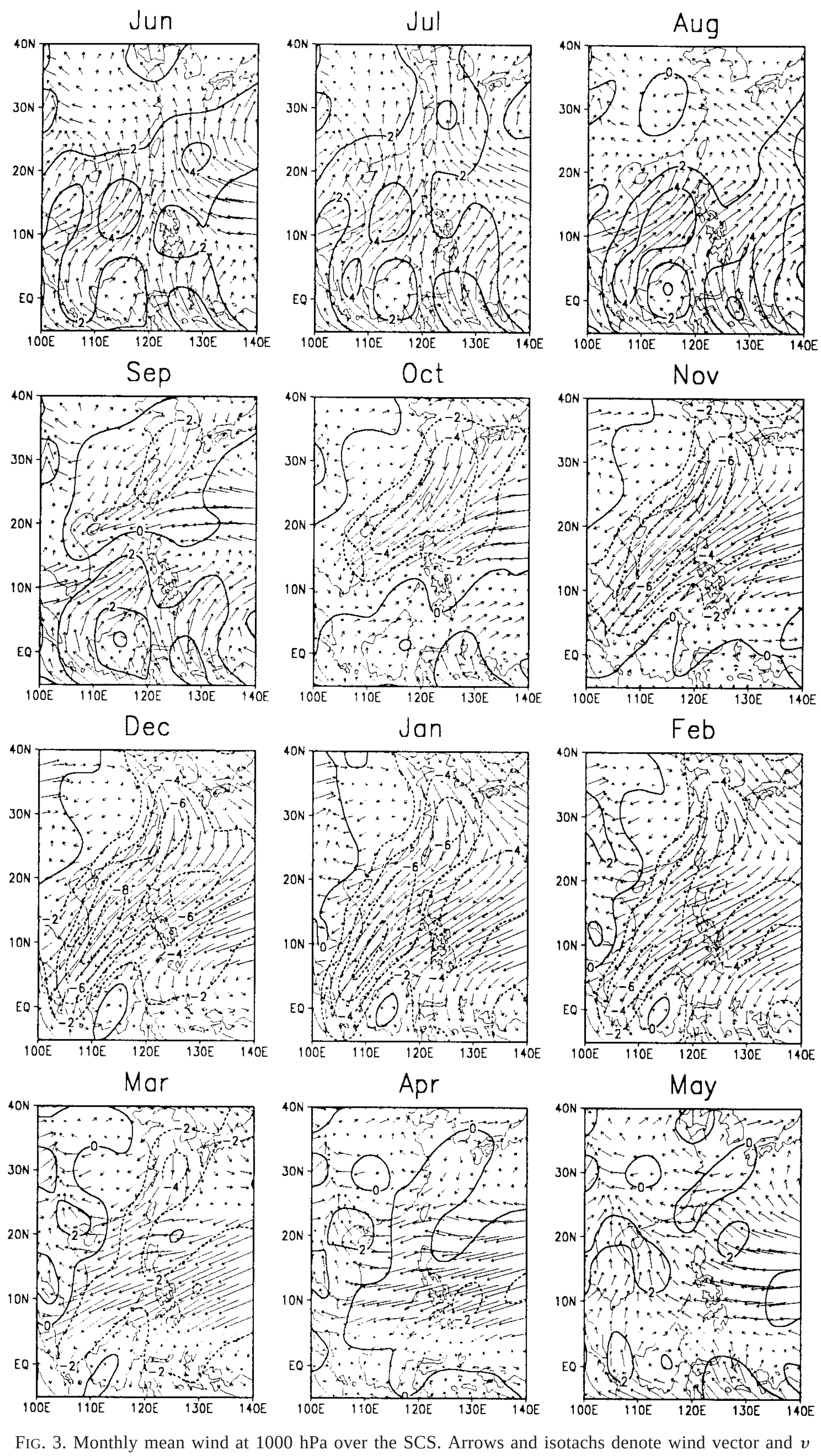

FIG. 3. Monthly mean wind at 1000 hPa over the SCS. Arrows and isotachs denote wind vector and v component (unit: m s^{-1}), respectively. Contour interval: 2 m s^{-1}.

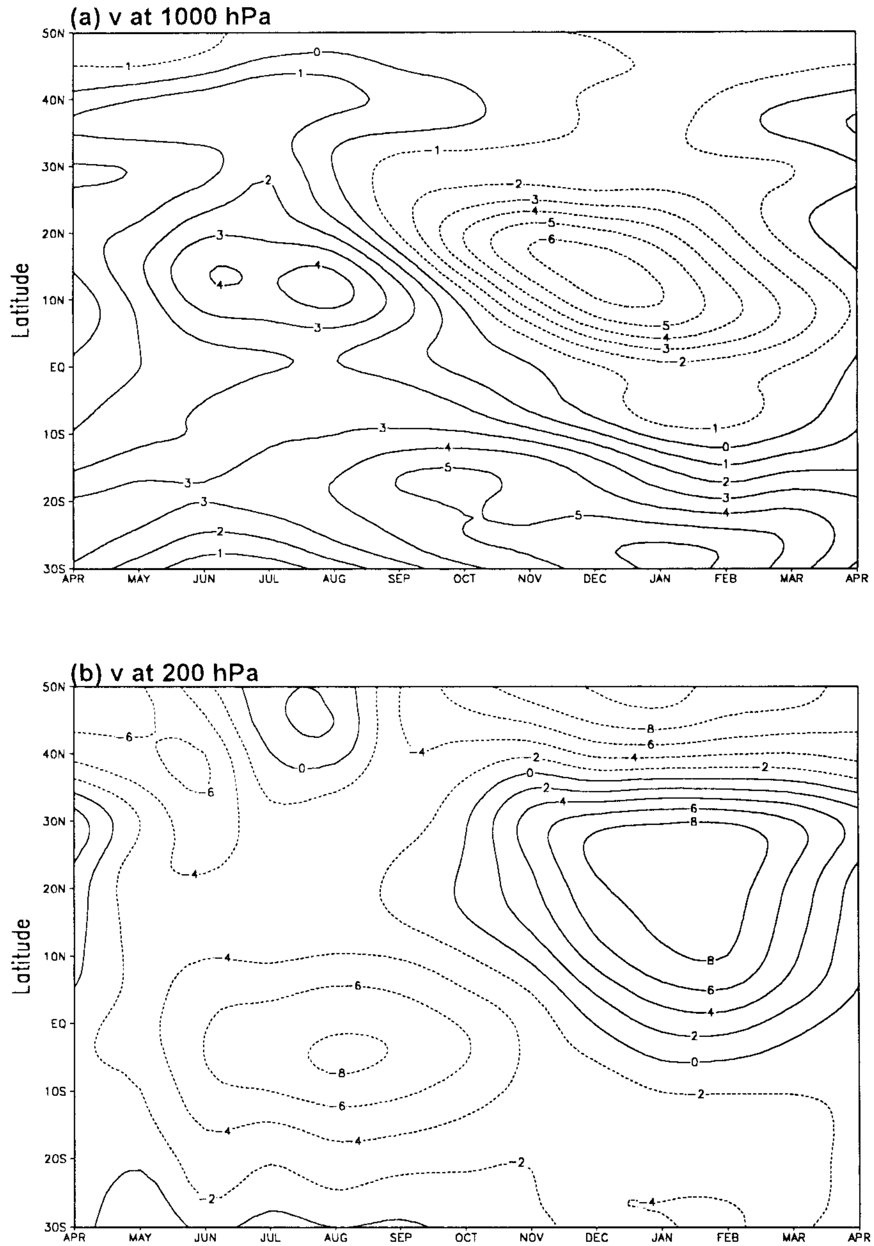

FIG. 4. Time–latitude sections of the 20-yr monthly mean v (averaged within 107.5°–120°E, unit: m s^{-1}) at (a) 1000 and (b) 200 hPa.

a monsoon index. The magnitude of this flow also reflects the intensity of the monsoon.

5. Unified monsoon index and its relation to the climate of south China

a. Defining the domain for the monsoon index

The averaged v fields of June–August (which represent the summer monsoon) and those of November–February (which reflect the winter monsoon) show that the maximum summer southerly flow and winter northerly flow are all located over the SCS (Fig. 6), where the maximum Z_v is found (see Fig. 2). Therefore, in this study the domain of the northern part of SCS (7.5°–20°N, 107.5°–120°E) is defined as the SCS monsoon region (SCSMR) over which the average of v is calculated to form a monsoon index. Note that in summer, a secondary maximum of v exists over the southern part of SCS, but it only reflects the cross-equatorial flow, whereas the main maximum in the northern part of SCS represents the combination of the two summer monsoon

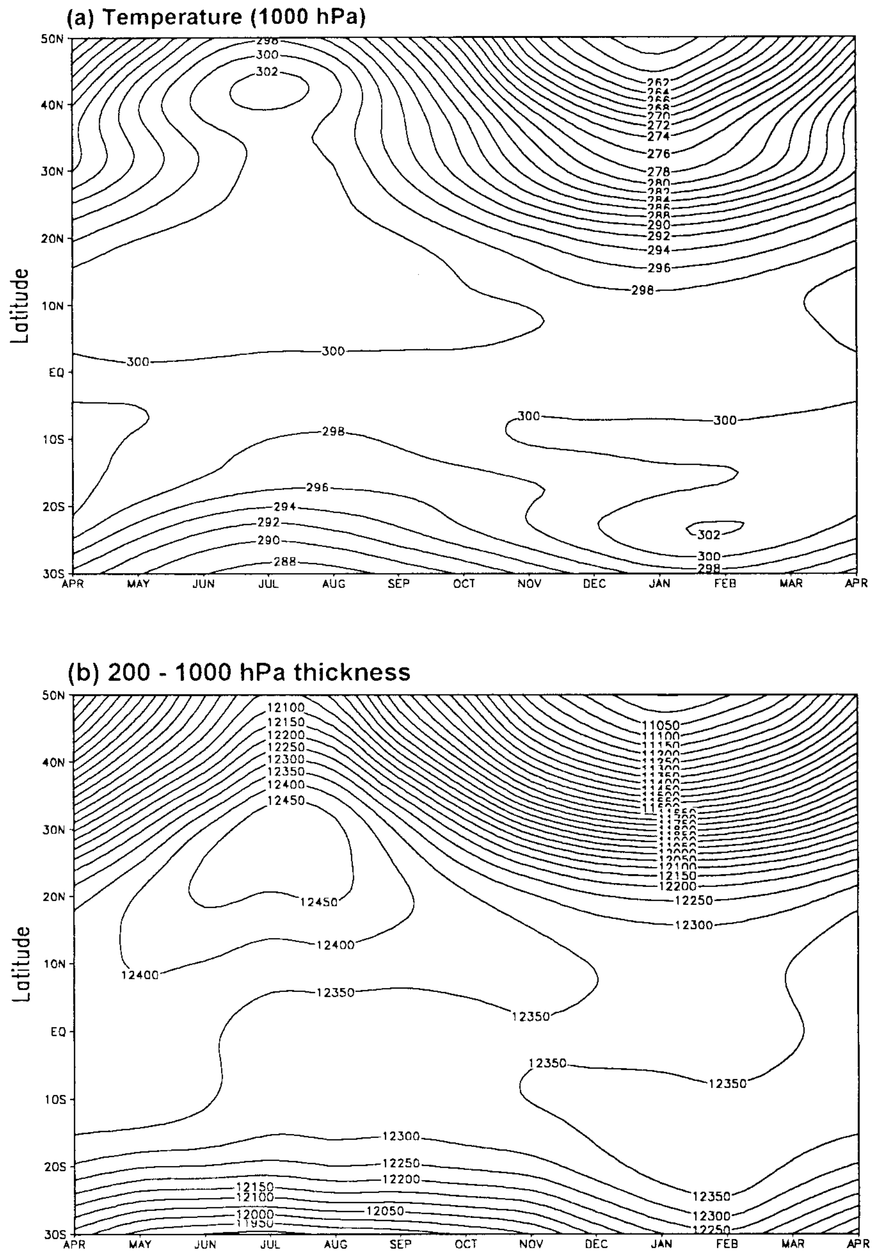

FIG. 5. Same as in Fig. 4 but for (a) T (unit: K) at 1000 hPa and (b) the thickness between 200 and 1000 hPa (unit: m).

flows. Therefore, it appears to be more appropriate to take the value of v averaged over the SCSMR as a possible monsoon index. Moreover, the v field over SCSMR in summer should be closely related to the summer rainfall of SC and perhaps even areas north of it.

b. Possible monsoon indices

The variations of the monthly v (at 1000 hPa, 200 hPa, and the difference between the two levels) averaged over the domain of SCSMR and 20 yr all show a clear annual cycle with transition periods occurring in April (spring) and October (autumn) (Fig. 7). Each curve has a similar amplitude between summer and winter. The curves for the upper and lower levels are exactly opposite during each season. The v_{1000} and v_{200} over SCSMR should therefore reflect the intensity of the meridional circulation in the region. In the next section, these three possible monsoon indices (v_{1000}, v_{200}, and $v_{1000} - v_{200}$) will be examined further for their usefulness.

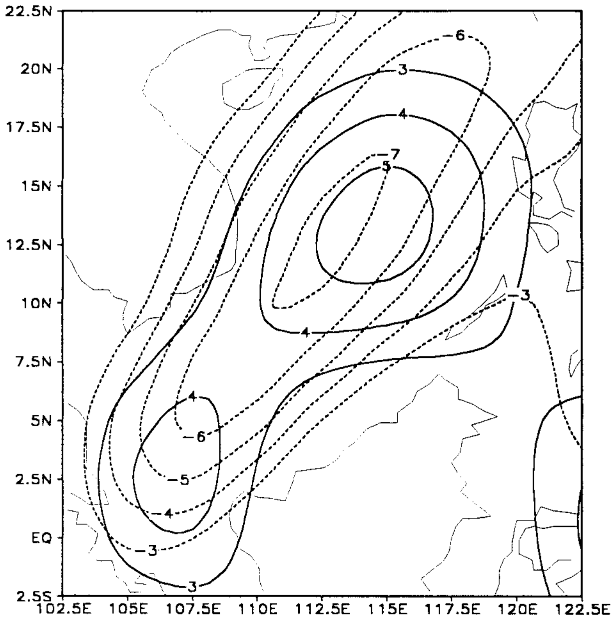

FIG. 6. The SCS monsoon region (SCSMR) for defining the monsoon index. Solid and dashed lines represent the monthly mean v averaged within the summer (Jun–Aug) and winter months (Nov–Feb). Isotachs with magnitudes less than 3 m s^{-1} are omitted.

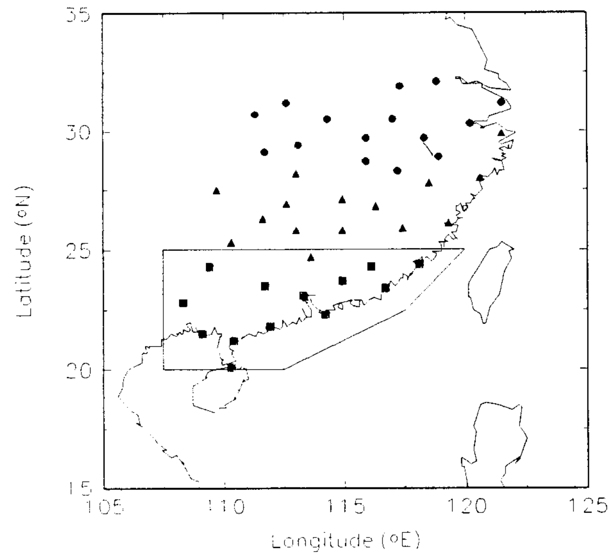

FIG. 8. Stations of summer rainfall over SC (squares), the mid–low reaches of the Changjiang River (dots), and the area between them (triangles). A pentagon domain that covers the stations over SC is defined for the calculation of the winter temperature of this region by using the NCEP gridpoint data.

c. Unified monsoon index and its relation to the SC climate

Chan and Shi (1999), studied the distribution of monthly rainfall for stations over eastern and southern China using the cluster analysis method and pointed out that three separate rainfall regions can be identified over southeast China, each with its own rainfall characteristics: the SC region (13 stations), the mid–low reaches of Changjiang River (15 stations), and a middle region between the two areas (15 stations), as shown in Fig. 8. The total rainfall from June through August for each year averaged over all stations within each region is taken to represent the summer rainfall over the region. Since SC is in the southeast edge of the continent and adjacent to the SCS, the climate of SC is chosen to be related to the monsoon intensity over the SCS. For the winter monsoon intensity, the NCEP gridpoint temperature averaged over a domain that covers the rainfall stations over SC (Fig. 8) is used as a proxy.

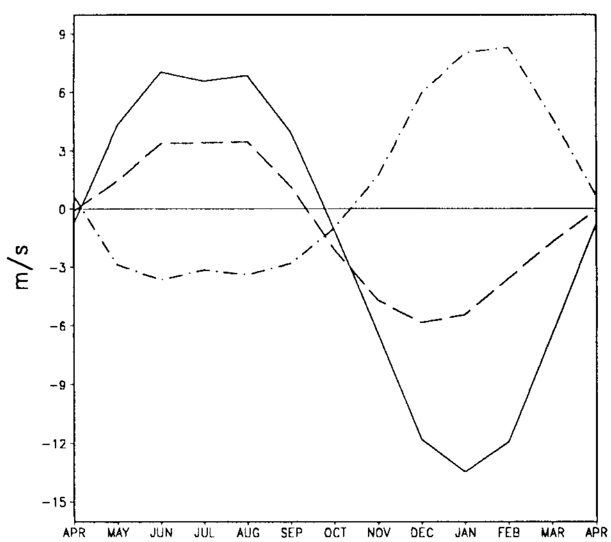

FIG. 7. Intra-annual variation of the 20-yr monthly mean v_{1000} (long-dashed), v_{200} (long-short-dashed), and $v_{1000} - v_{200}$ (solid) averaged over the SCSMR.

The correlation coefficients of the three possible monsoon indices with the summer rainfall over the three regions of southeast China and the winter temperature over SC are listed in Table 1. For the 19 winters (November–February), the temperature over SC shows a close relationship with the v_{1000} over the SCS. The correlation coefficient is 0.65, which is significant at the $\alpha = 0.01$ level (limiting value = 0.52). The v_{200} and $v_{1000} - v_{200}$, however, do not correlate well with the temperature. This is consistent with the results of Wu and Chan (1995, 1997a) that the winter surge is generally shallow when it reaches the SC, and it brings about

TABLE 1. Correlation coefficients of the three possible monsoon indices with the summer rainfall over the three regions and the winter temperature over the SC.

Rainfall/temperature	v_{1000}	v_{200}	$v_{1000} - v_{200}$
Rainfall (Changjiang)	−0.18	−0.27	0.11
Rainfall (middle region)	0.65	−0.42	0.62
Rainfall (south China)	0.58	−0.54	0.67
Temperature (south China)	0.65	0.03	0.19

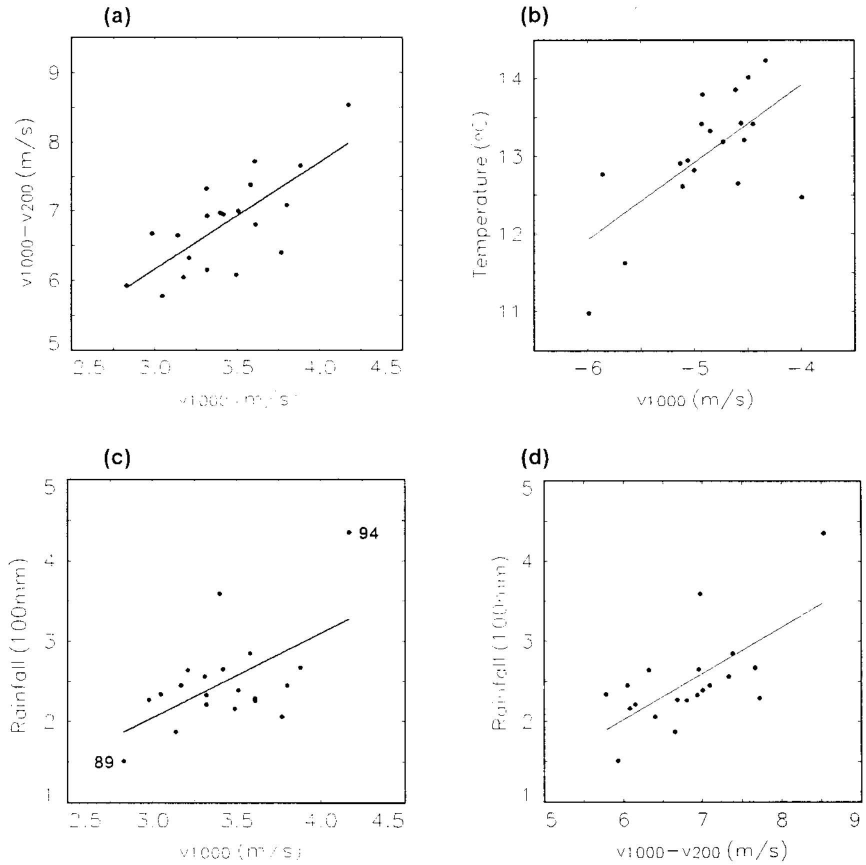

FIG. 9. Scatterplots depicting the relationship between (a) the summer v_{1000} and $v_{1000} - v_{200}$, (b) the winter v_{1000} and the temperature of SC, (c) the summer v_{1000} and the rainfall of SC, and (d) the summer $v_{1000} - v_{200}$ and the rainfall of SC.

sudden changes in the low-level temperature and pressure fields, but no significant changes at the upper levels.

For the 20 summers, a close relationship exists between the rainfall over SC and the three possible monsoon indices (v_{1000}, v_{200}, and $v_{1000} - v_{200}$ over the SCS). Correlation coefficients are 0.58, −0.54, and 0.67, respectively, which are all significant at the $\alpha = 0.01$ level (limiting value = 0.51). For the middle region, the correlations of the rainfall with v_{1000} and $v_{1000} - v_{200}$ of SCS are also significant at this level (correlation coefficients are 0.65 and 0.62, respectively). These results illustrate that the rainfall of SC is significantly related to entire summer monsoon circulation (the northward-shifted Hadley cell), that is, the flow at both the low and upper levels. This is because while the low-level flow induced by the lower heights/pressure brings in moisture, heavy rain can only occur if upper-level support (i.e., divergence) is available. It is also interesting to note that no significant correlation can be found between the rainfall over the Changjiang River region and each of the three indices v_{1000}, v_{200}, and $v_{1000} - v_{200}$ over the SCS. This result suggests that the summer rainfall over the mid–low reaches of the Changjiang River may be related to other factors such as the monsoon over the East China Sea and/or the midlatitude flow to its north. A similar monsoon index for the Changjiang River region may be put forward through the analysis of the features for summer and winter monsoons there. However, this is beyond the scope of the present work.

The v_{1000} and $v_{1000} - v_{200}$ of the summer season are highly correlated (Fig. 9a), with a correlation coefficient of 0.73. All these results suggest that the v_{1000} and $v_{1000} - v_{200}$ over the SCSMR may be defined as two indices for the summer monsoon, which reflect to a large extent the intensity of the rainfall over the wide area from SC to the south of the Changjiang River. On the other hand, only the v_{1000} in this region is related to the winter temperature. Therefore, in order to have one unified monsoon index, it is proposed that the value of v_{1000} averaged over the SCSMR be used as a unified index for both the summer (June–August) and the winter (November–February) monsoons.

To illustrate further the usefulness of the meridional wind, scatterplots between the v_{1000} and the winter temperature of SC, the summer rainfall of SC and the v_{1000}, as well as the $v_{1000} - v_{200}$ over the SCS, are made (Figs. 9b–d). Note the two particular years (1994 and 1989 shown in Fig. 9c) with extreme rainfall situations. The heaviest summer rainfall during the 20-yr period occurred in 1994 (440 mm) when the v_{1000} over the SCS period was also the strongest (4.2 m s^{-1}). By contrast, the summer rainfall in 1989 was the least (150 mm) of the 20 yr, and v_{1000} was also the weakest (2.8 m s^{-1}). Therefore, this unified monsoon index truly satisfies the requirement of representing the climatic conditions of SC.

6. Summary and discussion

a. Summary

Based on the analysis of the climatic features of the east Asia monsoon circulation, a unified index for both summer and winter monsoons for the South China (SC) region is proposed in this study using 20 yr of the NCEP reanalysis data. The basic idea is that although the wind direction reverses between winter and summer, both monsoons are driven by the same physical mechanism: the north–south temperature contrast in the case of the monsoons over SC.

To identify the region from which data should be extracted to form an index, the general regions of active summer and winter monsoons over the Asia–Pacific region (based on the distribution of the meridional wind) are mapped out. One of the most active regions is the South China Sea (SCS). In both winter and summer, the meridional winds at upper and low levels over the SCS are always in opposite directions. In fact, within the entire east Asia monsoon circulation, the low-level meridional winds in both seasons are the strongest over the SCS. This feature makes it possible to use the meridional wind of this area as a unified index for both monsoons. In summer, the active meridional wind at low level of the SCS can affect the summer rainfall of SC, while in winter the intensity of the v field may reflect the fluctuation of the temperature over SC. Indeed, the strength of v_{1000} over the SCS relates well to the summer rainfall as well as the winter temperature of the SC region. The quantity v_{1000} averaged over the northern part of the SCS is therefore proposed to be adopted as a unified monsoon index to represent the intensity of both the summer (June–August) and winter (November–February) monsoons over the south China region.

b. Discussion

As mentioned in the introduction, the east Asia summer monsoon is very complicated and results from a combination of north–south temperature gradient due to differences in the amount of insolation reaching different latitudes, land–sea contrast, topography, as well as midlatitude and even cross-equatorial influences (Tao and Chen 1987; Ding 1994). Therefore, while the winter monsoon may be adequately represented by the planetary-scale flow at the low levels (Wu and Chan 1995, 1997a), the use of the same flow (i.e., v_{1000}) as an index for the intensity of the summer monsoon may be questioned.

To address this question, it is necessary to consider the temporal and spatial scales of the monsoon to be studied. The complexities in the summer monsoon are usually highlighted when the onset, advance, or retreat of the summer monsoon in one region within the entire east Asia monsoon region is examined. The scales of the phenomena of interest are therefore synoptic and intraseasonal. However, the focus of the present study is on the seasonal changes over the entire east Asia monsoon region. The results in section 4 have clearly suggested that the primary physical mechanism of the monsoons is the meridional temperature gradient (integrated through the entire troposphere), the sign of which alternates between winter and summer. This thickness gradient must be converted to the meridional flow through the geostrophic adjustment process. It is therefore logical to use the magnitude of this flow as a simple index to represent the monsoons and their intensities. Although the index is only used in this paper for the monsoons over SC (because of its high correlation with the summer rainfall and winter temperatures in the region), it should reflect the planetary-scale circulation of the east Asia monsoon to a large extent.

In all previous studies of the monsoon problem, indices have been developed to represent the intensity of the either the summer or the winter monsoon. For the summer, in addition to rainfall amount over a region, various parameters have been used, such as horizontal pressure gradient (e.g., Tanaka 1997), sea surface temperature anomalies (e.g., Ose et al. 1997), or vertical shear of the zonal wind (Webster and Yang 1992; Li and Yanai 1996). Because of its lesser impact on society, very few studies have been made on the interannual variations of the winter monsoon. A brief summary of these studies is given in Wu and Chan (1997b). Basically, the average temperature over a region in China is used to represent the intensity of the winter monsoon.

The index developed in this study is therefore the first to ‘‘unify’’ the representation of the two monsoons, which is essential if the linkage between them is to be studied. To have one single index to indicate the intensity of both monsoons simplifies the definition of weak and strong monsoons. More importantly, this index represents the main physical process that drives the monsoons. Meehl (1997) has proposed a linkage between weak and strong monsoons over India with a biennial signal through the coupling between the atmosphere, ocean, and land. A similar mechanism may operate in the east Asia monsoon region although it will probably involve more components such as the more prominent winter monsoon, the vast area of the Pacific Ocean, and the maritime continent. Using the index proposed in this study to represent the intensity of the monsoons, it is possible to investigate whether weak and intense summer and winter monsoons over east Asia (or at least over south China) are linked and through what mechanisms. This topic will be the subject of the next study.

Acknowledgments. The authors would like to thank NCEP–NCAR for providing the reanalysis data, the Hong Kong Observatory for the rainfall data for Hong Kong, and the National Climate Center of China for providing the rainfall data for other stations in China. Thanks are extended to Mr. K. Cheung and Mr. K. S. Liu for their help in extracting the data. Comments from the two anonymous reviewers are gratefully acknowledged.

This research is sponsored by the Research Grant Council of the Universities Grants Committee of Hong Kong Grant 9040259.

REFERENCES

Boyle, J., and T. J. Chen, 1987: Synoptic aspects of the wintertime East Asian monsoon. *Monsoon Meteorology,* C. P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 125–160.

Chan, J. C. L., and J.-E. Shi, 1999: Prediction of the summer monsoon rainfall over South China. *Int. J. Climatol.,* in press.

Chang, C.-P., and G. T.-J. Chen, 1995: Tropical circulations associated with southwest monsoon onset and westerly surges over the South China Sea. *Mon. Wea. Rev.,* **123,** 3254–3267.

Chen, L., Q. Zhu, and H. Luo, 1991: Background of large-scale circulation for East Asia monsoons (in Chinese). *East Asia Monsoons,* L. Chen, Ed., Meteorological Press of China, 1–27.

Ding, Y., 1994: The summer monsoon in East Asia. *Monsoons over China,* Kluwer Academic Publishers, 1–90.

——, Z. Zhao, and S. He, 1988: A study of long-term mean circulation in the tropics and subtropics at 200 hPa for May–October (in Chinese with English abstract). *Sci. Atmos. Sin.,* **12,** 174–181.

Guo, Q., 1983: Analysis on the East Asian summer monsoon index and its variation (in Chinese with English abstract). *Acta Geogr., Sin.,* **38,** 207–217.

Krishnamurti, T. N., 1982: *Compendium of Meteorology, Vol. II, Part 4—Tropical Meteorology.* WMO 364, World Meteorological Organization, 428 pp.

——, 1985: Summer monsoon experiment—A review. *Mon. Wea. Rev.,* **113,** 1590–1626.

——, H. S. Bedi, and M. Subramaniam, 1989a: The summer monsoon of 1987. *J. Climate,* **2,** 321–340.

——, ——, and ——, 1989b: The summer monsoon of 1988. *Meteor. Atmos. Phys.,* **42,** 19–37.

Lau, K.-M., and S. Yang, 1997: Climatology and interannual variability of the Southeast Asian summer monsoon. *Adv. Atmos. Sci.,* **14,** 141–162.

Li, C., and M. Yanai, 1996: The onset and interannual variability of the Asian summer monsoon in relation to land–sea thermal contrast. *J. Climate,* **9,** 358–375.

Meehl, G. A., 1987: The annual cycle and interannual variability in the tropical Indian and Pacific Ocean regions. *Mon. Wea. Rev.,* **115,** 27–50.

——, 1997: The South Asian monsoon and the tropospheric biennial oscillation. *J. Climate,* **10,** 1921–1943.

Ose, T., Y. Song, and A. Kitoh, 1997: Sea surface temperature in the South China Sea—An index for the Asian monsoon and ENSO system. *J. Meteor. Soc. Japan,* **75,** 1091–1107.

Shi, S., and J. Chao, 1982: The summer monsoon in North China (in Chinese). *Proc. Symp. Summer Monsoon in South and East Asia,* Kunming, China, Chinese Meteor. Soc., 72–85.

Shukla, J., 1987a: Interannual variability of monsoons. *Monsoons,* J. S. Fein and P. L. Stephens, Eds., John Wiley and Sons, 399–464.

——, 1987b: Long-range forecasting of monsoons. *Monsoons,* J. S. Fein and P. L. Stephens, Eds., John Wiley and Sons, 523–548.

Tanaka, M., 1997: Interannual and interdecadal variations of the western North Pacific monsoon and Baiu rainfall and their relationship to the ENSO cycles. *J. Meteor. Soc. Japan,* **75,** 1109–1123.

Tao, S., and L. Chen, 1987: A review of recent research on the East Asian summer monsoon in China. *Monsoon Meteorology,* C. P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 60–92.

Webster, P. J., and S. Yang, 1992: Monsoon and ENSO: Selectively interactive systems. *Quart. J. Roy. Meteor. Soc.,* **118,** 877–926.

Wu, M. C., and J. C. L. Chan, 1995: Surface features of winter monsoon surges over South China. *Mon. Wea. Rev.,* **123,** 662–680.

——, and ——, 1997a: Upper-level features associated with winter monsoon surges over South China. *Mon. Wea. Rev.,* **125,** 317–340.

——, and ——, 1997b: Relationships between winter and summer monsoons over South China. Preprints, *22nd Conf. on Hurricanes and Tropical Meteorology,* Fort Collins, CO, Amer. Meteor. Soc., 637–638.

Yasunari, T., 1990: Impact of the Indian monsoon on the coupled atmosphere/ocean system in the tropical Pacific. *Meteor. Atmos. Phys.,* **44,** 29–41.