Overview of the South China Sea Monsoon Experiment

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ABSTRACT

The present paper gives an overview of the key project " South China Sea Monsoon Experiment (SCSMEX)" operated by the Ministry of Science and Technology of China during the period of 1996–2001. The SCSMEX is a joint atmospheric and oceanic field experiment which aims to better understand the onset, maintenance, and variability of the summer monsoon over the South China Sea (SCS). It is a large-scale international effort with many participating countries and regions cooperatively involved in this experiment. With the field observation in May–August 1998, a large amount of meteorological and oceanic data was acquired, which provides excellent datasets for the study of the SCS monsoon and the East Asian monsoon and their interaction with the ocean. The preliminary research achievements are as follows. (1) The earliest onset of the Asian monsoon over the SCS and Indo-China Peninsula has been well documented. From the viewpoint of the synoptic process, its onset is closely related to the early rapid development of a twin cyclone to the east of Sri Lanka. The conceptual model of the SCS monsoon onset in 1998 was put forward. The 50-year time series of the SCS monsoon onset date was also made. (2) Two major modes, namely the 30–60-day and 10–20-day oscillations were ascertained. The influences of the abnormal SCS monsoon on the precipitation over eastern China and its modes were identified. A strong (weak) monsoon over the SCS usually leads to less (more) precipitation over the middle and lower reaches of the Yangtze River basin, and more (less) precipitation in North China. (3) During the monsoon onset over the SCS, a wide variety of organized mesoscale convective systems (MCSs) were observed by a Doppler radar array deployed over the northern SCS. The relationship between large-scale circulations and MCSs during the monsoon onset process in 1998 was clearly revealed. It was suggested that there is a kind of positive feedback mechanism between large-scale circulations and MCSs. (4) The SST over the SCS during the early period influences the timing of the monsoon onset date and the monsoon's intensity. During the monsoon onset, the ocean undergoes a process of energy release through air-sea interaction. During the break phase of the SCS monsoon, the ocean demonstrates the process of energy re-accumulation. Obvious differences in the air-sea turbulent flux exchange between the southern and northern parts of the SCS due to different characteristic features of the atmosphere and sea structure were observed in those regions. (5) The verification of impact of intensive observations on the predictive performance is made by the use of regional models. The air-sea coupled regional climate model (CRCM) was also developed under the SCSMEX Project . The simulation of the oceanic circulation in 1998 produced with the model was well compared with the observations.

Key words: field experiment, South China Sea monsoon, low frequency oscillation (LFO), meso scale convective systems (MSCs), air-sea interaction, numerical simulation

1. Introduction

The Asian monsoon has a profound influence on the social and economic condition of over 60% of the earth's population. For centuries, successful forecasting of monsoon rainfall has been a matter of great concern for the people and countries in Asia and surrounding areas. The Asian monsoon can be divided into two systems: the South Asian monsoon and East Asian monsoon systems (Tao and Chen, 1987). The SCS (South China Sea) monsoon is one of the important subsystems of the East Asian monsoon. The

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SCS connects the monsoon originating in the Southern Hemisphere, the monsoon over the western Pacific Ocean, and the monsoon over the Indian Ocean due to its unique geographical location as a boundary region between the Asian continent and the western Pacific. The origin, development, and evolution of the SCS summer monsoon can greatly influence the weather and climate in East Asia and Southeast Asia (Ding, 1994; SCSMEX Project Office, 1995).

In recent years, the study of the SCS monsoon once again became a focus in the field of monsoon and climate variability. Through the joint effort of scientists from many countries/regions over many years, the unique features of the activities of the SCS monsoon have been revealed. Tao and Chen (1987) put forward that the Asian monsoon breaks out earliest over the SCS, usually in middle May, then moves northward to Mainland China and the western Pacific Ocean to the south of Japan, and finally moves northwestward to the Bay of Bengal and the Indian Peninsula. So, the onset of the monsoon over the SCS and adjacent areas may be regarded as a signal of the beginning of the Asian monsoon (Ding and Murakami, 1994; Tanaka, 1994). Recently, Wu and Zhang (1998) further pointed out that the onset of the Asian monsoon consists of three phases: the first onset of the monsoon over the eastern part of the Bay of Bengal during the early days of May, then the onset of the East Asian monsoon on 20 May, and the final onset of the Indian monsoon on about 10 June.

The relationship between the Asian summer monsoon and precipitation, especially the linkage of the summer monsoon to the Meiyu/Baiu season precipitation, has also been investigated by numerous researchers (Yoshino, 1965; Tao and Chen, 1987; Lau et al., 1988; Ding, 1992; Yamazaki et al., 1999). The rainy season in China as well as in East Asia generally begins with the onset of the summer monsoon 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 experiences three stable stages and two sudden northward jumps, namely being stationary over South China, the Yangtze River and the Huaihe River basins, and North China respectively, and then retreating rapidly southward, thus leading to the end of the major precipitation season in summer in China (Guo and Wang, 1981). On the other hand, rainfall intensity and seasonal positions as well as their variations are also significantly modulated by fluctuations of the summer monsoon, especially in the low frequency domain (Lau et al., 1988). Furthermore, the interannual variability of the Asian monsoon also exerts an important effect on precipitation and climate regimes in East Asia, even on the global scale (Yasunari and Seki, 1992; Tanaka, 1997). The drought/flood extremes, extreme cold/hot summers and other damaging climate disasters are basically caused by the great interannual variability and intraseasonal variability of the monsoon. In particular, the early or late arrival of the summer monsoon, its rapid or slow northward movement, and its intensity variation directly influence the temporal and spatial distributions of the major monsoonal rain belt in summer in East Asia and the occurrence of drought/flood during the rainy season (National Climate Center, 1998). Recently, Lau and Weng (2000) reported their new finding that there are two distinct climate teleconnection patterns that link major U.S. summer droughts and floods to variability in the Asian summer monsoon, mainly in the SCS and the West Pacific. Therefore, the study of the Asian summer monsoon, especially the summer monsoon over the SCS, not only has a regional implication but also a global effect. The above-described scientific rationale contributes to the scientific motivation behind launching the South China Sea Monsoon Experiment (SCSMEX).

SCSMEX is a multi-national atmospheric and oceanographic observation plan, and is also the first large-scale joint research project between meteorologists and oceanographers for SCS. SCSMEX is closely linked to and coordinated with activities of national weather services and research institutions of East Asian countries and adjacent regions as well as ongoing and planned China, U. S., and international field experiments and research programs such as the Global Energy and Water Experiment (GEWEX) and Climate Variability and Predictability (CLIVAR). Many countries or regions were involved in the enhanced and intensive observations of SCSMEX, including 10 provinces in South China, and Taiwan, Hong Kong, and Macao, U. S., Australia, Japan, Thailand, Vietnam, Malaysia, Singapore, Brunei, Indonesia, and the Philippines. The primary goal of SCSMEX is to provide a better understanding of the key physical processes for the onset, maintenance, and variability of the monsoon over Southeast Asia and southern China leading to improved predictions (SCSMEX Project Office, 1995). To attain this goal of SCSMEX, the following specific scientific objectives were aimed at:

(1) To describe and document the space-time evolution of the large-scale atmospheric circulation, thermodynamic fields, as well as basic ocean flow patterns and thermohaline structures associated with the SCS monsoon.

(2) To identify the influence of heating contrasts between SCS and surrounding regions and the role of

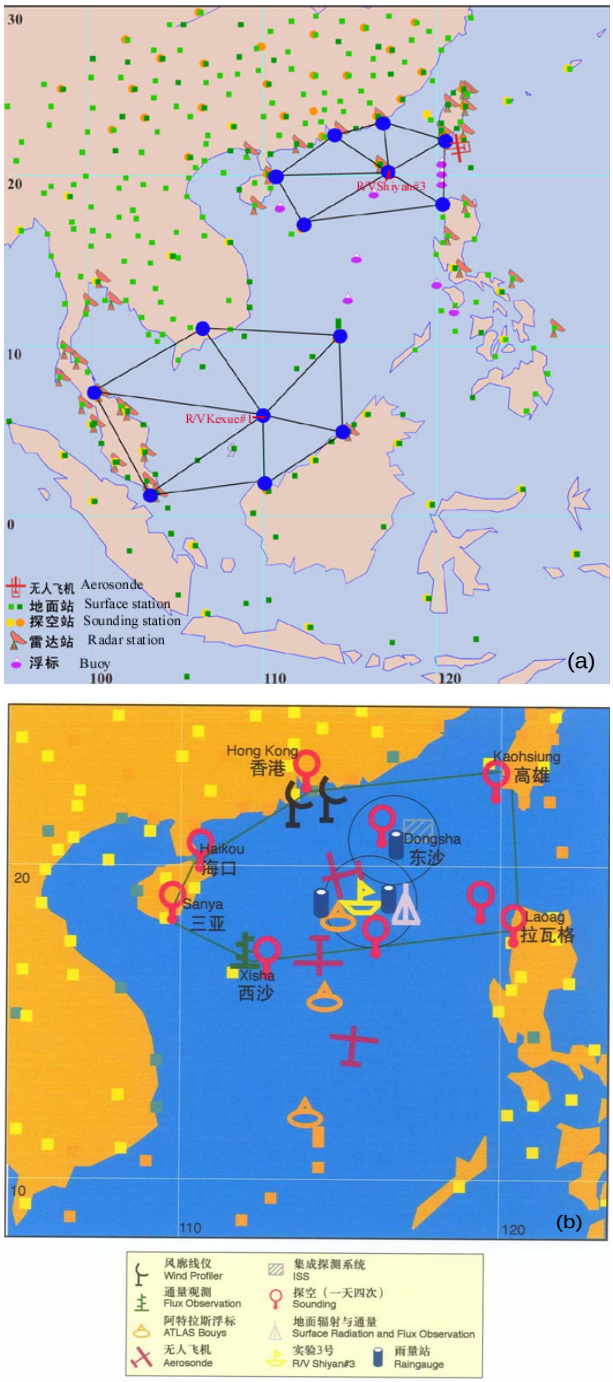

Fig. 1. (a) The network of the SCSMEX field observation in May–August (1998); and (b) Special field observation platform domain in the northern part of the SCS (SCSMEX Project Office, 1998).

early monsoon (April–May) convection and multi-scale processes in the SCS in the abrupt transition and subsequent evolution of the East Asian monsoon.

(3) To elucidate physical processes in oceanic response to monsoon forcing and air-sea interaction in SCS and relationships with adjacent oceans.

(4) To assess and improve the ability of regional and global models in simulation and prediction of the monsoon onset in Southeast Asia and in southern China.

2. Brief description of field observations and data acquisition

A four-month field phase that covered the period from 1 May to 3 August 1998 is one of the core components of SCSMEX. the project included the design of a large-scale observation region and an intensive observation domain. The former included a large Asian-West Pacific region (10°S–40°N, 70°–150°E) with the focus on conventional observations; the latter was located on the SCS and its surrounding regions (10°S–30°N, 95°–130°E) (Fig. 1a). Field observations consisted of an atmospheric observation network, an oceanographic observation network, an air-sea interface observation network, and a satellite observation network. The observation system consisted of the most advanced atmospheric and oceanic observation platforms and instruments including radiosonde, surface observation network, weather radar, a scientific research ship, aerosondes, satellite observation, oceanic boundary layer and flux measurement, integrated sounding system (ISS), radiation, ATLAS moorings, drifting buoys, ADCP (Acoustic Doppler Current Profile), CTD (Towed Profiling), and airborne expendable bathythermographs (AXBT), etc. (Fig. 1b). Under the support of the participating countries/regions, the four-month field observations were completed successfully. A wealth of information and data was obtained on the early onset of the monsoon in the northern region of the SCS, and on the evolution and the northward migration of the monsoon to the Yangtze River Basin in the context of El Niño events, which provides an excellent basis for further research.

There were two intensive observation periods (IOP) in the enhanced phase of field observation for SCSMEX: 5–25 May and 5–25 June. The first IOP focused on monitoring the onset of the SCS monsoon and its sudden seasonal change as well as the implications for precipitation in South China and Southeast Asia. The second IOP focused on monitoring atmospheric and oceanic conditions over SCS during the period of the mature phase and northward migration of the East Asian monsoon, and the implications for precipitation in the Yangtze River basin, the Korean Peninsula, and Japan.

The SCSMEX has set up a comprehensive and complete database from April 2001, which includes

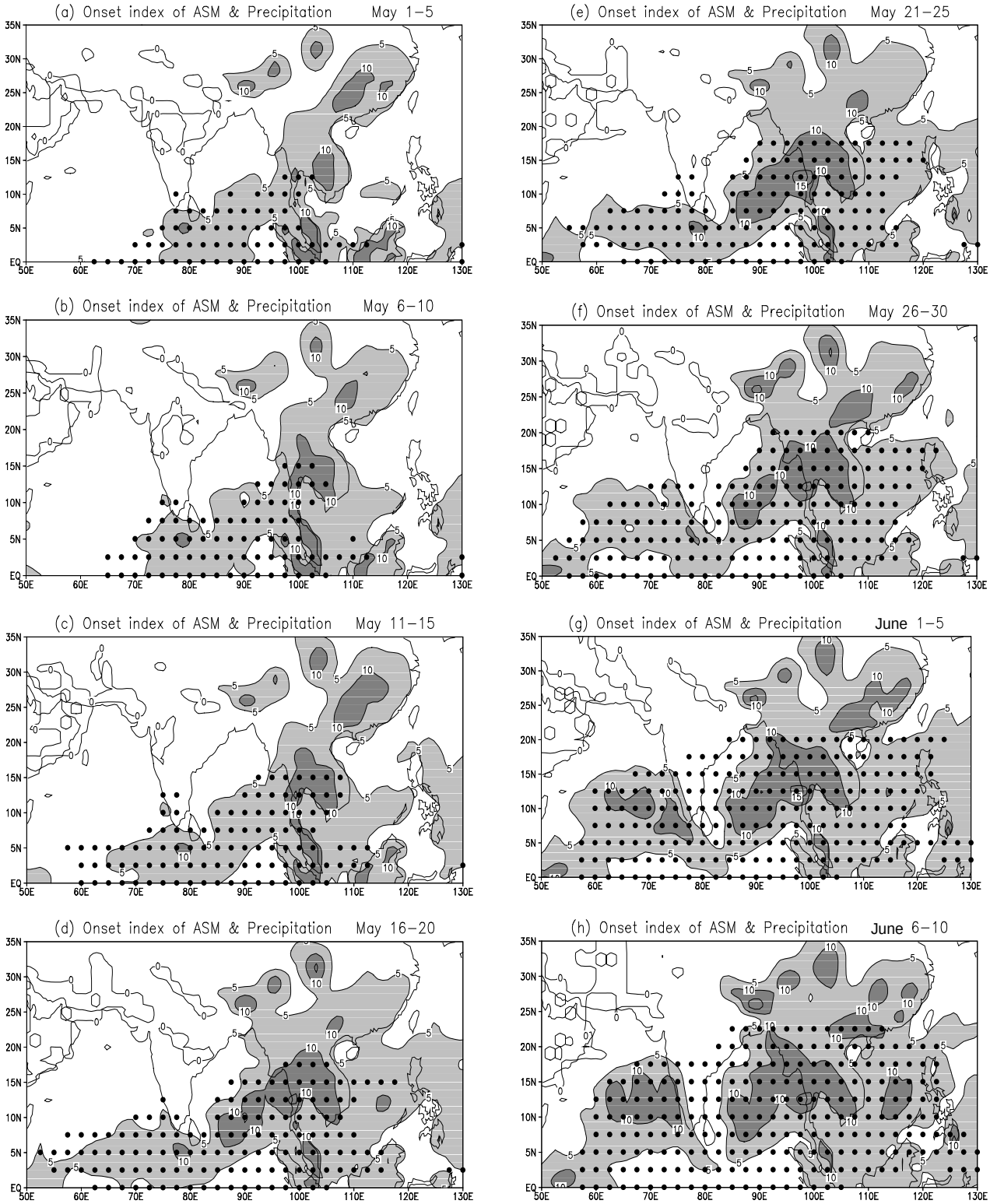

Fig. 2. Climatological pentad-averaged precipitation rates (mm d^{-1}) for 1–5 May to 6–11 June in sequence. Light and dark shadings indicate precipitation regions greater than 5 mm d^{-1} and 10 mm d^{-1}, respectively. The black dots represent the location of the onset of the summer monsoon. (Zhang et al., 2004)

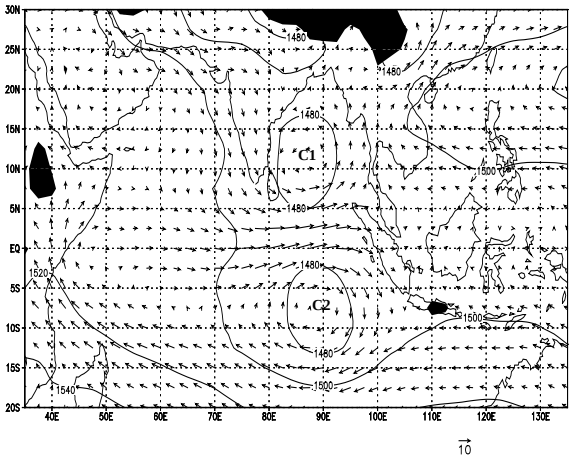

Fig. 3. The composite 850-hPa streamline pattern averaged for 13 cases for one pentad before the onset. The 13 cases used for the average include the following years: 1957, 1968, 1969, 1972, 1973, 1981, 1982, 1983, 1984, 1992, 1993, 1997, and 1998). (Zhang et al., 2001b)

meteorological observation data, special observation and oceanographic observation data, satellite cloud imagery, radar observation data, limited area assimilation data, TBB=Blackbody temperature data, precipitation data retrieved (http://ncc.cma.gov.cn/exdocs/index.shtml). The data obtained from the field observation has also been used in four-dimensional data assimilation system by Japan, USA, and others. At present, these data has been widely used at home and abroad. American scientists have already used these data to carry out theoretical and numerical studies. They hope to cooperate with Australia (including China) to verify their operational mesoscale model, and other countries and regions (especially Japan) have also utilized these data to improve and verify their operational model.

Under the support of the Ministry of National Science and Technology, the SCSMEX has been a great success not only in field observations, but also in scientific achievements . Up to now, this project has published three monographs and three special issues in various journals. About 222 scientific papers have been published, which have had a great influence at home and abroad, leading to the further understanding of the physical process of the East Asian monsoon. It is also noted that the *Climatological ATLAS for*

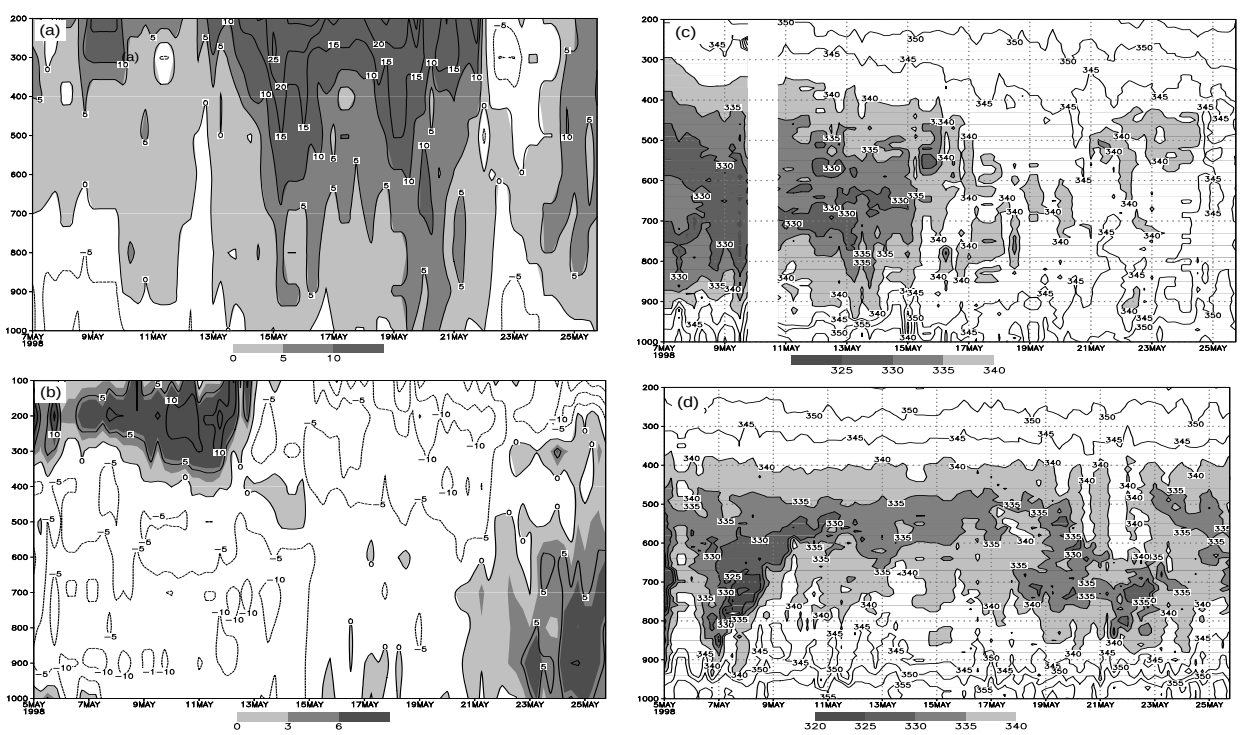

Fig. 4. Height-time cross sections of zonal wind and pseudo-equivalent potential temperature at research vessel *Shiyan#3* (a, c) and research vessel *Kexue#1* (b, d) in 1998. For (a) and (b), the solid lines denote westerly wind and the dashed lines easterly wind. The westerly wind is shaded. The units are m s^{-1} and the contour interval is 5 m s^{-1}. For (c) and (d), the values below 340 K are shaded and the contour interval is 5 K. Research vessels *Kexue#1* and R/V *Shiyan#3* were stationary at 6°15′N, 110°E and 20°29′39″N, 116°57′8″E, respectively, during the IOPs of 1998. (Ding and Liu, 2001)

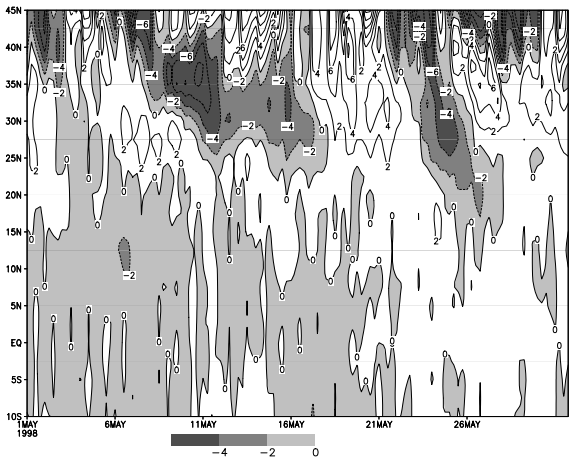

Fig. 5. Latitude-time cross section of 850-hPa-temperature departure averaged for longitudinal range of 110°–120°E for May 1998. The departure is obtained from subtracting the monthly mean temperature of May 1998 from the daily temperature. The units are °C. (Ding and Liu, 2001)

Asian Summer Monsoon published by the Macau Foundation in cooperation with the SCSMEX Project may be the first complete atlas of the Asian monsoon up to now. The main research achievements of the SCSMEX will be summarized in the following.

3. Onset of summer monsoon over the SCS

The fact that SCS is also a region where the Asian monsoon breaks out earliest, besides Indo-China Peninsula has been well documented by a great number of observations and research (Fig. 2) (Zhang et al., 2004). Some investigators have also pointed out that the earliest summer monsoon occurs over the Indo-China Peninsula (Matsumoto, 1997; Lau and Yang, 1997). The exact onset date, characteristics, evolution of the SCS monsoon, and its relationship with flooding, especially in 1998, have also been revealed (Wang et al., 2001). A 50-year time series of the SCS monsoon onset date has been created (He et al., 2001). From the viewpoint of the synoptic process, its onset is closely related to the early rapid development of a twin cyclone to the east of Sri Lanka (Fig. 3) (Zhang et al., 2001b; Ding and Liu, 2001). The conceptual model of the SCS monsoon onset in 1998 has been put forward based on the observational data from the upgraded upper-air radionsonde data obtained by the research vessels *Kexue#1* and *Shiyan#3*, which were stationary at 6°15′N, 110°E and 20°29′39″N, 116°57′8″E, respectively, during the IOPs of 1998. It has been pointed out that the SCS monsoon onset in 1998 mainly consisted of two phases (Fig. 4) (Ding and Liu, 2001). The first onset of the summer monsoon over the northern part of SCS occurring in the fourth

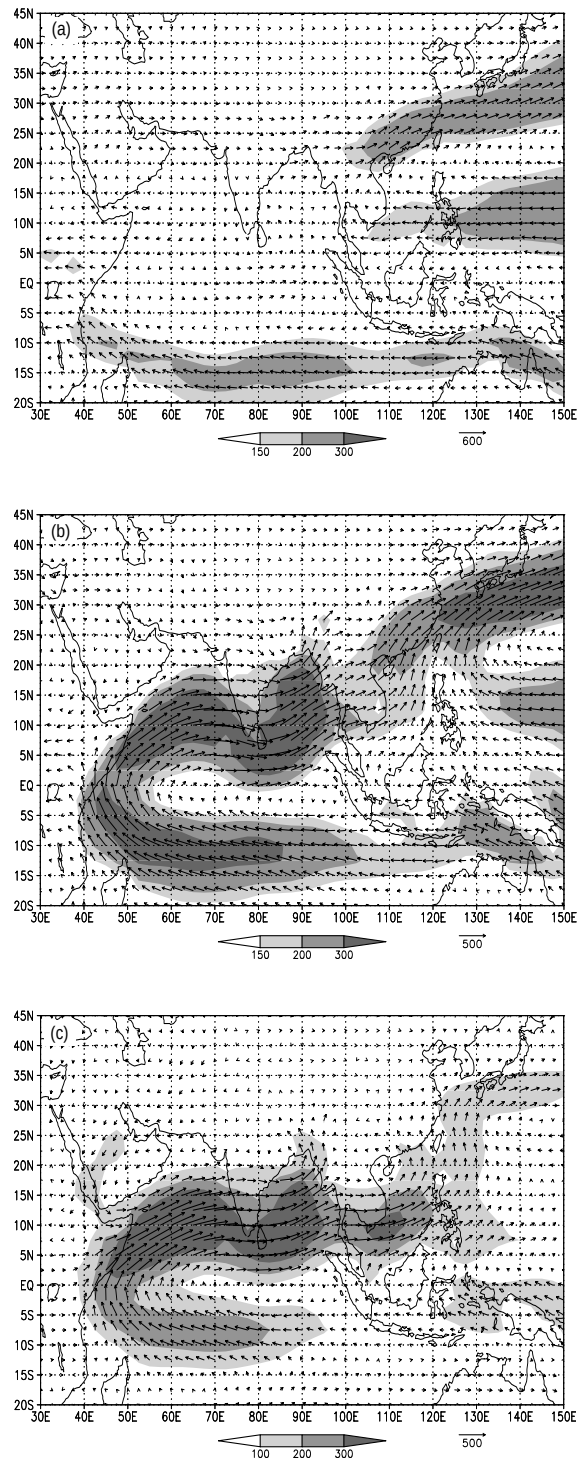

Fig. 6. Moisture transport patterns averaged for 1990–1999. Prior to the onset (the 6th pentad of March–the 3rd pentad of May) (a), after the onset (the 5th pentad of May–the 2nd pentad of July) of the SCS summer monsoon (b), and the difference of the above two episodes (c). The strong moisture transport is shaded. Units: kg m^{-1} s^{-1}. (Sun, 2002)

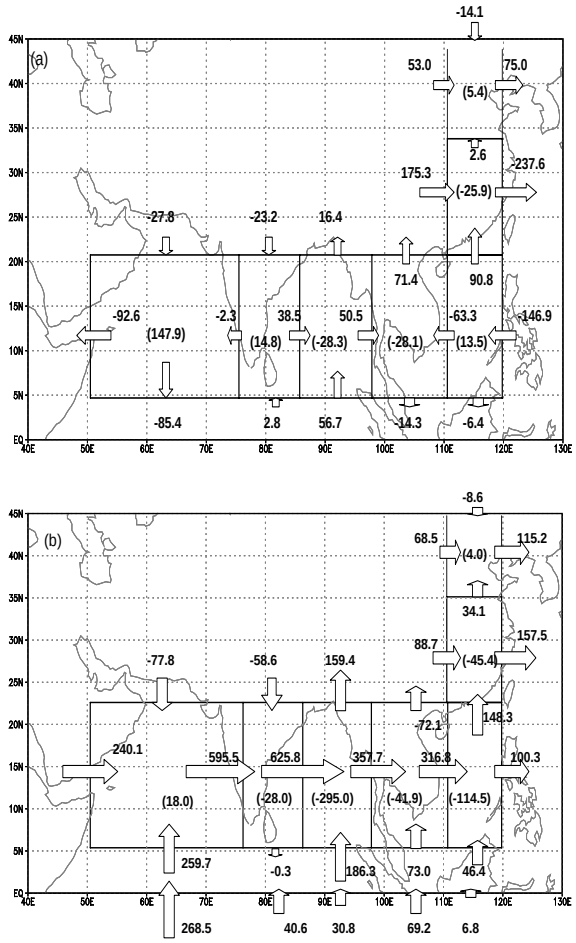

Fig. 7. Moisture budgets averaged for 1990–1999 for various monsoon regions prior to the onset (the 1st pentad of April–the 2nd pentad of May) (a) and after the onset of the SCS summer monsoon (June–August) (b). Units: 10^6 kg s^{-1}. (Sun, 2002)

pentad of May was baroclinic in nature, which was caused by the interaction between the weather systems at mid latitudes and the tropical monsoon air current (Figs. 4a, c and Fig. 5). The second large-scale monsoon onset in the fifth pentad of May was tropical in nature, which was induced by a rapid change in the large-scale tropical circulation features (Figs. 4b, d).

Before and after the onset of the South China Sea summer monsoon, the patterns of moisture flux undergo a significant change. Prior to the onset (Fig. 6a), the moisture transport is generally weak, mainly concentrating on the northern and southern parts of the subtropical high. The moisture in the southern Indian Ocean cannot flow northward into the Asian monsoon region. After the onset, the moisture coming from the Southern Hemisphere flows into the Asian region and forms a continuous moisture channel (Fig. 6b) (Sun, 2002). The moisture budgets prior to and after the onset of the SCS summer monsoon are also different (Fig. 7). Before the onset of the SCS summer monsoon, the inter-hemispheric moisture transport is rather weak and even southward. The northward moisture transport across the northern boundaries of various regions is generally weak, except for the regions of the Indo-China Peninsula and SCS. The moisture sinks occur in the regions of the Bay of Bengal, the Indo-China Peninsula, and South China, where enhanced precipitation may be observed. After the onset, the whole picture of the moisture transport and budget rapidly changes and becomes well-organized. The cross-equatorial flow has its maximum moisture transport in the western part of the equatorial Indian Ocean. The second maximum moisture transport is located in the equatorial East Indian Ocean. In the South Asian and Southeast Asian monsoon regions, one may see consistent eastward moisture transport, all the way down to the SCS. The moisture sinks from the Indian Peninsula to the SCS are consistent with the major observed precipitation regions, with the Bay of Bengal having the maximum sink (Sun, 2002).

4. Development of mesoscale convective systems over the SCS during the monsoon onset process over the SCS

During the monsoon onset over the SCS, one can observe a wide variety of organized mesoscale convective systems (MCSs) by using the Doppler radar array deployed over the northern SCS. By the analysis of retrieved precipitation from dual-Doppler radar during the SCSMEX, about eight obvious precipitation processes with life spans of 6–12 hours or longer were observed just during 15–19 May, which mainly resulted from MCSs (Fig. 8a). These MCSs can be divided into three types according their migration (the first type: migration from northwest to southeast; the second type: migration from southwest to northeast; and the third type: stationary). The relationship between large-scale circulations and MCSs during the monsoon onset process in 1998 was clearly revealed. Before the monsoon onset, the large-scale background provided favorable synoptic and dynamic conditions for the formation of the mesoscale convective activities. The establishment of the monsoon trough and shear line at the low levels was conducive to the formation and maintenance of the MCSs (Fig. 8b); after the summer monsoon onset, the occurrence of persistent and large-scale mesoscale convective activities produced obvious feedback directed toward the large-scale circulations, namely the release of latent heat driven by enhanced convective activities resulted in intense atmospheric heating over the northern SCS (Johnson and Paul,

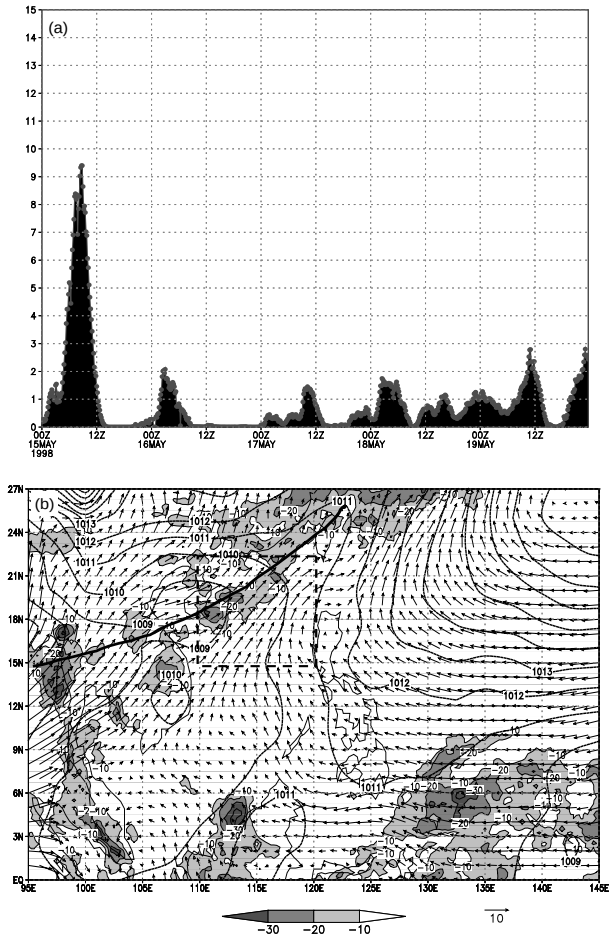

Fig. 8. (a) Retrieved precipitation per ten minutes from dual-Doppler radar observations during 15–19 May 1998, which mainly resulted from mesoscale convective systems (units: mm h^{-1}); (b) 850-hPa wind field, sea-level pressure (units: hPa) and TBB (units: °C) during 15–19 May 1998. Dashed line box: the region investigated in the northern SCS; bold black line: monsoon trough.

2002). Thus the meridional temperature gradient over the SCS and Indo-China Peninsula was reversed from upper-level to lower-level and to a considerable some extent, contributed to the significant change in the large-scale circulations in this region, possibly including the eastward retreat of the subtropical high out of the Indo-China Peninsula and the SCS. Therefore, it is suggested that there is a kind of positive feedback mechanism between the large-scale circulations and the MCSs.

5. The low frequency oscillation of summer monsoon over the SCS and its teleconnection

The characteristics of the low-frequency oscillation of the SCS monsoon have been ascertained. The 30–60-day and 10–20-day oscillations are the two major modes (Fig. 9) (Xu and Zhu, 2002) that greatly influence the activity of the SCS monsoon. On the one hand, before the monsoon onset, the intra-seasonal oscillation is obviously enhanced and extended from the region to the east of the Philippines to the SCS (Mu and Li, 2000). The westerly wind (positive) phase of the 30–60 day oscillation initiated the onset of 1998 SCS summer monsoon and the increase in kinetic energy (Fig. 10). On the other hand, the anomaly of the intra-seasonal oscillation plays an important role in the inter-annual anomaly of the SCS summer monsoon, namely the strong (weak) intra-seasonal oscillation corresponds to the strong (weak) SCS summer monsoon. The influences of the abnormal SCS monsoon on the precipitation over eastern China have been

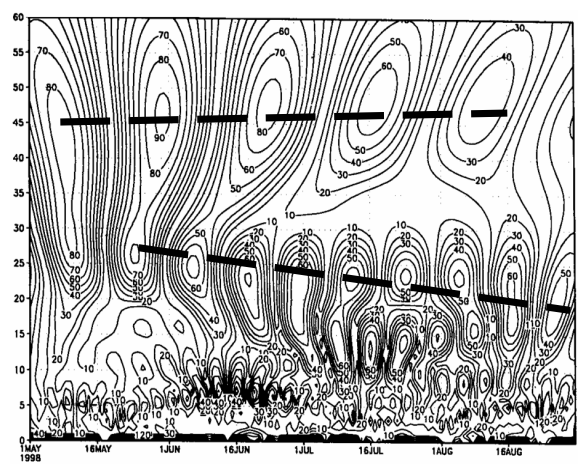

Fig. 9. Morlet wavelet analyses of zonal wind at 850 hPa in the SCS. Abscissa: time; ordinate: time period; unit: d. (Xu and Zhu, 2002)

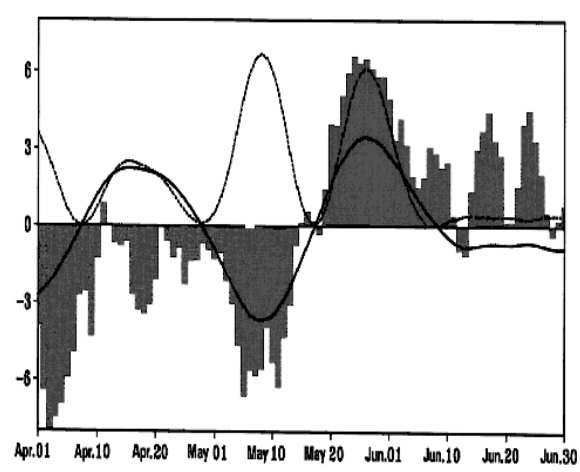

Fig. 10. 850-hPa zonal wind over the SCS region in 1998 (5°–20°N, 105°–120°E) (shaded) and temporal evolution of the 30–60-day low-frequency zonal wind (solid line) and kinetic energy (dashed line). (Mu and Li, 2000)

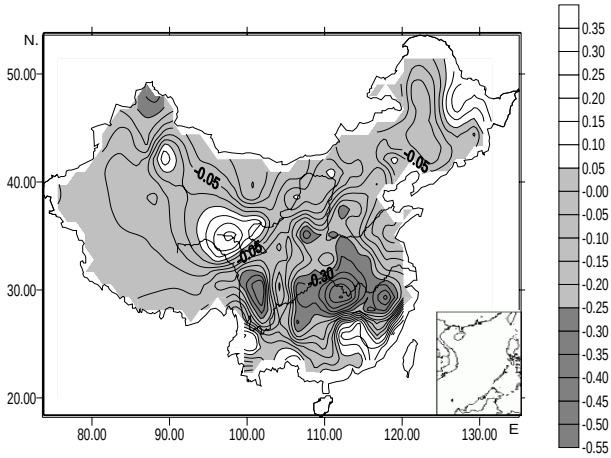

Fig. 11. The distribution of the correlation coefficient of the SCS monsoon and the precipitation from June to August in China. (Zhang et al., 2001b)

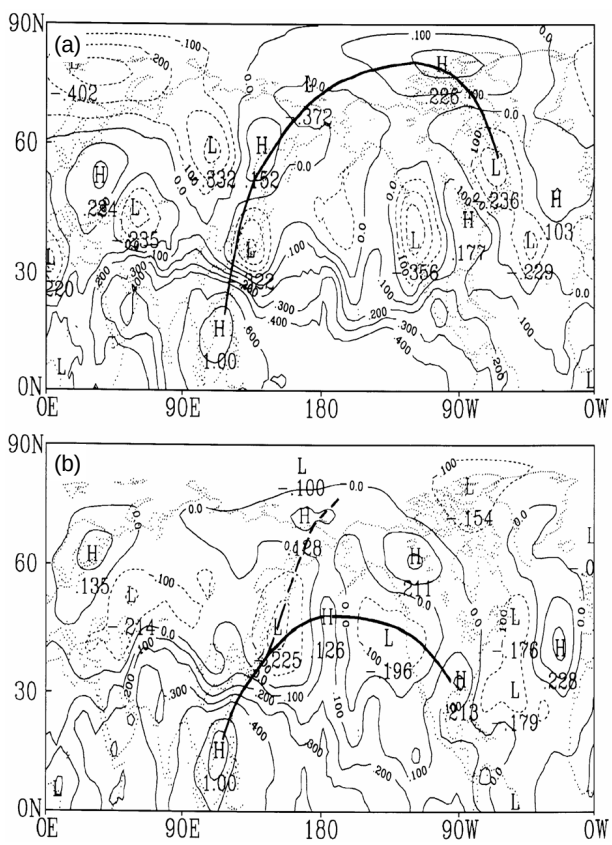

Fig. 12. Correlation of the 500-hPa height over the Northern Hemisphere in strong (a) and weak (b) SCS monsoon years. The fiducial point is at 15°N, 112.5°E. (Li, 2001)

ensured. A strong (weak) monsoon over the SCS usually leads to less (more) precipitation over the middle and lower reaches in the Yangtze River basin, and more (less) precipitation in North China (Zhang et al., 2001b) (Fig. 11). Also, the influences of the abnormal SCS monsoon on the atmospheric general circulation and the climate over the Northern Hemisphere and its basic teleconnection routes were put forward (Fig. 12). Different East Asia-Pacific-North America (EAP) wave trains can not only influence East Asia, but also the weather and climate in North America. Recently, some American scientists have begun to regard the monsoon and the SST of the SCS and its neighboring areas as an indicator in their mainland drought/flood forecasts (Li, 2001).

6. Air-sea interaction and oceanic thermodynamic process over the SCS

The unique features of the interaction between the ocean and the SCS monsoon were revealed through special oceanic observations. The SST over the SCS during the early period influences the earliness or lateness of the monsoon onset date and the monsoon's intensity. Obvious warming SST can be clearly found in the ocean before the monsoon onset. After the monsoon onset, the disturbance of the monsoon may affect the SST in the neighboring regions, with a weak cooling and rapid revival of warming measured by ATLAS buoys in the SCS, whereas variation of the SST, in turn, influences the evolution of the monsoon through different scale thermodynamic and dynamic processes, thus influencing the weather and climate of the West Pacific Ocean, Southeast Asia, and even North America (SCSMEX Project Office, 1999).

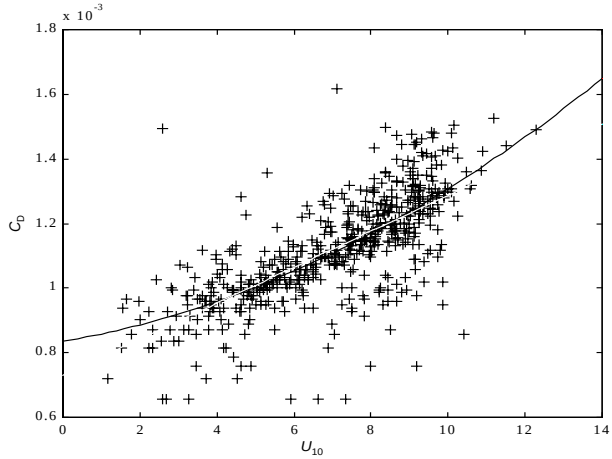

Fig. 13. C_D as a function of mean wind U_{10} by the eddy correlation method. U_{10} is the wind speed at the height of 10 m. $1000C_D$=0.056U_{10}^2+0.732. (Yan et al., 2000)

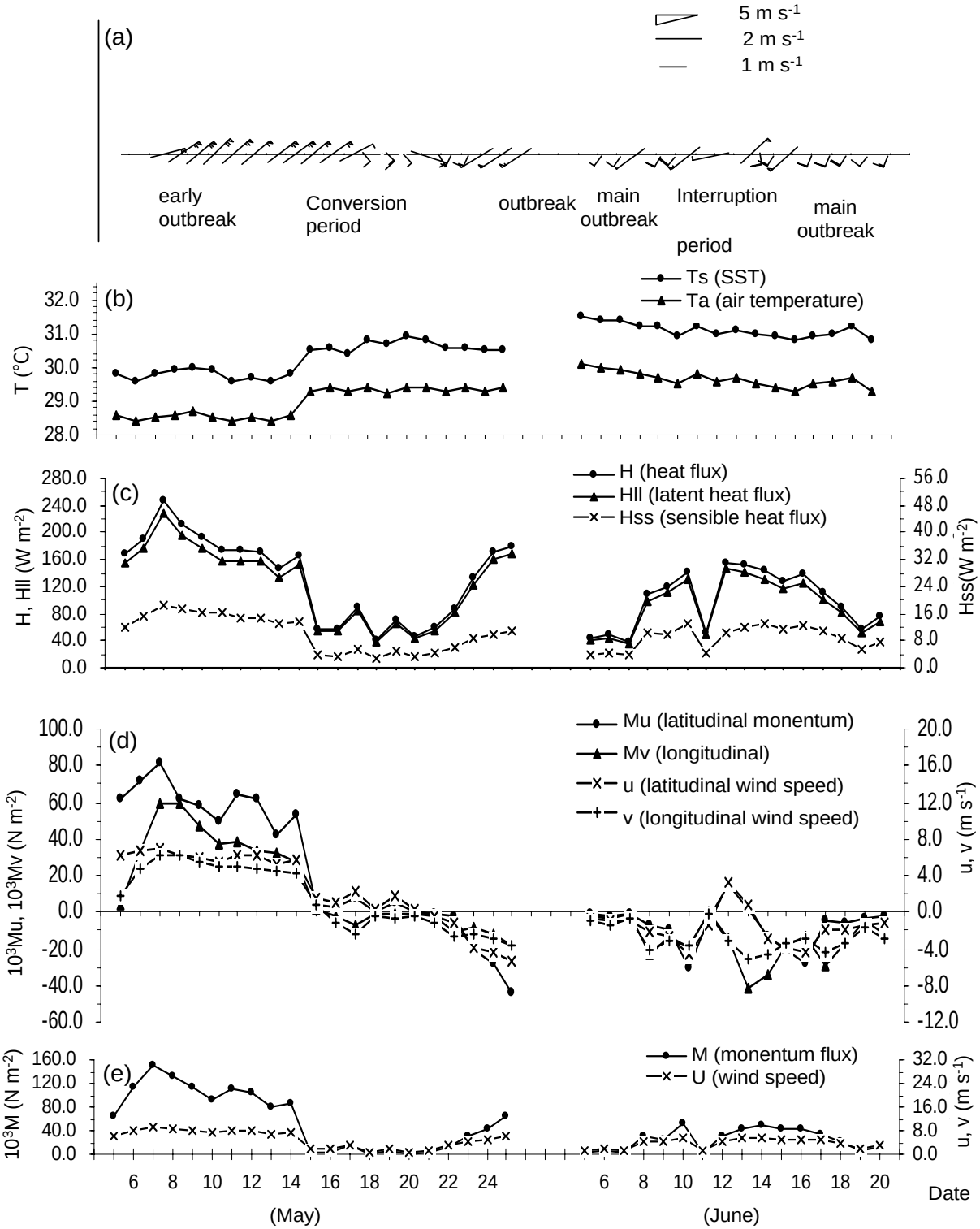

Fig. 14. Daily variation of daily mean values for atmospheric and oceanic elements and turbulent fluxes collected by *Kexue*#1 in 1998: (a) wind vector; (b) SST and air temperature; (c) heat flux, latent heat flux, and sensible flux; (d) zonal wind and momentum flux, meridional wind and momentum flux; (e) wind speed and momentum flux. (Qu et al., 2000)

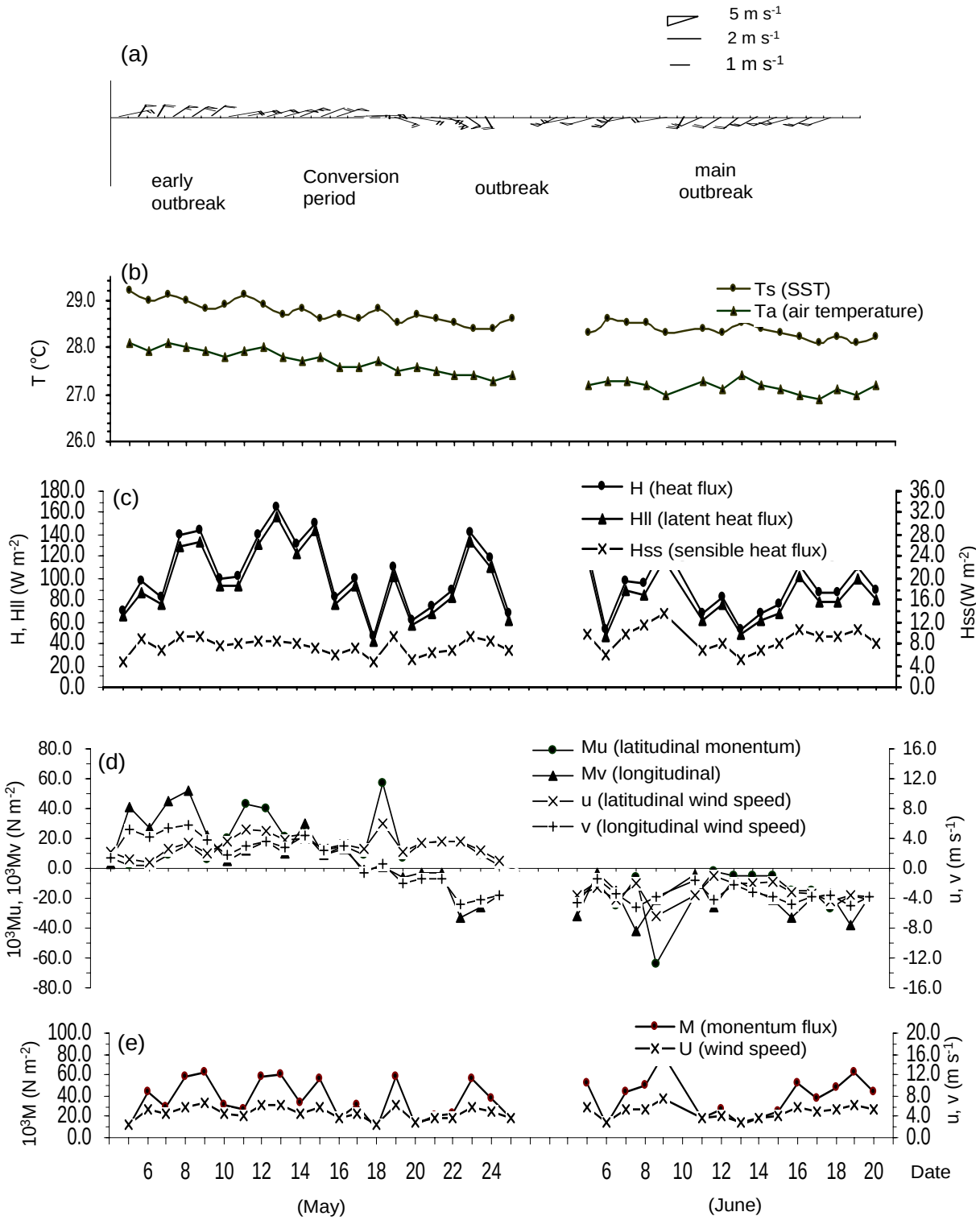

Fig. 15. Daily variation of daily mean values for atmospheric and oceanic elements and turbulent fluxes collected by *Shiyan*#3 in 1998: (a) wind vector; (b) SST and air temperature; (c) heat flux, latent heat flux, and sensible flux; (d) zonal wind and momentum flux, meridional wind and momentum flux; (e) wind speed and momentum flux. (Qu et al., 2000)

Table 1. The comparison of surface fluxes at Xisha Islands in the SCS with other field experiments. (Yan et al., 2000).

Elements	SCS Xisha Tower 14 May–22 Jun 1998	Nansia platform 19–24 Sep 1994	Hakuho ship 12–26 Nov 1992	Moana wave buoy 4 Nov–3 Dec 1992	Wecoma buoy 4 Nov–3 Dec 1992	WHOI buoy 4 Nov–3 Dec 1992
Momentum flux (N m^{-2})	0.10		0.030	0.020	0.017	0.020
Sensible flux (W m^{-2})	7.8	6.0	5.5	6.0	4.6	7.0
Latent flux (W m^{-2})	110–130	129.2	102.4	89.7	86.0	92.0
Bowen Ratio	0.047–0.071	0.046	0.054	0.067	0.053	0.076

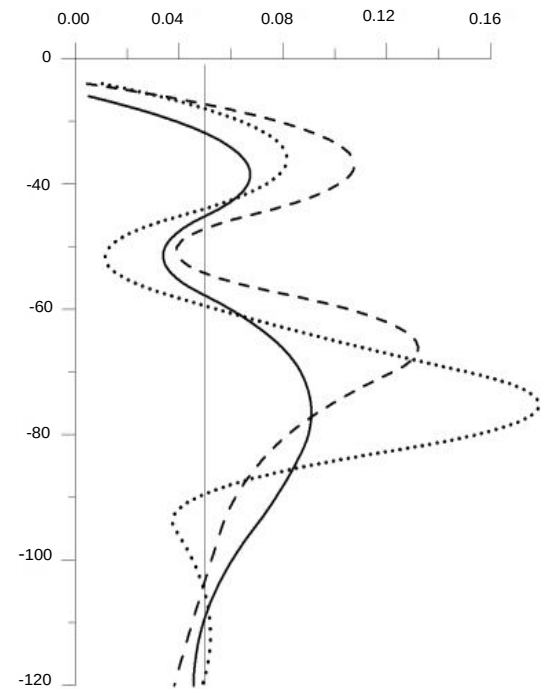

Fig. 16. Vertical temperature gradient at SCS1 on April (solid line); at SCS2 on April 1 (dashed line); at SCS 3 on March 27 (dotted line) (Liu et al., 2001). SCS1 (18°N, 115°E), SCS2 and SCS3 (12°N, 114°E) represent three ATLAS buoys, respectively,

A wealth of observation data of turbulence and radiation was obtained. Based on these data, the parameters of the turbulence structure, air-sea exchange coefficients and the air-sea sensible heat, momentum, and moisture exchange were subsequently computed. The results and their comparison with other field experiments are listed in Table 1 (Yan et al., 2000). When the speed surpasses 3 m s^{-1}, the drag coefficient C_D increases linearly with the wind speed (Fig. 13) (Yan et al., 2000). These results reveal that the heat and moisture exchanges are well comparable with those obtained by other field experiments, with the moisture flux dominating, which is a general feature of surface fluxes in tropics. In addition, it is also found that the surface heat and moisture vary abruptly with the SCS monsoon onset. In particular, the net balance of the latent heat flux and oceanic heating varies apparently. The results suggest that the ocean undergoes a process of energy accumulation before the SCS monsoon onset. During the monsoon onset, it undergoes the process of energy release. During the break phase of the SCS monsoon, the ocean exhibits the process of energy re-accumulation.

Also, atmospheric and oceanic data collected by *Shiyan*#3 and *Kexue*#1 during the IOP in SCSMEX98 were used to calculate the air-sea turbulent flux exchange. Some characteristics of the air-sea exchange were analyzed by using the eddy correlation method (Qu et al., 2000). Obvious differences were found in the characteristics of atmosphere and sea structure, and in the air-sea turbulent flux exchange between the southern and northern parts of the SCS. Moreover, the variation of SST is mainly related to the latent flux transfer besides the global radiation (Figs. 14 and 15).

The seasonal and intraseasonal variability of the thermocline and relative surface height in the central SCS were investigated using the time series of sea temperature measured from three ATLAS buoys of SCSMEX in 1998 deployed by Taiwan scientists (Liu et al., 2001). They found that the thermocline becomes deeper in winter, owing to the great loss of heat on the sea surface. This feature was more evident in the northern part than in the southern part of the central SCS. The intraseasonal variation of the thermocline was mainly controlled by the geostrophic vorticity and was out of phase with sea surface height. Furthermore, a double-thermocline phenomenon occurred in the SCS: in spring (April), owing to maximum net downward heat flux at the surface, a new thermocline appeared above 80 m and the old thermocline remained at 80 m deep (Fig. 16).

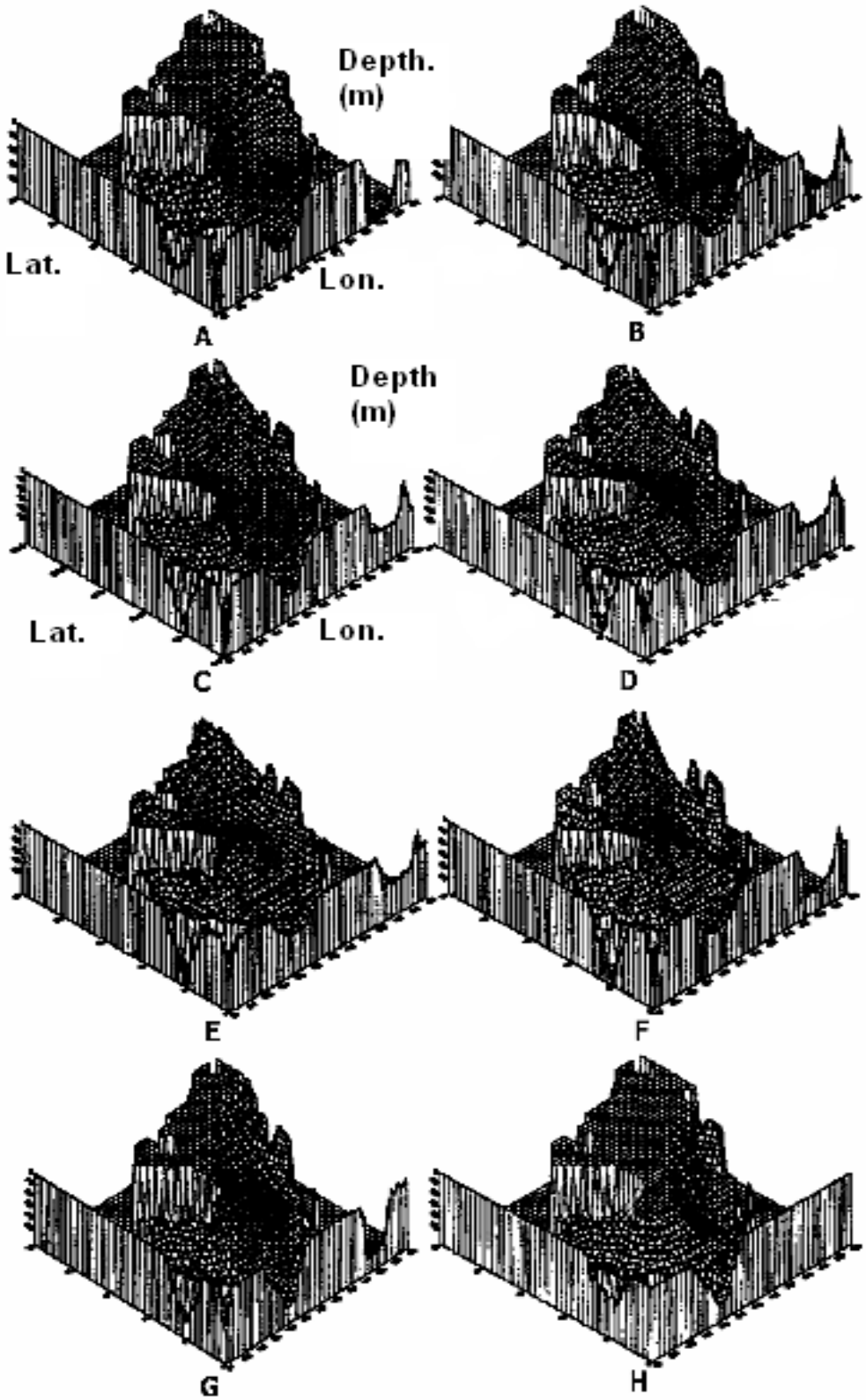

Fig. 17. Mean 28°C constant temperature envelop surface in the South China Sea (from Zhang et al., 2001a). A–H represent May–November, respectively.

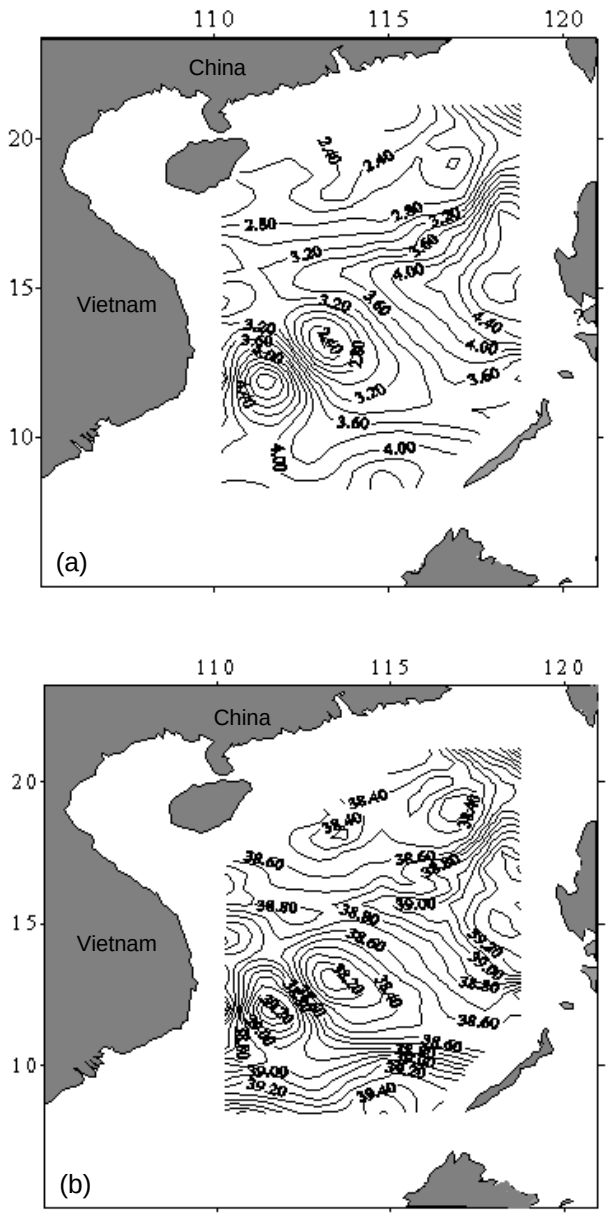

Fig. 18. Current distribution from ADCP (at 50 m) (a) and stream function distribution (at 200 m) (b) during period from June to July of 1998. (Wang and Xu, 2001)

Besides these, the stage features of the distributions and the vertical structure of the sea temperature at the central region of the warm waters (8°N, 113°E) were explored in detail by Zhang et al. (2001a). Based on the 28°C constant temperature envelope surfaces, the evolution processes of warm waters were discovered (Fig. 17). It was found that from April to November, the 28°C constant temperature envelope appeared in a pot-like pattern, with different sizes and depths, expressing the evolution processes of the warm waters.

The SCS circulation variation around the onset of the summer monsoon was revealed by using the CTD data of two cruises of SCSMEX research vessels (Wang and Xu, 2001). It was suggested that the SCS circulation displays two high-pressure zones and two low-pressure zones during this period, i.e., there are anticyclonic circulations to the east of Vietnam and to the west of the Philippines, and cyclonic circulations in the northern and middle parts of the SCS (Fig. 18).

7. Numerical simulation of the summer monsoon over the SCS

The reanalysis dataset obtained from the SCSMEX four-dimensional data assimilation system has been used widely at home and abroad. The scientists of the Hongkong Observatory improved the model initial fields and short-range forecasts, particularly in the first few hours, by using the SCSMEX datasets as inputs. The impact of intensive observations is increasingly more significant in higher resolution model runs (SCSMEX Project Office 2003). By exploring the predictability of the monsoon, Liu and Ding (2003) simulated the whole process of the monsoon onset, active-break cycle, and large-scale northward advance of the major seasonal rain belt by using RegCM2-NCC. They successfully reproduced the position and movement of the seasonal rain belt in summer 1998 in China (Fig. 19). It is evident that one can simulate the monsoon activity when high resolution data and a good model are available. More interestingly, an air-sea coupled regional climate model (CRCM) has also been developed under the SCSMEX Project. The simulation of the oceanic circulation in 1998 was compared with the observation, though some details need to be improved (Fig. 20) (Ren and Qian, 2001). The simulation of the 1998 monsoon onset and its evolution by the CRCM (coupled regional climate model) also suggests that the CRCM simulates the atmospheric field well (e.g., wind, height, temperature, and precipitation). It seems that the CRCM can provide us a potentially improving method to forecast the SCS monsoon and even the East Asian monsoon in the future.

8. Concluding remarks

The SCSMEX is a joint atmospheric and oceanic field experiment which aims at a better understanding of the onset, maintenance, and variability of the summer monsoon over the South China Sea. It is a successful large-scale international effort with many participating countries and regions cooperatively involved in the experiment. With the field observation in May–August 1998, a large amount of meteorological and oceanic data was acquired, which provides excellent datasets for the study of the SCS monsoon and

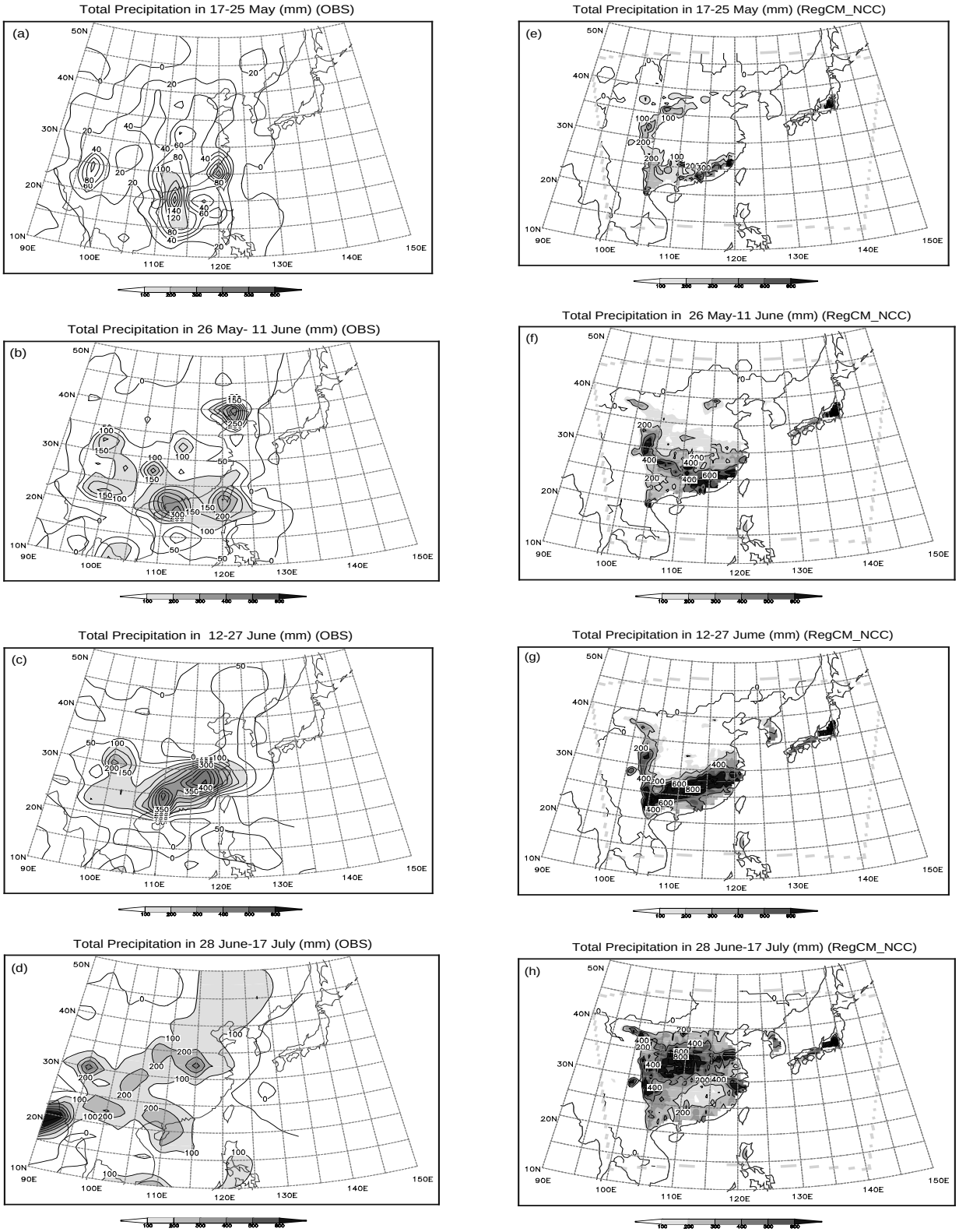

Fig. 19. Observed (a–d) and simulated (e–h) precipitation distributions corresponding to the different stages of the monsoon evolution in 1998 (units: mm). The simulated precipitation patterns are produced by the regional climate model RegCM_NCC. (Liu and Ding, 2003)

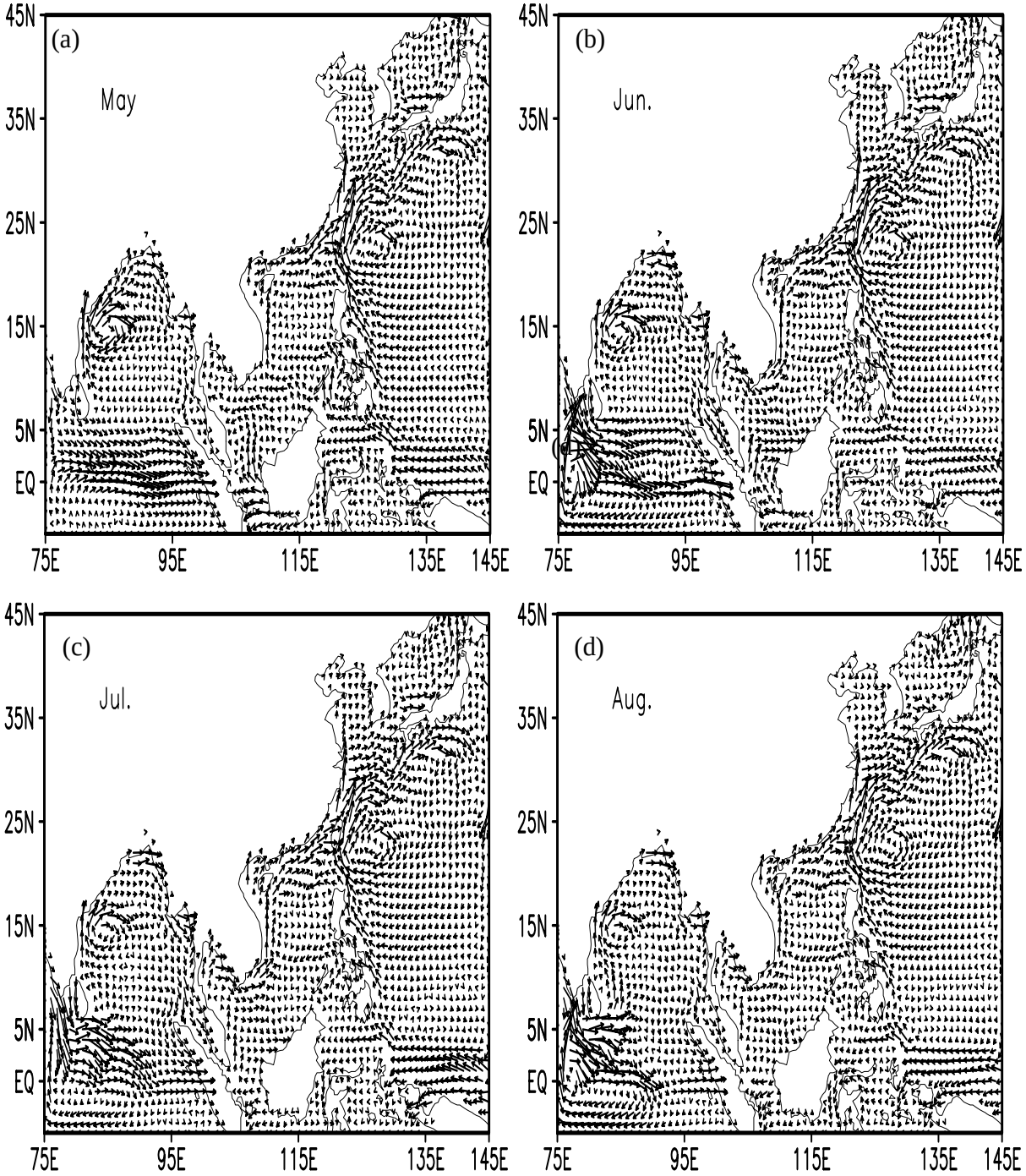

Fig. 20. Monthly oceanic general circulation of May to August in 1998 simulated by the regional air-sea coupled model (CRCM). (Ren and Qian, 2001)

the East Asian monsoon and their interaction with the ocean. The main research results may be summarized as follows.

(1) The Asian monsoon breaks out earliest over the SCS and the Indo-China Peninsula which was well documented. From the viewpoint of the synoptic process, its onset was closely related to the early rapid development of a twin cyclone to the east of Sri Lanka. The conceptual model of the SCS monsoon onset in 1998 was put forward. A 50-year time series of the SCS monsoon onset date was also reconstructed.

(2) Two major low frequency modes, namely the

30–60-day and 10–20-day oscillations in the SCS were ascertained. The influences of the abnormal SCS monsoon on the precipitation over eastern China and its modes were deter- mined. A strong (weak) monsoon over the SCS usually leads to less (more) precipitation over the middle and lower reaches of the Yangtze River basin, and more (less) precipitation in North China.

(3) During the monsoon onset over the SCS, a wide variety of organized MCSs was observed by the Doppler radar array deployed over the northern SCS. The relationship between large-scale circulations and MCSs during the monsoon onset process in 1998 was clearly revealed. It was suggested that there is a kind of positive feedback mechanism between large-scale circulations and MCSs.

(4) The SST over the SCS during the early period influences the timing of the monsoon onset date and its intensity. The surface fluxes are closely related to the monsoon activity. During the monsoon onset, the ocean undergoes the process of energy release. During the break phase of the SCS monsoon, the ocean experiences the process of energy re-accumulation. Obvious differences are observed in the air-sea turbulent flux exchange between the southern and northern parts of the SCS due to different characteristic features of the atmosphere and sea structure in those regions. During the onset process, the oceanic circulation and structure in the SCS show significant changes and features, i.e., with the double thermocline and multiple mesoscale eddies found.

(5) The impact of intensive observations in the SCSMEX is increasingly more significant based on the forecast experiment using the regional models. The air-sea coupled regional model CRCM has also been developed under SCSMEX Project. The simulation of the oceanic circulation produced with the model was comparative with the observation.

Up to now, the preliminary research results have been very encouraging for us to better understand the Asian monsoon as reported in the present paper. However, there are still some important aspects which need to be further investigated, such as 1) what is the driving mechanism of the SCS monsoon onset? 2) what part does the meso-scale convection play during the SCS monsoon onset period? 3) how can we improve the prediction of the monsoon event with dynamic models using a data initialization system with the assimilation of SCSMEX datasets? Further work is now underway to investigate these problems.

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