BASIC CLIMATOLOGICAL FEATURES OF AIR-SEA HEAT EXCHANGES IN THE SOUTH CHINA SEA (SCS) REGION AND THEIR RELATIONS WITH THE SCS MONSOONS*

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ABSTRACT

By using the NCEP reanalysis data set in 1979—1995, the fluxes of the latent heat, the sensible heat and the net long-wave radiation in the South China Sea (SCS) are expanded by means of EOF in order to discuss the basic climatological features in the SCS. The detailed analysis shows that the air-sea heat exchanges in different SCS regions have different seasonal variations. The middle and the north of the SCS are the high value regions of the air-sea heat exchanges during the winter and the summer monsoon periods, respectively, the seasonal variations of air-sea heat exchanges in the south of the SCS are small. In addition, the proportions of different components in the total air-sea heat exchanges have different seasonal variations in different regions. The results show that the SCS monsoon and the air-sea heat exchanges in the SCS region are the accompaniments of each other, the great difference of the sensible heat flux between the Indochina Peninsula and the SCS before the SCS summer monsoon onset may be one of the triggers of the latter. There maintains a high value center of the sensible heat flux before the 13th dekad, its disappearing time consists with that of the summer monsoon onset. It means that as far as the SCS local conditions are concerned, the northwest of the Indochina Peninsula is probably a sensitive region to the SCS summer monsoon onset and the land may play a leading role in the SCS summer monsoon onset.

Key words: air-sea heat exchange in the South China Sea, EOF, SCS (South China Sea) monsoon, seasonal variation

I. INTRODUCTION

The ocean plays an important role in the climate formation and variation of different time scales. The interactions between air and sea are realized by energy exchange, and the anomaly of energy exchange between air and sea is one of the factors which can lead to the anomaly of ocean and atmospheric circulations. So, it is very important to understand the physical mechanism of air-sea interaction when we analyze the thermal effects of ocean on atmosphere.

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The SCS is a semi-enclosed tropical deep ocean basin surrounded by mainland and islands, and the unique geographical surroundings form the special circulation and weather condition in the SCS through the thermodynamic and dynamic processes. Recently, great attention is paid to the important position of the SCS due to the deep studies of the basic climatological features, tropical circulation systems and the monsoon climate of the SCS (Yan et al. 1993; Liang 1991; Wang and Ding 1997). It is the basic work of air-sea interaction study to reveal the spatial and temporal distributions of air-sea heat exchanges (including the latent heat, the sensible heat and the net long-wave radiation) in the SCS, and it is also a key to the development of a good ocean-atmospheric coupled model. The previous studies (Wang et al. 1997; Yan 1997) are limited to the discussions of the air-sea heat exchanges based on the regional and the monthly mean, the problems of the seasonal variation features in different sea regions and the relations with the development of the SCS monsoon etc. have not been carefully sdudied.

In this paper the above problems are carefully analyzed by using the fluxes of the latent heat, the sensible heat and the net long-wave radiation in NCEP (National Center for Environmental Prediction, USA) reanalysis data set which is basically in agreement with the results calculated by Yan et al. (1993) and, therefore, believable in precision.

II. DATA AND METHODS

By using the dekad mean fluxes of the latent heat, the sensible heat and the net long-wave radiation in the SCS in the NCEP reanalysis data set of 1979—1995 (the sensible heat fluxes of 1986, 1987, 1993 are missing), 36 dekad climatological mean values of air-sea heat exchanges in the SCS (10°S—30°N, 90—130°E) are calculated and expanded by means of EOF, the basic climatological features of the air-sea heat flux exchanges are discussed by using the first two spatial vectors and their corresponding time coefficients. Then, the spatial and temporal features of the air-sea heat exchanges as well as its relations with development of the SCS monsoon are revealed by analyzing the figures of the time-latitude sections, the time-latitude sections of proportions and the climatic mean sensible heat fluxes in the 10th—15th dekads.

III. RESULT ANALYSIS

1. *The Basic Climatological Features of Air-Sea Heat Exchanges in the SCS*

The results of calculation show that the annual mean fluxes of the latent heat, the sensible heat and the net long-wave radiation in the SCS are all from sea to air, with the latent heat being the largest, the net long-wave radiation the second and the sensible heat the smallest among the three components. The spatial variations of both the latent and the sensible heat are large. The latent heat has its maximum in the middle ocean basin around 10°N with the value of 146 W m^{-2}. It is smaller in the north basin but still larger than 100 W m^{-2}. To the south of 8°N the latent heat is smallest with the values $\leqslant$100 W m^{-2}. The distributions of the annual mean sensible heat indicate that the low values are in the south and the high values in the north with a range from 1 to 33 W m^{-2}. The distributive features of the net long-wave radiation are similar to those of the sensible heat, but the distributive pattern does not change much in the whole SCS with a range of 47 — 51 W m^{-2}.

The climatological dekad mean data of the latent, the sensible heat and the net long-wave radiation of 17 years are expanded by means of EOF ($n=36$), and the contributions of the first eigenvectors of the three components to the total variances are 94%, 75% and 98%, respectively. Therefore, the first eigenvectors (named the first spatial pattern) of the three components can demonstrate their climatological features, respectively, and the corresponding time coefficients show the seasonal variation features.

The first spatial patterns of the latent heat, the sensible heat, and the net long-wave radiation are shown in Figs. 1a, 1b and 1c. The three vector fields are all positive, suggesting that there are the same phase variations in the whole sea region. The spatial distribution of the latent heat flux (Fig. 1a) is consistent with the shape of the ocean basin, the axis of high value is orientated from the northeastern open ocean (the western Pacific) southwestward to the center of the SCS ocean basin. The previous researches (He

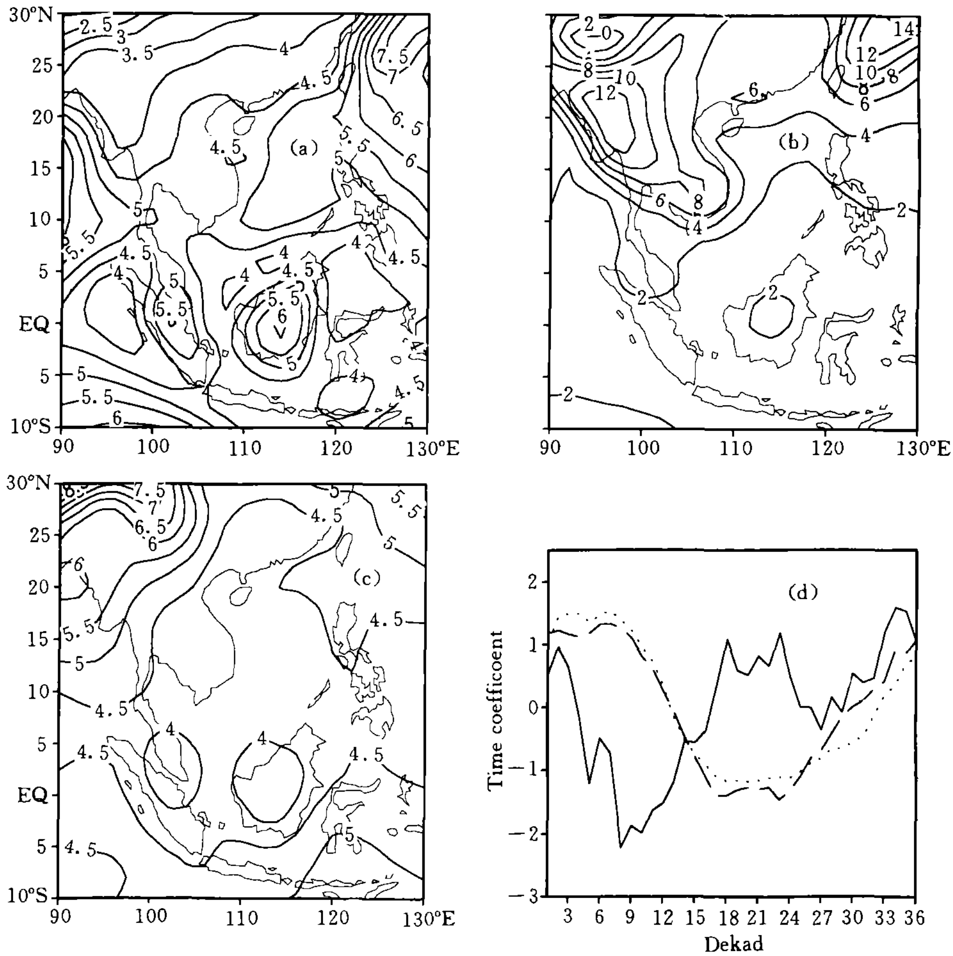

Fig. 1. The first spatial patterns of the latent heat (a), the sensible heat (b), the net long-wave radiation (c) and the corresponding time coefficients (d). —— latent; ···sensible; — — net long-wave radiation.

and Guan 1997) showed that the largest interannual variations of the upper ocean temperature in the SCS occur in the central ocean basin, which is possibly also the most sensitive region of air-sea interaction. The contour lines in the area, south of the central SCS, are zonally distributed and form a low value region around 5°N. There is a high value region over Indonesia, which suggests that not only the strongest atmospheric heat sources in the whole globe in winter but also the strong air-sea heat exchanges are located over Indonesia. The latent heat in the Indochina Peninsula is also small, the values decrease from south to north, and the case is reversed in the sea.

The sensible heat flux is determined jointly by the wind and the air-sea temperature difference. The north part of the SCS adjoins the Asian Mainland and thus is often influenced by the dry cold air in the winter monsoon, with an obvious seasonal variation of temperature and a large air-sea temperature difference. The south of the SCS is less influenced by the mainland, so the temperature and humidity are high throughout the whole year and the air-sea temperature difference is much smaller than that in the north. Therefore, the sensible heat is higher in the north and lower in the south, the contour lines in the north parallel the coastline and the high value region occurs in the Indochina Peninsula (see Fig. 1b).

The first spatial pattern of the net long-wave radiation (Fig. 1c) is similar to that of the latent heat (Fig. 1a) with the high value axis from northeast to southwest and the value decreasing from north to south gradually. The low value occurs in Indonesia. However, the differences in the whole region are small and the distributions are even.

It can be seen from above analyses that the distributions of all the three components are contrary in land and sea. For the latent heat, the high value appears in the sea and the low in the land, the values decrease from north to south in the sea, but from south to north in the land north of 10°N. The distributions of the sensible heat and the net long-wave radiation are opposite as compared to that of latent heat.

The corresponding time coefficients of the first patterns are shown in Fig. 1d (after standardization). The figure reflects the seasonal variation of the latent heat (solid line), the sensible heat (dotted line) and the net long-wave radiation (long dashed line) of the whole region mean. It demonstrates that the seasonal variation of the sensible heat is similar to that of the net long-wave radiation: large in winter half year (the time coefficient after standardization is positive), small in summer half year (the time coefficient after standardization is negative) and mediate value in spring and autumn, with the time coefficient in spring being larger than that in autumn and the evolution being even and continuous. Such single peak feature is related to the SCS monsoon. The features of the SCS monsoon are that the winter monsoon is stronger than the summer monsoon and the air-sea contrast in winter is larger than that in summer. Meanwhile, there is plenty of rain in summer as well as corresponding increase of cloudiness and water-vapor content. Consequently, the feature of the sensible heat and the net long-wave radiation being stronger in winter than that in summer appears.

The seasonal variation of the latent heat has a structure of two peaks, which is *different from that of the above two components. The two peaks are large in winter and* summer and small in spring and autumn with several abrupt increase and decrease in the evolution process. indicating that the seasonal variation is not continuous. The main peak and the secondary peak in winter half year occur in the 1st dekad of December (the 34th dekad) and in the 2nd dekad of January (the 2nd dekad). respectively. which are related to the maximum wind speed in the north of the SCS in December (Yan et al. 1993). February and March are the transition periods from winter to spring. and during this period wind changes from northeastern to southwestern. It is also the period of early preparation for the summer monsoon onset. and the latent heat has two abrupt changes. The smallest value of the whole year takes place in the 2nd dekad of March (the 8th dekad). The latent heat increases steadily from the 1st dekad of April to the 2nd dekad of May. Then. after the 2nd dekad of May. it increases suddenly and at the same time the summer monsoon bursts out. The sudden increase of the wind speed induces the increase of the latent heat. The time coefficient of the latent heat has two obvious peaks. one in the 3rd dekad of June and the other in the 2nd dekad of August. and a weak peak (between them). They are all in agreement with the two peaks of western wind during summer monsoon period (in the 6th pentad of June and the 5th pentad of August respectively. Wang and Ding 1997). It is noticed from above sections that the SCS summer monsoon and the latent heat intensify each other: the SCS summer monsoon onset promotes the rapid increase of the latent heat and the vapor transportations. and the latters provide the sources of heat and vapor to the maintenance of the summer monsoon. In addition. the latent heat over the SCS in winter is stronger than that in summer. which is probably related with the cumulus convective activities triggered by the cold surge in winter (Liang 1991).

From the 3rd dekad of August to the 3rd dekad of September (the 24th — 27th dekad), the latent heat decreases with the weakening and withdrawal of the SCS summer monsoon. After the 1st dekad of October (the 28th dekad). the summer monsoon withdraws from the China Mainland completely. the circulation changes from the summer pattern to the winter pattern and the strong winter monsoon governs the most SCS regions. Consequently. the three air-sea heat exchange components begin to increase.

The contributions of the second eigenvectors of the three components to the total variances are 5%. 15% and 2%. respectively. They are very small and can be considered as the fluctuations upon the climatological fields (figure omitted). The second spatial patterns of the latent heat and the sensible heat are similar to each other. they are positive in the land and larger than that in the sea. The zero contour line of the latent heat parallels the coastline to the north of 5°N. then turns eastward. divides the sea region into two parts with positive in the south and negative in the north in out-of-phase variation with each other. But the zero contour line of the sensible heat is northeastern-southwestern to the north of 10°N. then it turns eastward and forms a contrary distribution with positive in the land and negative in the sea along the east-west direction and with positive in the south of the SCS and negative in the north. the high value region in the Indochina Peninsula.

The values of the second spatial pattern of the net long-wave radiation decrease from south to north. and the northeastern-southwestern zero contour line crosses the ocean basin and the southern end of the Indochina Peninsula. with negative values to the north of the zero contour line and positive values to the south. A low value center occurs in the northwestern coast of the Indochina Peninsula.

The variation tendencies of the time coefficients of the second spatial patterns (after standardization, figure omitted) are all with a single-peak. Among them, the time coefficient of the latent heat leads that of the net long-wave radiation for about one month. Their large value is in summer and small in winter, but the maximum sensible heat occurs in the 2nd dekad of April (the 11th dekad).

The thermodynamic effects of this pattern are that the latent heat in the north of the SCS becomes weaker during the summer period, but stronger in the mainland and the south part of the SCS, the values increase larger in mainland than in the south of the SCS. At the same time, the net long-wave radiation decreases in the northwest of the SCS region (including the land) and increases in the southeast. The contrary case to the above happens in winter. In spring and summer, the sensible heat becomes stronger in the mainland and the low latitude sea regions and weaker in the middle and the north of the SCS. In other seasons, the case is reversed.

2. *The Seasonal Variation Features in Different SCS Regions*

In order to study the seasonal variation features of the air-sea heat exchanges in the different SCS regions, we average the grid values between 100°E and 126°E at the same latitude (The Indochina Peninsula is excluded) to get the mean values of the air-sea heat exchanges at several latitudes, then draw the time-latitude sections as in Fig. 2.

The time-latitude section of the latent heat is shown in Fig. 2a, the obvious feature in Fig. 2a is that the high value regions occur in the north of the SCS in the 2nd dekad of January (the 2nd dekad) and at the beginning of December (the 34th daked), the values are small and slowly changing over there in March — October. Another two high value regions (in the 3rd dekad of June and the 2nd dekad of August) are located in the middle of the SCS (around 11°N). The temperature and the vapor in the south of the SCS are both high throughout the year and less influenced by mainland, so the annual variations of the latent heat are small, but we can still notice that the latent heat in June — September is larger than that in other months.

The maximum value in the high center is >140 W m^{-2} in the summer monsoon and extends to north periodically. Wang and Ding (1997) demonstrated that the SCS summer monsoon bursts out in the middle of the SCS firstly, with two high centers of western wind around 11°N in the SCS in June and August, respectively. Then, they extend to south and north and the extending speed to north is larger than that to south. It is evident that the structures of latitudinal distribution and temporal evolution of the latent heat are similar to that of the summer monsoon.

The development of the two high closed centers of the latent heat around 19°N in the north of the SCS in the winter monsoon is probably related to a strong wind belt from the Taiwan Straits and the Bashi Channel to the west of the Nansha archipelagos (Yan et al. 1993). The maximum values of the above two high centers are both larger than that in the summer monsoon.

When Fig. 2a is compared with the time coefficient curve of the latent heat in Fig. 1d, it is noticed that the general temporal variation features of the latent heat in the SCS in the

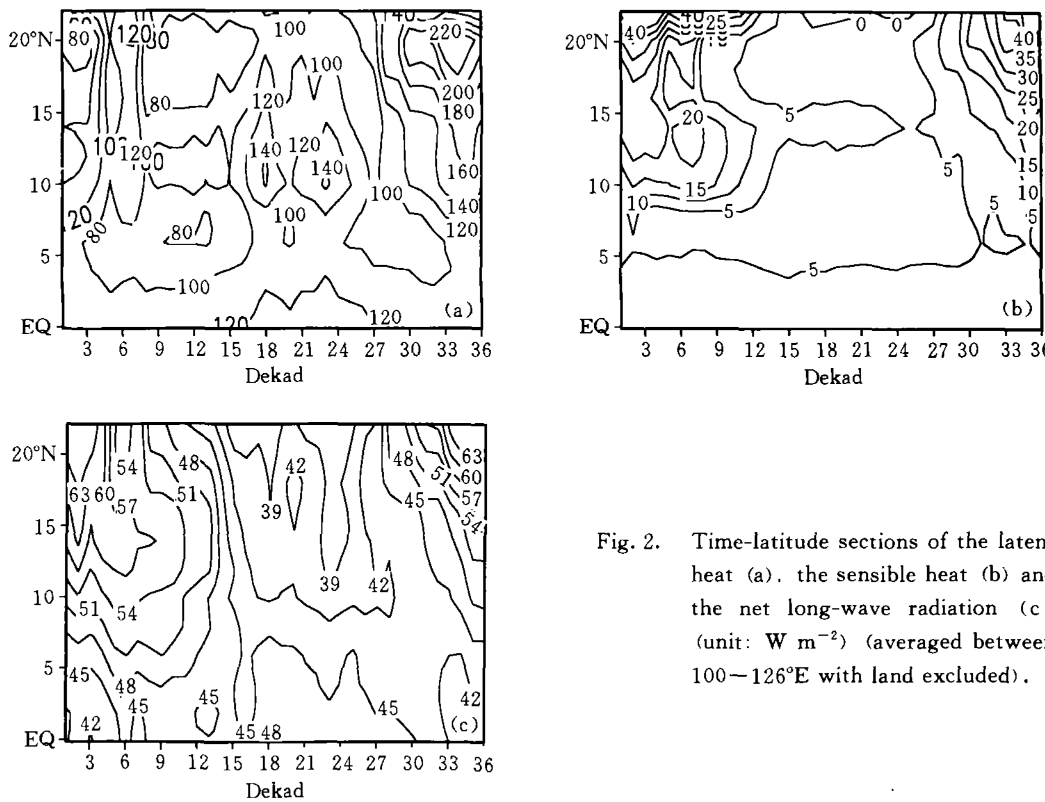

Fig. 2. Time-latitude sections of the latent heat (a), the sensible heat (b) and the net long-wave radiation (c) (unit: W m^{-2}) (averaged between 100—126°E with land excluded).

summer monsoon are chiefly represented by the feature in the middle of the SCS and Indonesia, but by the feature in the north of the SCS in the winter monsoon.

Because the air-sea temperature difference and the SST difference between the south and the north of the SCS are small during the SCS summer monsoon period, the sensible heat (see Fig. 2b) is the lowest at this time and its difference between the south and the north of the SCS is small. The sensible heat to the south of 20°N is $\leqslant 5$ W m^{-2}, but is positive, which means the heat is still from the sea to the air. In the summer monsoon, the negative values occur to the north of 20°N close to the land. In the winter monsoon, due to the influences of the strong wind belt, the ocean current and the mainland, the high value center in the whole sea regions occurs in the north of the SCS and the maximum value is >35 W m^{-2}, with the seasonal variation of the sensible heat being the largest in that area of the SCS. The seasonal variations in the middle and the south of the SCS are not as large as that in the north.

The net long-wave radiation (Fig. 2c) in winter is stronger than that in summer in the SCS except at the low latitude, but the annual amplitude is not large. In the summer monsoon, there are two low value centers (<39 W m^{-2}) in the north of the SCS extending southward to the middle of the SCS. In the winter monsoon, because the air-sea temperature difference in the north of the SCS is large and the moisture content as well as the cloudiness are smaller than that in the south of the SCS, the maximum value of the net long-wave radiation (>66 W m^{-2}) appears in the north. In the low latitude sea regions, the net long-wave radiation in the summer monsoon is a little larger than that in the winter monsoon and that in the middle and the north of the SCS in the corresponding periods.

We can see from the above analyses that the "key region" of the air-sea interaction in the SCS during the summer monsoon period is in the middle of the SCS, while the "key region" during the winter monsoon period is in the north of the SCS. These two "key regions" are both the high value regions of the air-sea heat exchanges during the winter and the summer monsoon periods, respectively, and also the regions with strong annual variations.

3. *Proportions of the Three Air-Sea Heat Exchange Components and Their Seasonal Variations in Different Sea Regions*

For the annual mean (figure omitted), the proportions of the latent heat, the sensible heat and the net long-wave radiation to the total flux are 0.6—0.72, 0.04—0.12, 0.26—0.32, respectively. Therefore, the latent heat is the dominant part.

We can get the time-latitude sections of proportions of the latent heat (a), the sensible heat (b) and the net long-wave radiation (c) by using the same method as in above section (see Fig. 3). Two high regions corresponding to those in Fig. 2a during the summer monsoon period can be seen from Fig. 3a, in which the proportions are larger than 0.75. This demonstrates that along with the increasing latent heat in the middle part of the SCS during the summer monsoon period, the latent heat is also increasing its proportion among the total heat provided by the sea to the air. Therefore the latent heat takes an important position in the air-sea heat exchanges. Together with the SCS summer monsoon the latent heat provides heat and vapor to the air, and such kind of air-sea interactions can not only affect the activities of the synoptic system over the SCS region, but also have certain influences on the weather and climate over the China Mainland.

The proportions of the latent heat in different sea regions during the winter monsoon and the transition periods are not as large as that during the summer monsoon period, but are still more than half of the total heat.

The spatial and the temporal distribution features of proportion of the sensible heat (Fig. 3b) are similar to those in Fig. 2b, the annual variations of proportion in the whole sea regions are all of a single-peak. Its proportion in the summer monsoon is the smallest (<0.03) and much increased in the north during the winter monsoon period with some values larger than 0.15.

A high value region (in the middle and the north of the SCS with the central value >0.4) and a secondary high (in the south with the central value >0.35) of proportion of the net long-wave radiation occur in March—April. Combined with Fig. 2a, we can see that the latent heat at the same time is the lowest in the year, so the thermal effect of the net long-wave radiation on the air seems to be more important during this period than in other seasons. Though the net long-wave radiation increases in winter, the increasing speed is much smaller than that of the other components, leading to the decrease of its proportion. During the summer monsoon period, there are two low value centers at 12°N extending southward and northward (the periods are the 3rd dekad of June and the 2nd dekad of August).

The annual variations of proportions of the three components in the south of the SCS

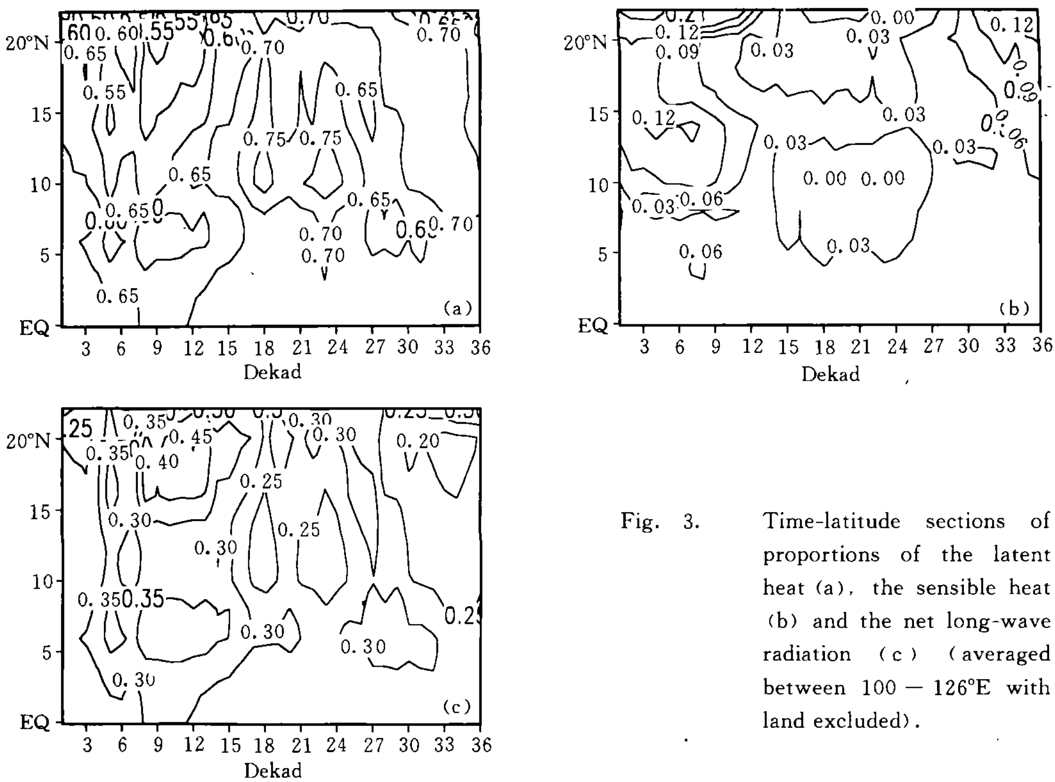

Fig. 3. Time-latitude sections of proportions of the latent heat (a), the sensible heat (b) and the net long-wave radiation (c) (averaged between 100 — 126°E with land excluded).

are not very large. The proportion of the latent heat is about 0. 65. the sensible heat is 0. 03—0. 06 and the net long-wave radiation is 0. 3.

4. *Probable Relationship between Air-Sea Heat Exchanges and the SCS Summer Monsoon Onset*

There are many studies about the features and the mechanisms of the SCS summer monsoon onset at present (Wang and Ding 1997: Yan 1997: Zhu et al. 1997; Xie et al. 1998: Peter and Chang 1997). These studies mainly focused on two parts. one is the variations of the large-scale atmospheric circulation and the atmospheric heat source related to the SCS summer monsoon. the other is the effects of the SCS local conditions on the SCS summer monsoon onset. They showed that the SCS summer monsoon onset is possibly the results of the joint effects of the seasonal process of the large-scale atmospheric circulation. the corresponding atmospheric heat sources and the SCS local conditions. Then. what is the relationship between the air-sea heat exchanges in the SCS regions and the SCS summer monsoon onset? Can the preceding signal of the latter be found from the former? These are the subjects we are interested in.

It is known that the surface sensible heat affects the thermal conditions of the lower atmosphere layer directly. so its horizontally non-uniform distribution must cause the non-uniform thermal conditions of the lower atmosphere layer. and thus affect the thermal contrary between sea and land and promote the development and maintenance of the monsoon circulation. We compare and analyze the seasonal variation features of the sensible heat in the SCS and the Indochina Peninsula. Figure 4 shows that the sensible heat in the Indochina Peninsula increases continuously from 6 W m^{-2} in October, up to about 60 W m^{-2} in the 8th—11th dekad of the second year. The variation tendency of its difference between the Indochina Peninsula and the SCS is similar to above, and the difference increases from −4 W m^{-2} in November to about 50 W m^{-2} in the 8th—11th dekad of the second year. After the 11th dekad, the sensible heat in the Indochina Peninsula and its difference between the Indochina Peninsula and the SCS drop rapidly. It is evident that the thermal contrary between the SCS and the Indochina Peninsula is remarkable, which makes the Indochina Peninsula be a relative heat source compared with the SCS. This thermal effect can affect not only the atmospheric vertical motion, but also its temperature field, causing the horizontal motion to change. This helps to increase the horizontal pressure gradient between the Indochina Peninsula and the SCS and to lead the southwestern air stream into the SCS regions. Therefore, the great difference of the sensible heat between the Indochina Peninsula and the SCS before the SCS summer monsoon onset is possibly one of the triggers of the SCS summer monsoon onset.

The 17-year mean sensible heat from the 10th to 15th dekad in the SCS regions is shown in Fig. 5. We can see that a high value center maintains in the northwest of the Indochina Peninsula from the 10th—13th dekad (the 1st dekad of April—the 1st dekad of May), from the 11th dekad, it begins to decrease, up to the 14th dekad (the 2nd dekad of May), it disappears suddenly. At the same time, the SCS summer monsoon bursts out. Figure 6 is similar to Fig. 5 but for the mean of the years with the later summer monsoon onset among the 17 years (1982, 1983, 1987, 1991, 1992, 1993, 1995; Xie et al. 1998). Compared with the climatic mean in Fig. 5, the high value center in the northwest of the Indochina Peninsula in the 12th dekad does not decrease compared with that in the 11th dekad. Up to the 13th dekad, it decreases to some extent, but is still stronger than that of the climatic mean. Up to the 14th dekad, there still exists a weak center in the northwest

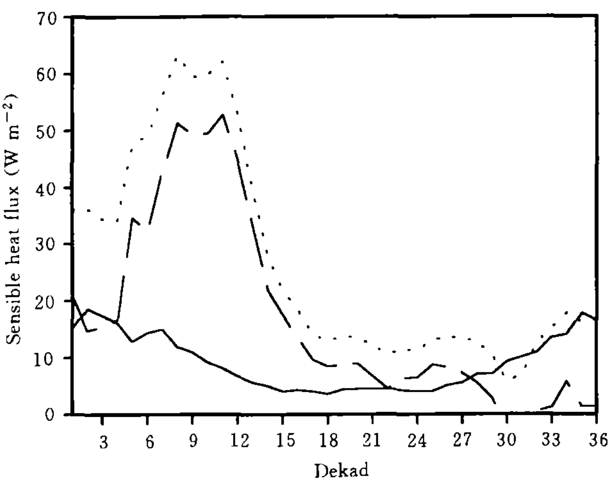

Fig. 4. Seasonal variation of the sensible heat flux (unit: W m^{-2}). The dotted line, solid line and long dashed line indicate the Indochina Peninsula, the SCS, the difference between the Indochina Peninsula and the SCS respectively.

of the Indochina Peninsula (at this moment, the high center of the climatic mean disappeared already). it disappears in the 15th dekad, one dekad later than that of the climatic mean. We can also notice from Fig. 5 and Fig. 6 that the variation is not very large

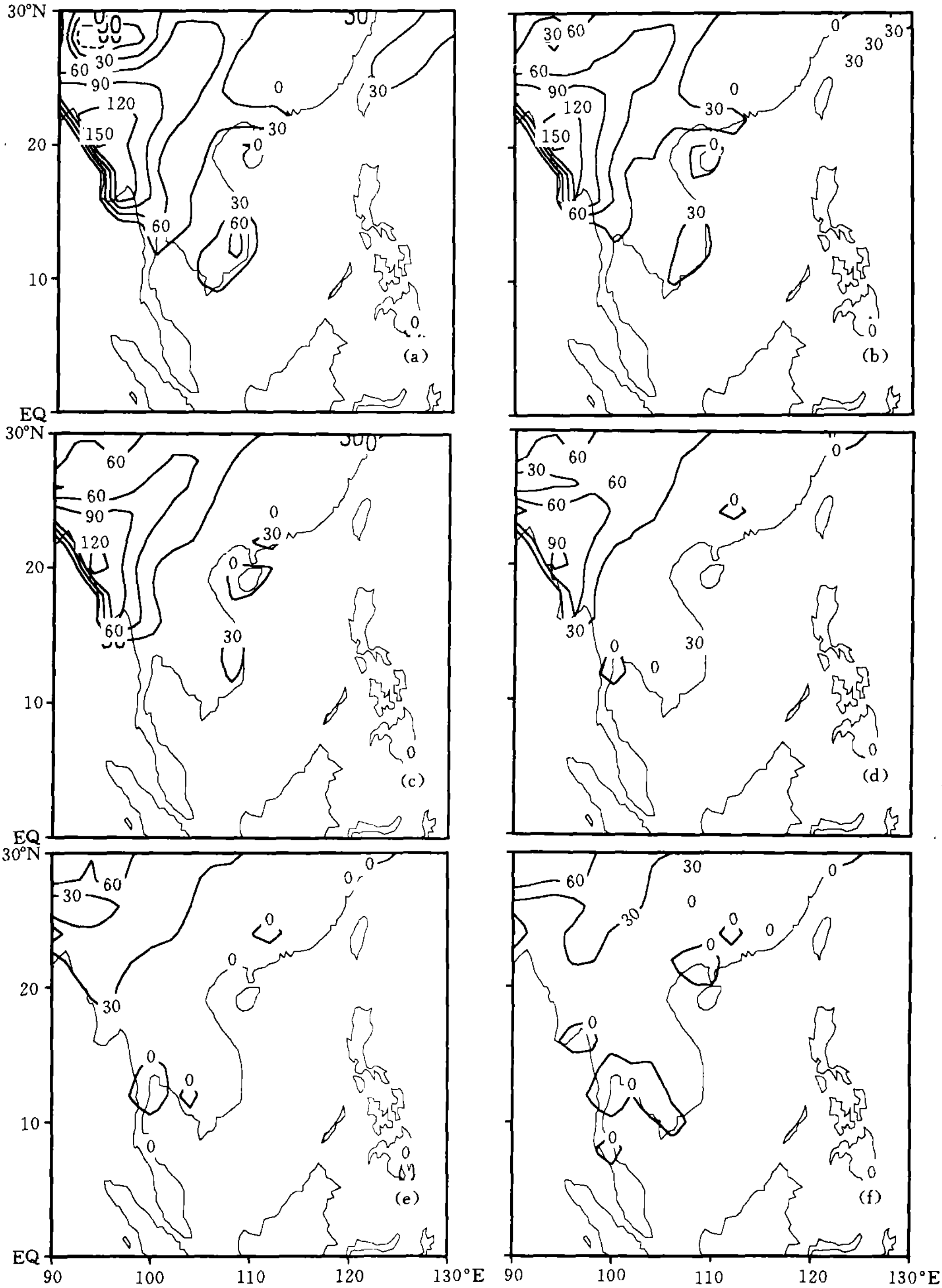

Fig. 5. Climatic mean sensible heat flux from the 10th to the 15th dekad (a—f) (unit: W m^{-2}).

in the sea before and after the summer monsoon onset. It is obvious that as far as the SCS local conditions are concerned, the northwest of the Indochina Peninsula is probably the sensitive region to the SCS summer monsoon onset, and the land may play a leading role in

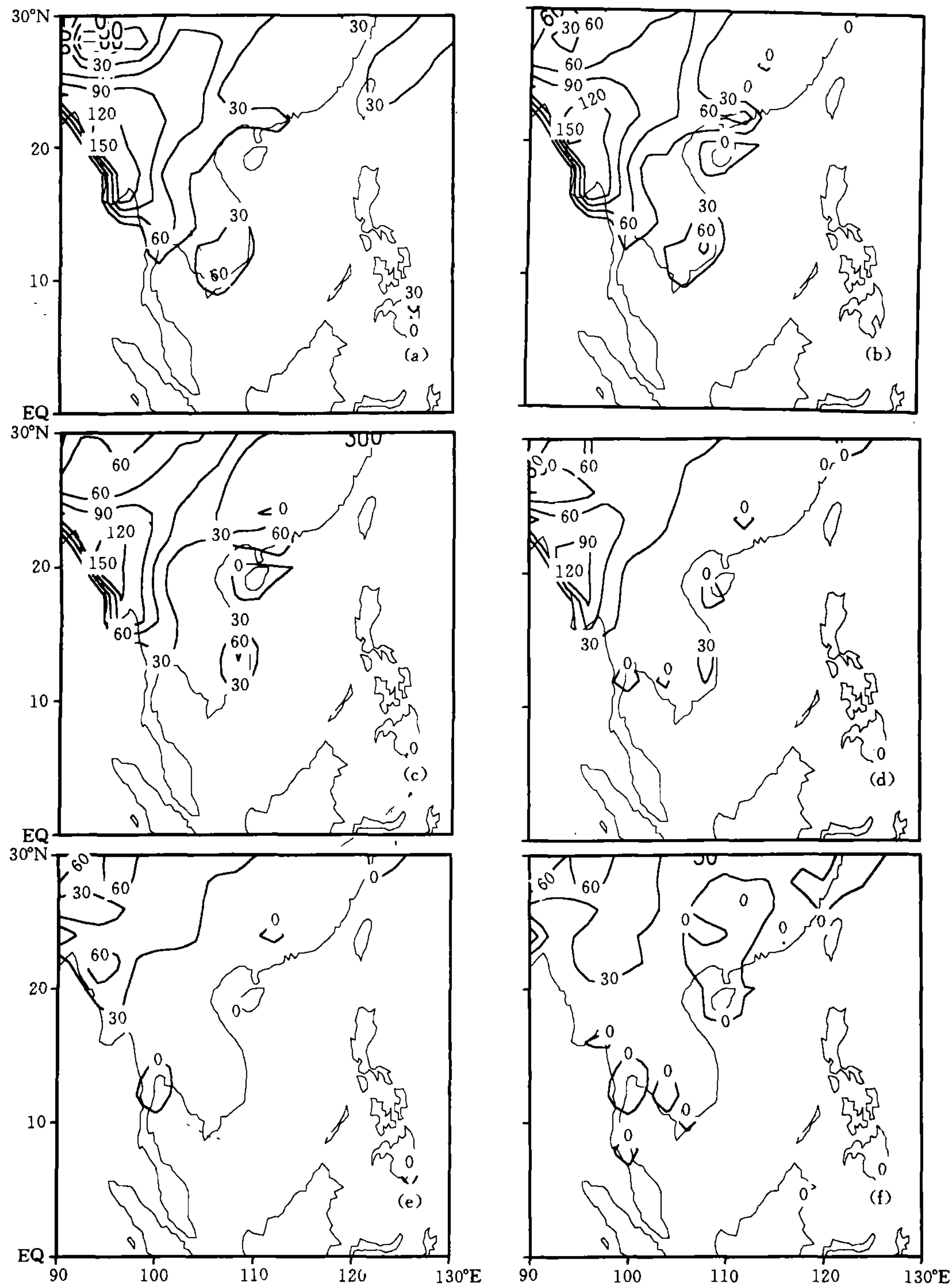

Fig. 6. As in Fig. 5, but for later summer monsoon onset years.

the SCS summer monsoon onset. The inherent mechanism process can be discussed by the numerical simulation which will be our future studies.

IV. CONCLUSIONS

(1) The 17-year mean fluxes of the latent heat, the sensible heat and the net long-wave radiation in the SCS are all from sea to air, the latent heat is the largest, the net long-wave radiation the second and the sensible heat the smallest among the three components. The EOF results show that the three components have different spatial distributions and different seasonal variation features.

(2) The seasonal variation features of the air-sea heat exchanges of the three components in different sea regions are different. The middle and the north of the SCS are the high value regions during the winter and the summer monsoon periods, respectively, and are also the strong annual variation regions. The seasonal variation of air-sea heat exchanges in the south of the SCS is small.

(3) The proportions of different components in the total air-sea heat exchanges have different seasonal variations in different regions. The proportion of the latent heat exchange in the middle of the SCS is the largest during the summer monsoon period, while the heating effect of the net long-wave radiation on the air seems to be more important in March and April than that in other seasons. The proportion of the sensible heat becomes a little larger only in the north of the SCS during the winter monsoon period.

(4) The relationship between the SCS summer monsoon and the air-sea heat exchange is accompaniment, they are mutually dependent and promote each other. Before the SCS summer monsoon onset, the great difference of the sensible heat between the Indochina Peninsula and the SCS is possibly one of the triggers of the SCS summer monsoon onset. As far as the SCS local conditions are concerned, the northwest of the Indochina Peninsula is probably a sensitive region to the SCS summer monsoon onset, and the land may play a leading role in the SCS summer monsoon onset.

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