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A Case Study on a Strong Tropical Disturbance and Record Heavy Rainfall in Hat Yai, Thailand during the Winter Monsoon

Angkool WANGWONGCHAI*[1,2,3], ZHAO Sixiong[2] (赵思雄), and ZENG Qingcun[2] (曾庆存)

[1] *Department of Mathematics, King Mongkut's University of Technology Thonburi, Bangkok* 10140, *Thailand*

[2] *Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[3] *Graduate School of Chinese Academy of Sciences, Beijing* 100039

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ABSTRACT

The evolutionary process and structural characteristics of the atmospheric circulation and synoptic situation which caused the record heavy rainfall with a precipitation amount of 550 mm in Hat Yai, Thailand from 20 to 23 November 2000 is studied. In the study, the modern three dimensional observational data were collected as completely as possible, and detailed analyses were made. It is revealed that the cold surges of the Asian winter monsoon that originate from Siberia can arrive at the lower latitudes, including South Thailand, Malaysia, Indonesia, cause strong heavy rainfall there, and interact with weather systems in the near-equatorial regions of the Southern Hemisphere. This is strongly supported by Chinese scientist's original finding in 1930s. The strong convective cloud clusters in the above areas are generated by the direct influence of the cold surges, and are related with the South China Sea disturbances in the lower troposphere. The maximum of the convergence of total moisture flux near South Thailand in the situation under study implies that the water vapour supply is abundant and very favorable to the occurrence of the heavy rainfall. The release of latent heat enhances the Hadley Circulation also. The feedback of the strong severe weather on climate indeed exists, and there are pronounced interactions between the multi-scale systems and between both hemispheres.

Key words: Hat Yai, Thailand, heavy rainfall, Hadley circulation

1. Introduction

It is well recognized that the Asian countries are significantly influenced by the summer monsoons (the complex systems consisting of the East Asian monsoon and the Indian monsoon) due to their interannual variabilities of precipitation and their products such as the water supply and disasters (flooding and drought). Therefore, the summer monsoons have been and still are quite interesting research subjects in the world meteorological sciences. At present, the general features of the summer monsoons have been revealed to some extent. In particular, the advance and retreat of the summer monsoons and the associated heavy rainfall have been intensively investigated (see for example, Chu, 1934; Tu and Huang, 1944; Ramage, 1971; Huang and Tang, 1987; Tao and Chen, 1988; Ding, 1994; Zeng et al., 1994; Zeng and Li, 2002; Zhao et al., 2004).

In contrast, the Asian winter monsoon has been intensively investigated only during the cold air outbreaks and their associated significant weather events such as strong cold fronts, high winds, abrupt temperature drops and intensive cyclones in the East Asian continent, Korea and Japan (Ding and Krishnamurti, 1987). There is only scarce knowledge about cold surges which are the systems following the cold outbreaks. Chang and Lau (1980) observed that the arrival of the surges may consist of two steps: the edge passage of the high-density cold-air current reflected by a drastic increase in surface pressure ($p_{\rm s}$), and the thermal frontal passage indicated by a sharp drop in dewpoint ($T_{\rm d}$). The separation time between these two steps becomes large in the downstream tropical areas (Chen et al., 2002). Even very few investigations can be found in the literature about the behavior of the winter monsoon in the low latitudes,

*E-mail: angkool.wan@kmutt.ac.th

although early in 1936 there was a detailed analysis of very few and incomplete but very valuable data at that time. Li (1936) was able to reveal the fact that the strongest cold air outbreak from Siberia can reach Southeast Asia, even passing across the equator and causing severe weather there; and similar phenomena can be found after the strongest cold air outbreak from Australia, influencing the typhoon formation in the western Pacific Ocean areas. For a long time after Li, there was almost no deep research work on such extreme events due to the lack of observations and data.

In order to have a better understanding of the winter monsoon in the low latitudes, the winter phase of the Monsoon Experiment (WMONEX) was conducted and extended from 1 December 1978 to 5 March 1979. During the month of December, a major intensive observation period was mounted and some results were reported (WMONEX; Greenfield and Krishnamurti, 1979).

The main goals of WMONEX aim at the clarification of some main scientific problems regarding the Asian winter monsoon, for example, (1) the general circulation during the winter monsoon and its variations; (2) the structure and the energetics of the cold surges; (3) the interaction between multi-scale systems and/or the interaction between both hemispheres, if they exist; (4) the impact of cold surges on the severe weather, especially in lower latitude areas. After the implementation of WMONEX, many serious research works have been undertaken to address the above problems.

For the first problem, Murakami (1979) studied some characteristic features of cold surges during northern winter using wind and temperature data over China, the East and South China Sea, and so on. The 20–30-day oscillations were discussed. Sumi and Murakami (1981) studied the large-scale aspects of the 1978–79 winter circulation over the greater WMONEX region.

For the second problem, Lau and Lau (1984) studied the structure and energetics of midlatitude disturbances accompanying the cold-air outbreak over East Asia.

For the third problem on the multi-scale interaction and tropical-midlatitude interaction, a summary of pre- and post-WMONEX research of cold surges, especially the tropical-midlatitude interaction, was given in a comprehensive review by Lau and Chang (1987). It should be emphasized that pre- and post-WMONEX research focused primarily on the interaction between the East Asian cold surge and the planetary-scale circulation, particularly on the enhancement of tropical convection, the intensification of the local Hadley circulation, and the speed increase of the East Asian jet caused by the cold surge.

For the fourth problem, Lau and Lau (1984) investigated the structure and energetics of the cold-air outbreak over East Asia. Ding and Krishnamutri (1987) analyzed the heat budget of the Siberian high during the winter monsoon. Li and Zhao (1996) explored the structure and dynamics of the strong cold front in East Asia during the cold season. Chen et al. (2002) performed a case study of an East Asian cold surge. Zhao et al. (2002) studied the snowfall in Northern China in December 2001. However, so far, the research has mostly been concentrated on East Asia, the Northwest Pacific and the South China Sea. In the Indo-China Peninsula, especially in Thailand and Malaysia, only very few studies on the cold surge impact were reported. It should be pointed out, unfortunately, that during WMONEX, especially in December, the winter monsoon was weaker and precipitation lower than normal in the low latitudes, and a moderate/weak northeast monsoon flow was steady throughout. No deep surge vortex formed, but frequent eddies over the South China Sea were observed (Greenfield and Krishnamuti, 1979). So no severe weather system was observed in Southeast Asia during WMONEX, so that some aspects of the aforementioned four scientific problems still need to be clarified, especially the last two problems. Since WMONEX, especially in the last 15 years, more and more observation networks and meteorological satellite techniques have been developed, and many strong disturbances with associated severe weather such as that originally revealed by Li (1936) have occurred. Investigations of these weather systems are not only of scientific interest but also of practical importance.

In this paper, a typical case of a strong disturbance with very heavy rainfall is investigated. During the last ten days of November 2000, a strong heavy rainfall occurred in Hat Yai (the location is shown in Fig. 6), Songkhla province and produced serious flooding. A precipitation amount of 549.4 mm was reported there during the days from 20 to 23 November. There were 81.5, 219.4, 146.3 and 102.2 mm per day on 20, 21, 22, and 23 November, respectively. The monthly mean precipitation amount in November for 1973–2003 at Hat Yai was 307.1 mm, whereas the precipitation amount in November 2000 at Hat Yai reached 926.9 mm, which is 619.8 mm more than the average during the above-mentioned 31 years (1973–2003). People, livestock, farmland, houses and public utilities were seriously affected by this flood. According to the official statistics, the total damages in Songkhla province were about 46 million US dollars. It was one of the most serious floodings in the history of Thailand.

For a better understanding of the occurrence of the heavy rainfalls, its circulation characteristics, and related weather systems, analyses are conducted in this paper using the data from 73 surface stations, 5 upper air soundings in Thailand, and hourly GMS satellite images, NCEP reanalysis data, and surface maps of the China Meteorological Administration.

2. Climatological background in Thailand

Thailand is located in the central southern part of the Indo-China Peninsula. The majority of the country belongs to the tropical monsoon climate. There are three seasons: mid October to mid February of the next year is the "dry season", mid February to mid May is the "hot season", and mid May to mid October is the "rainy season". The yearly mean precipitation amount ranges from 1000 to 2000 mm, and there is more than 3000 mm per year in the mountainous and coastal areas. It should be emphasized that precipitation is quite varied among various areas in Thailand. The above-mentioned situations exist mainly in central and northern Thailand. However there is another picture of the seasonal variation of precipitation in southern Thailand, especially in the area next to Malaysia. The monthly mean precipitation climatology over 31 years (1973–2003) of Hat Yai is given in Fig. 1. It can be seen that the heavy rainfalls occur there during the winter monsoon season, strong heavy rainfall appears in November with a monthly value of 307.1 mm, and on average, the winter monsoon rainfall is greater than the summer monsoon rainfall in this area. This means that the climate there is different from that in central and northern Thailand.

There are also pronounced interannual variabilities in climate during the winter monsoon, especially in precipitation. For example, a total monthly rainfall amount of 926.9 mm at Hat Yai Airport station (6.91°N, 100.43°E) in southern Thailand was reported in November 2000, which was about three times greater than climatological mean (307.1 mm).

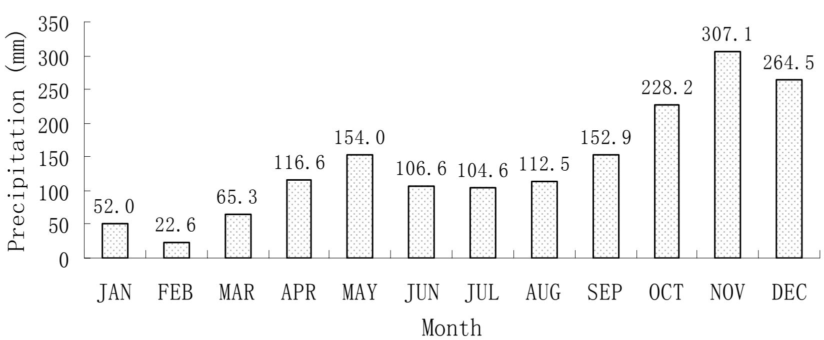

Fig. 1. Monthly mean precipitation (mm) over 31 years (1973–2003) at Hat Yai Airport station.

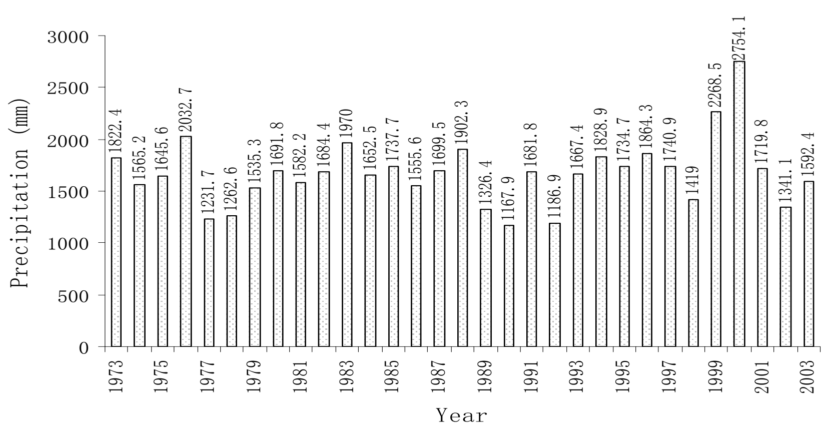

Fig. 2. Annual total precipitation (mm) during 1973–2003 at Hat Yai Airport station.

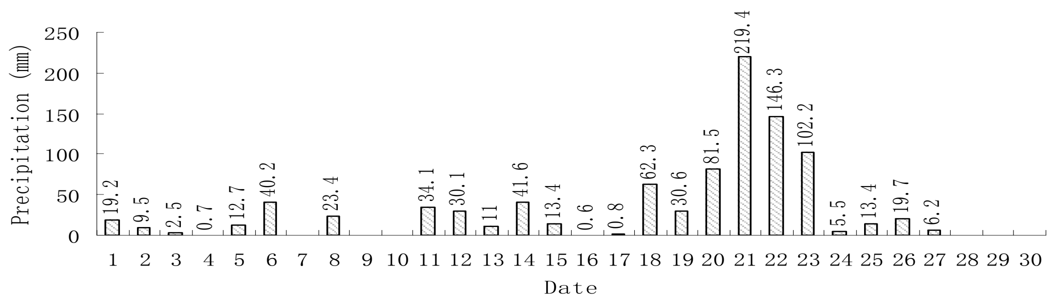

Fig. 3. Daily precipitation amount (mm) in November 2000 at Hat Yai Airport Station.

The annual total precipitation during 1973–2003 is given in Fig. 2. It can be seen that the minimum of annual total precipitation (1167.9 mm) occurred in 1990, and the maximum of annual total precipitation (2754.1 mm) occurred in 2000. This implies that the influence of the winter monsoon is very significant.

It should be noted that due to the interannual variability of the winter monsoon (Zhang et al., 1997), the maximum rainy month can be different from year to year. 38.71% of the time it is November, 29.03% of the time December, and 22.58% of the time October, but it is never January nor February, the months with predominately strong northeast wind during the winter monsoon.

This implies that the strong heavy rainfall in southern Thailand and Malaysia is related not only to the terrain distribution, but mostly with the atmospheric general circulation variation in various years. The cold air just arriving at southern Thailand in early part of the winter season and the small vortex (disturbance) triggered by the northeast wind (cold surge) may be the main factors causing the heavy rainfalls during the winter monsoon in Southeast Asia.

3. A record heavy rainfall in Hat Yai, Thailand

As mentioned in the past section, there was a record annual total precipitation of 2754.1 mm at Hat Yai in 2000. In association, there was also a record monthly precipitation amount of 926.9 mm in November, which was 619.8 mm more than the 31-year average (1973–2003). In particular, very strong and very heavy rainfalls during the three days from 21 to 23 November approached 500 mm in total, which is already larger than the climatological monthly mean of 307.1 mm for November.

Figure 3 shows the daily precipitation amount in November 2000. It can be seen that a pronounced raining weather lasted from 18 to 23 November with a maximum daily precipitation of 219.4 mm on 21 November.

In this paper, we will make a detailed case study of this event of record heavy rainfalls.

4. The large scale weather system during heavy rainfall in southern Thailand

First of all, we would like to note that the primary objective of the Winter Monsoon Experiment (WMONEX) was to investigate the structural features of low-level monsoonal surges and the mechanisms that are responsible for the development of near-equatorial disturbances over the Malaysia-South China Sea region. Since these regional monsoon phenomena are intimately related to the large-scale aspects of the winter circulation over a much more extensive area, the greater WMONEX region was defined as extending from the Arabian Sea and Indian Ocean to the central North and South Pacific, between 40°N and 30°S. Most of the previous synoptic studies over the greater WMONEX region have focused on the large-scale aspects of the winter monsoon circulation.

Southern Thailand and Malaysia are located very near the equator. Therefore, the circulation is quite different not only from that in the middle latitudes, but also from central and northern Thailand in the tropical region. In this area, the pronounced characteristics are the interaction between the Northern and Southern Hemispheres.

The China Meteorological Administration surface weather map at 0000 UTC 22 November 2000 (Fig. 4) shows that there was a cold air mass in middle latitudes moving southward to the lower latitudes. It was a typical cold surge.

The associated streamline and temperature distribution at 850 hPa are shown in Figs. 5 and 6 respectively. These figures were constructed are made by us using the NCEP data. It can be seen from these charts that in the middle latitude area, a related anticyclone associated with the high pressure existed in China, Korea and Japan. A northeast current from the east edge of the anticyclone passed through the

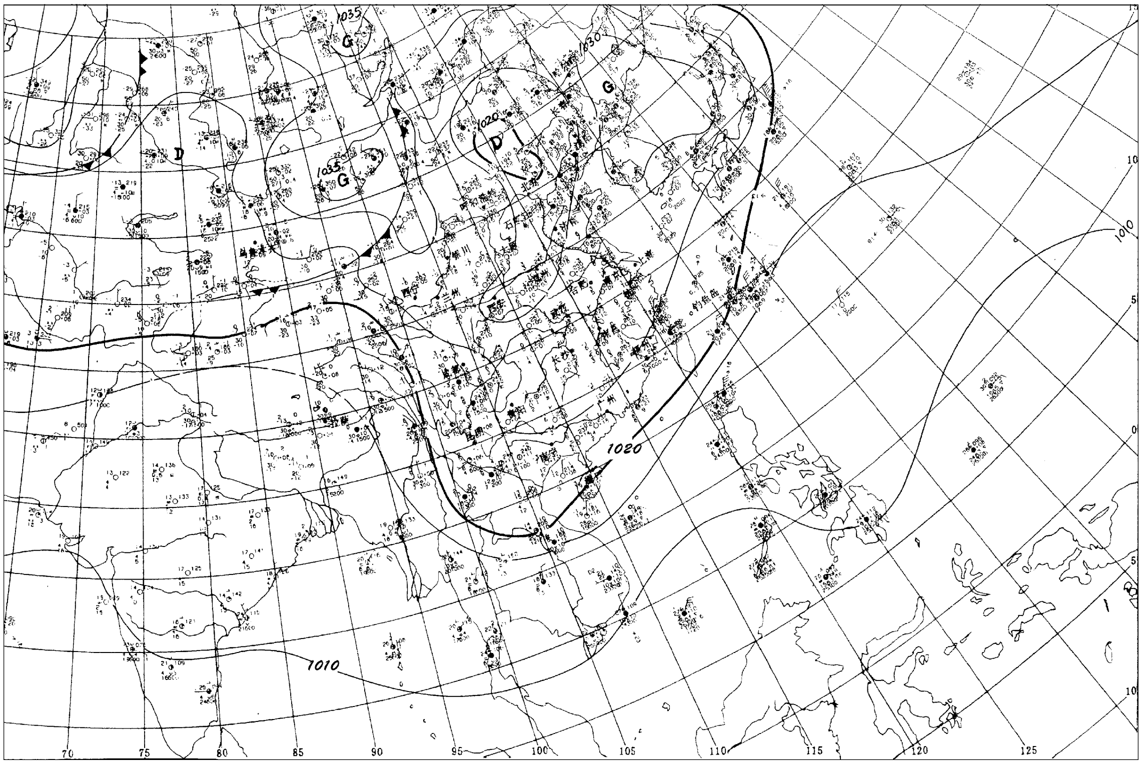

Fig. 4. Surface weather map (by the China Meteorological Administration) at 0000 UTC 22 November 2000 (G: high pressure area, D: low pressure area)

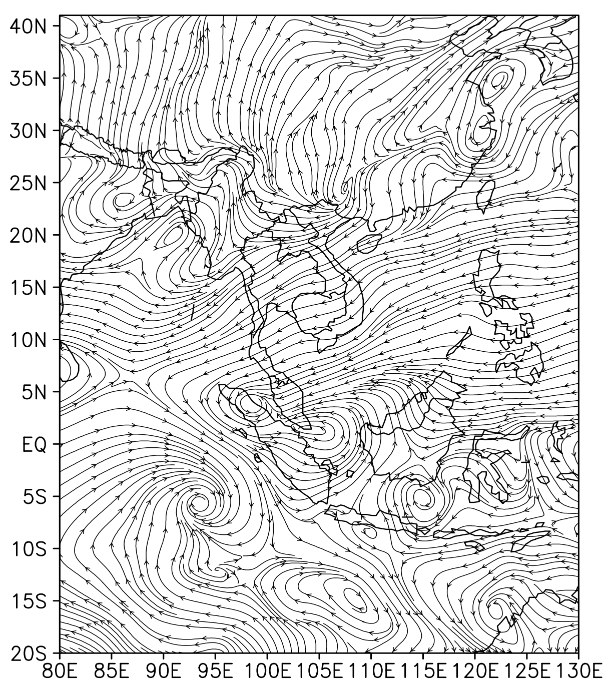

Fig. 5. 850 hPa streamlines at 0000 UTC 22 November 2000.

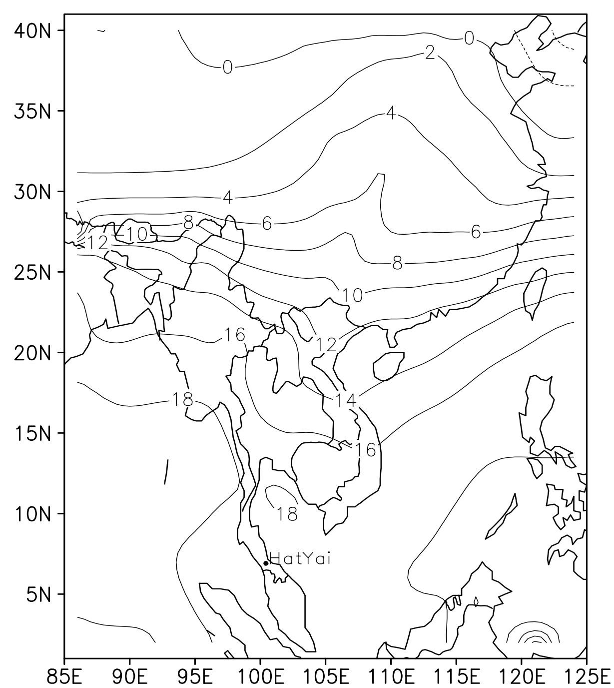

Fig. 6. 850 hPa temperature (°C) at 0000 UTC 22 November 2000.

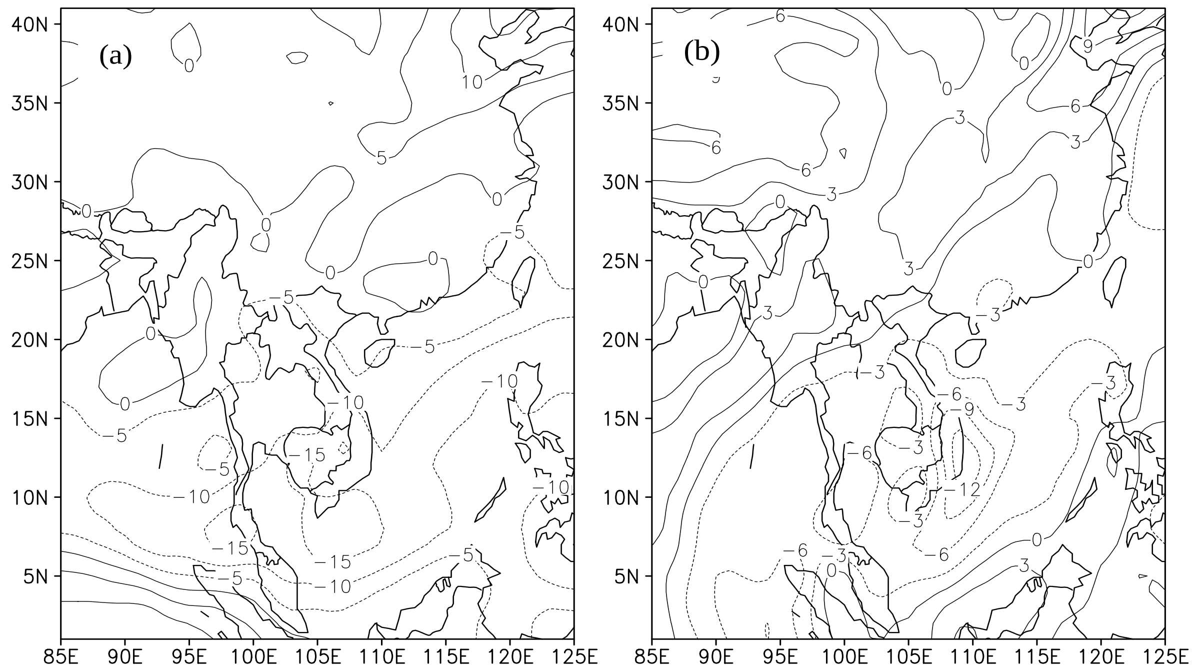

Fig. 7. 850 hPa speed (m s^{-1}) of the wind components at 0000 UTC 22 November 2000, (a) zonal wind (positive–west wind); (b) meridional wind (positive–south wind).

East China Sea, South China Sea, Indo-China Peninsula, and then to the Bay of Bengal. It turned into a northwest current at 5°N and then produced cyclonic disturbances between Malaysia and Sumatra. These are just the weather systems bringing heavy rainfall there. It should be noted that the cold surge during these days was stronger, and at the same time, a cross-equatorial current was extended and entered into the Northern Hemisphere. The cyclonic disturbance was associated closely with the above-mentioned two currents from the two hemispheres. This is very similar to that described in Li's (1936) paper.

From the u and v component wind field as shown in Figs. 7a and 7b, the northeast winds prevailed in the Northwest Pacific, South China Sea and the Indo-China Peninsula. This implies that the stronger cold air broke. The maximum of the eastern wind was in South Vietnam, between 7° and 10°N, around 106°E, with a wind speed of around 15 m s^{-1}, whereas the maximum of the northern wind was between 10° and 15°N, around 110°E, with a wind speed reaching 12 m s^{-1}. The above-mentioned strong wind area was just located east of the heavy rainfall area in South Thailand. In the south of the strong northeast wind, a west and a south wind prevailed in Sumatra and Borneo. The significance convergences were shear zone form and intensify between the northeast and southwest winds. There was a very favorable area where the convergence systems and disturbances in the wind fields formed.

It is also found that the cold surge was very shallow in the vertical, on average less than 1.5 km, hence it can only be seen at 850 hPa and lower. The shallower part was cold air which moved southward. It can be seen in Fig. 6 that the cold air pushed down along the east coast of China, passed through South China, and entered into the Indo-China Peninsula. In comparison with the Philippines on the east side and the Bay of Bengal on the west side, the temperature of the Indo-China Peninsula was lower, with the 16°C isotherm reaching to 14°N.

As can be seen in Fig. 8b at 700 hPa, instead of northeast flow of a cold surge, there was a tropical easterly wind coming from the low latitudinal Pacific Ocean to the South China Sea, and a street of narrow elongated anticyclones which extended from Taiwan Island of China to northern Thailand and the Bay of Bengal. This anticyclonic street separated the circulations of the westerlies from the tropical ones. In addition, streamlines at higher levels, i.e., at 200 hPa in Fig. 8a, show that there was an anti-cyclonic system centered over the Philippines. It covered the Northwest Pacific, South China Sea and Indo-China Peninsula. The east current on the south of the anticyclone diverged significantly. The east current was divided into two sub-currents. One sub-current turned to be strong and northward first and occupied the whole

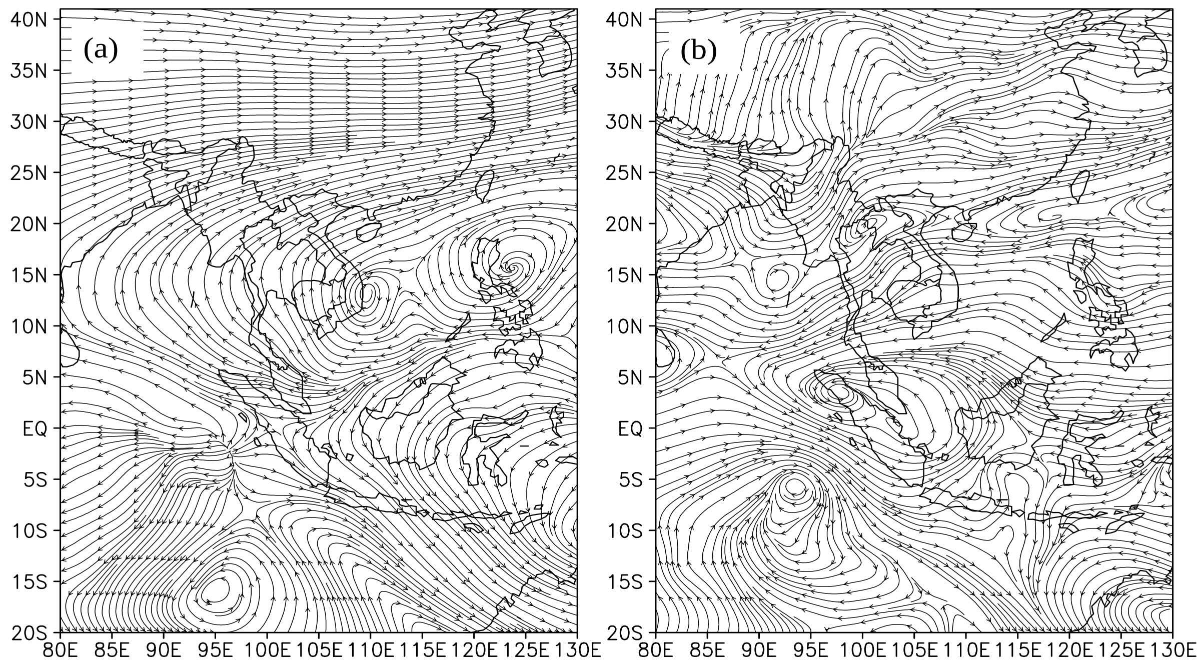

Fig. 8. 0000 UTC 22 November 2000 streamlines at (a) 200 hPa ; (b) 700 hPa.

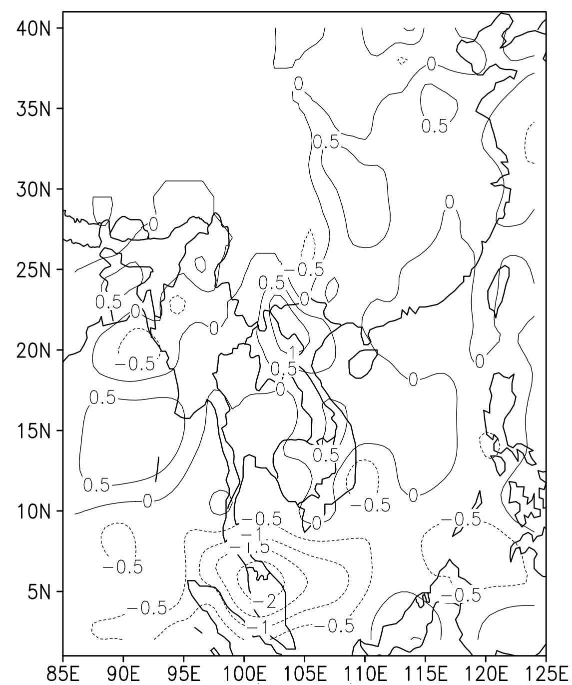

Fig. 9. 850 hPa divergence field (10^{-5} s^{-1}) at 0000 UTC 22 November 2000.

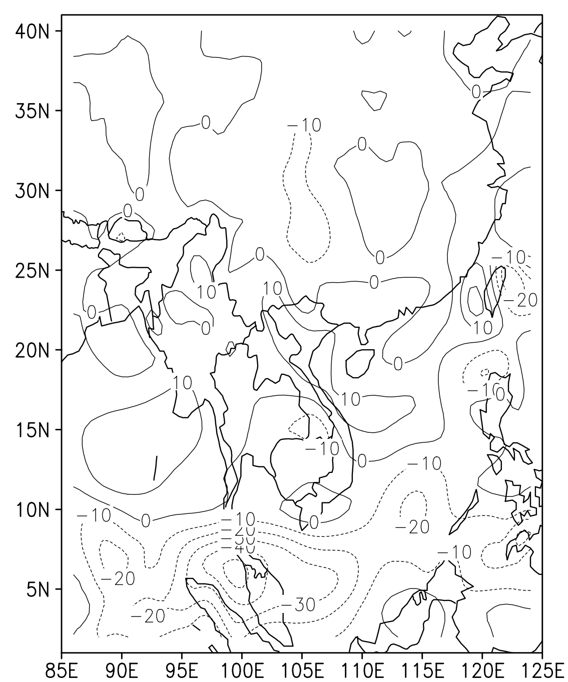

Fig. 10. Divergence of total moisture flux (kg m^{-2} day^{-1}) in the vertical column at 0000 UTC 22 November 2000.

Indo-China Peninsula, Malaysia, and the Bay of Bengal, and then turned to South China. The other subcurrent along the south-southwest crossed the equator to enter into the Southern Hemisphere. The strong divergence zone between the above-mentioned two subcurrents was just located to the east of the Malaysian

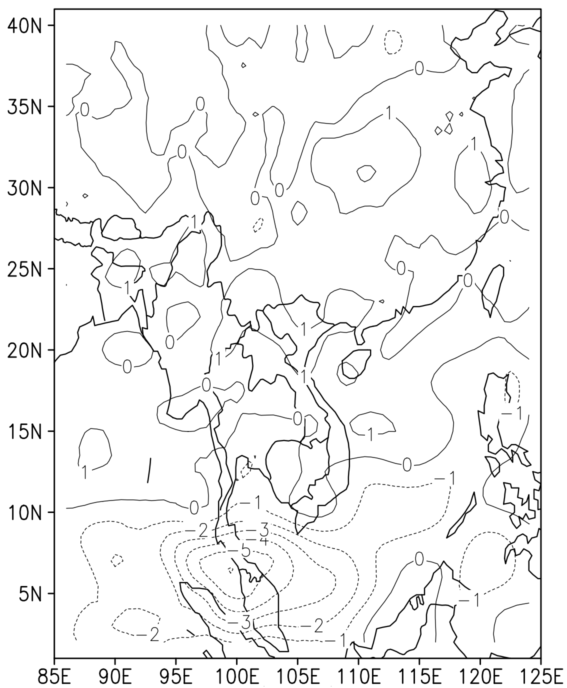

Fig. 11. 500 hPa vertical motion (10^{-1} Pa s^{-1}) at 0000 UTC 22 November 2000.

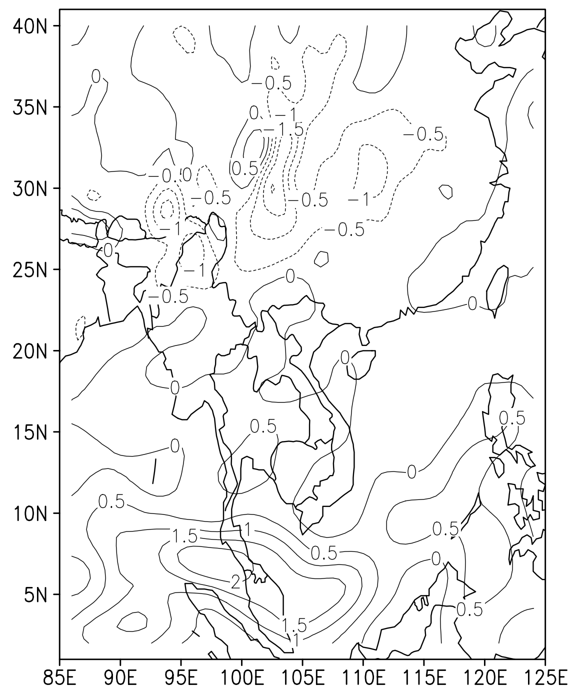

Fig. 12. 200 hPa divergence (10^{-5} s^{-1}) at 0000 UTC 22 November 2000.

Peninsula.

This vertical structure clearly shows the strong interactions of westerlies with tropical circulations, and the weather systems there were of mixed type. In particular, during the winter monsoon in the Northern Hemisphere, the strong northeast wind in the lower troposphere can arrive at lower latitudes. At the same time, due to the effect of the northeast trade wind, the equatorial west wind and cross-equatorial current can come together, and some complex situations can appear, even producing mesoscale vortexes that bring about serious damages.

From Figs. 5 and 8b, it can be clearly seen that there were two mesoscale vortexes located between the Malaysian Peninsula and Sumatra Island at 850 hPa, but they were combined as a large-scale cyclone at 700 hPa. The vortex system was associated closely with the convergence zone at 850 hPa (Fig. 9). The maximum of convergence at 850 hPa was in the east part of the vortex rather than in the central area. It is well understood that precipitation intensity depends on two factors, water vapor supply and upward motion. For this reason, the supply ability rather than the transportation ability of the water vapour is calculated.

Figure 10 gives the distribution of divergence of total moisture flux in the air column at 0000 UTC 22 November 2000. A negative value means the convergence of moisture flux and water vapour supply is positive. It is revealed that there was a convergence zone of moisture flux south of 10°N, with the maximum in South Thailand and the Malaysian Peninsula. Therefore, much moisture was concentrated in the abovementioned area, and it provided the very favourable condition for heavy rainfall.

However, only the condition of the water vapour is not enough. As mentioned before, the other important factor associated with heavy rainfall is strong upward motion which transports the water vapor to the middle and upper troposphere, causes condensation, and finally, precipitation. Figure 11 gives the vertical motion at 500 hPa for 0000 UTC 22 November 2000. It is seen that there was also an upward motion area south of 10°N, where the center of strong upward motion was very close to the maximum of convergence of total moisture flux. In this situation, it can be understood that the two factors were both very favorable to the strong precipitation in South Thailand and North Malaysia.

Generally speaking, a strong convection is always characterized by strong convergence in the lower troposphere and strong divergence in the upper part. This feature is also very pronounced in our case. As seen in Fig. 12, a strong divergence zone at 200 hPa existed, south of 10°N, with the maximum just in South

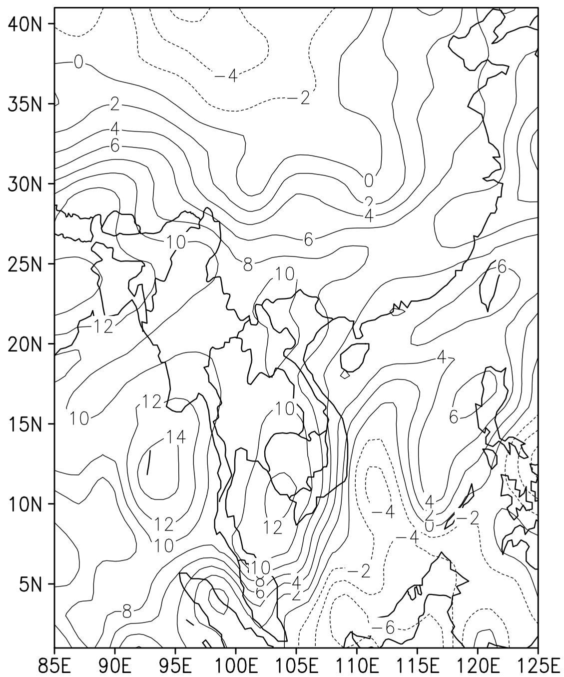

Fig. 13. 200 hPa meridional wind (m s^{-1}) at 0000 UTC 22 November 2000.

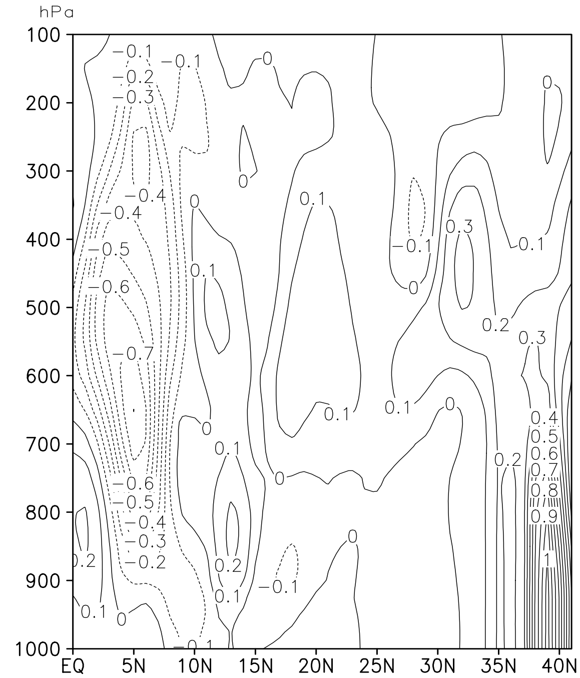

Fig. 14. Vertical cross section of vertical motion (10^{-1} Pa s^{-1}) along 100°E at 0000 UTC 22 November 2000.

Thailand and North Malaysia.

5. The tropical Hadley circulation and the interactions between middle and low latitudes

The strong convective activities in the lower latitudes triggered by the cold surge not only produce severe weather in the tropical region, but can also give feedback to the tropical atmospheric general circulation, and they probably enhance the Hadley circulation. To better understand this feedback, it is convenient to calculate the meridional wind first and then combine it with the vertical motion to obtain the picture of the Hadley circulation.

Figure 13 shows the distribution of the meridional wind at 200 hPa for 0000 UTC 22 November 2000. The very significant feature is that there exists a strong southerly wind from the Malaysian Peninsula, through the Indo-China Peninsula, then South China, East China to Japan. On the contrary, it can be seen that there is a stronger northerly wind in the lower troposphere in the above-mentioned region (Fig. 7b).

The vertical cross section of the vertical motion along 100°E is shown in Fig. 14. It can be seen that the boundary between the downward motion north of it and the upward motion south of it is around 10°N. The completed figure of the triggering of the cold surge to the convection activities and enhancing Hadley circulation can be seen in Fig. 15a. The comparison between Figs. 15a and 15b shows clearly that the intensive weather systems triggered by the strong cold surge very much enhance the regional tropical Hadley circulation. This is one kind of interaction between the middle and low latitudes as mentioned by Lau et al. (1983) and Yen and Chen (2002).

Pearce (1988) pointed out that the cold surge from East Asia triggers the convective activities not only over the ocean to the northwest of Borneo, but also in North Malaysia, Indonesia, New Guinea, and North Australia. Therefore, these areas become the strongest of the three heavy rainfall areas in the global tropical zone (the other two centers are located in Africa and South America, respectively). Due to the occurrence of the convection and precipitation, water vapor condenses and the latent heat releases so that a heat source is formed in this region, thus playing an important role in the global heat budget.

It can be found from the climatological maps that during the winter monsoon (December–February), the rainfall amounts are substantially larger over the Malaysia-Indonesia region as compared to other tropical regions. This region can be identified as a primary energy source region. The experiences of meteorologists in these regions tell us that the majority of occasions of heavy rainfall over Malaysia and the South China Sea are due to tropical disturbances developing along the low level, near the equatorial trough around 5°–10°N. These disturbances are possible when the northeast trades are sufficiently deep and broad, surging south-southwestward from north of the South China Sea and eventually merging with the near-equatorial trough and the equatorial westerlies. The case under our study is a very typical example. Energy derived from the rains may then act to keep the local Hadley circulation vigorous. Despite the fact that violent tropical storms or other vigorous disturbances are extremely rare over the Malaysia-South China Sea region, the winter monsoon circulation undergoes rather drastic changes in association with phase changes between wet and dry spells, which are similar in some respect to the "active" and "break" conditions during the summer monsoon.

6. The release of latent heat and the warming of the atmosphere

To clarify the dynamical and thermodynamical characteristics, the upper air sounding data at Songkhla Station (about 36 km away from Hat Yai Airport Station) are analysed. There are five upper air sounding stations in Thailand. They are Chiang Mai, Ubon Ratchathani, Bangkok, Phuket and Songkhla. Generally, when cold air arrives in the lower latitude area, the temperature drop is not obvious, and sometimes only the wind speed increases. However, in our case here, the decrease of temperature at the above five stations occurred, even though the magnitude is small.

At Songkhla at 1000 hPa, the temperature drops were 25.7°C at 0000 UTC 20 November and 25.1°C at 0000 UTC 21 November, respectively. The layer of 100% relative humidity was only below 850 hPa on 20 November, the layer of 90% relative humidity reached to the middle troposphere on 21 November. And the layer from 850 hPa to 400 hPa was saturated (100%), even to 300 hPa with a value of 98% on 22 November. These mean that the lower part of the troposphere was cooled, and yet these characteristics are not found in the other days of this month. This implies that the vertical transportation of moisture reached to the middle-upper atmosphere in the deeper layers. It should be noticed that the deep moisture layers formed and were related closely with the convergence of the wind fields. It can also be found that the northeast wind at 850 hPa predominated during 20–23 November 2000. Moreover, the wind speed increased obviously, being 16 knots at 0000 UTC 20 November, 22 knots at 0000 UTC 21 November and 34 knots at 0000 UTC 22 November.

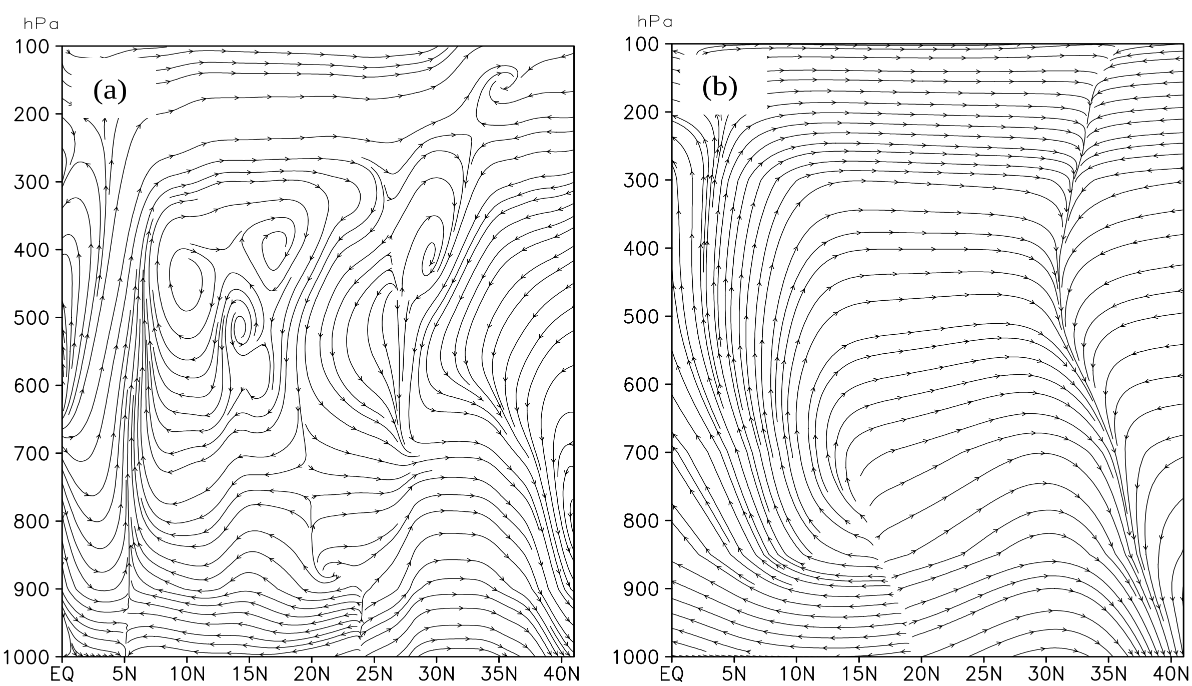

Fig. 15. (a) Vertical cross section of vertical motion (10^{-1} Pa s^{-1}) and meridional wind (m s^{-1}) along 100°E at 0000 UTC 22 November 2000. (b) Climatological vertical cross section of vertical motion (10^{-1} Pa s^{-1}) and meridional wind (m s^{-1}) along 100°E for November.

Table 1. Upper air sounding data at Songkhla station (7.18°N, 100.62°E) at 0000 UTC during 20–23 November 2000.

	Standard Pressure Level (hPa)									
	1000	850	700	600	500	400	300	200	150	100
20 November 2000										
Dynamic Height	66	1484	3128	4398	5856	7583	9705	12461	14254	16568
R_h (%)	100	100	58	91	83	62	51			
T (°C)	25.7	18.2	11.3	2.6	–4.1	–13.9	–28.7	–52.8	–68.1	–86.5
T_d (°C)	25.7	18.2	3.3	1.3	–6.6	–19.6	–35.6			
θ_{se} (K)	355	348.1	335.4	340	342.7	343.7	347.1			
DRCT (°)	290	50	60	90	70	40	80	110	110	110
SKNT (kt)	6	16	13	9	12	9	11	15	19	19
21 November 2000										
Dynamic Height	65	1477	3114	4375	5829	7553	9671	12419	14190	16493
R_h (%)	81	84	88	89	92	90	84			
T (°C)	25.1	17	8.6	1.3	–5.1	–14.6	–29.7	–54.3	–70.2	–86.7
T_d (°C)	21.6	14.3	6.7	–0.3	–6.2	–15.9	–31.5			
θ_{se} (K)	342	337.3	337.4	336.2	341.8	345.1	346.7			
DRCT (°)	100	80	90	40	60	80	80	100	110	110
SKNT (kt)	10	22	14	17	15	22	19	18	19	39
22 November 2000										
Dynamic Height	68	1484	3123	4388	5844	7572	9702	12476	14267	16562
R_h (%)	94	100	100	100	100	100	98			
T (°C)	26.5	17.1	9.1	2.2	–4.8	–14	–27.6	–52	–68.5	–85.5
T_d (°C)	25.4	17.1	9.1	2.2	–4.8	–14	–27.8			
θ_{se} (K)	355.2	343.9	342.3	340.9	343.8	347.4	351			
DRCT (°)	40	70	80	90	70	90	140	140	140	140
SKNT (kt)	17	34	22	14	14	28	26	30	33	47
23 November 2000										
Dynamic Height	79	1485	3119	4381	5836	7563	9690	12454	14241	16531
R_h (%)	79	89	85	86	85	82	70			
T (°C)	22.9	16.4	8.5	1.5	–4.6	–13.9	–28.4	–52.5	–69.4	–87.9
T_d (°C)	19.1	14.6	6.1	–0.6	–6.7	–16.3	–32.1			
θ_{se} (K)	333.1	337.2	336.3	336.1	341.9	345.7	348.4			
DRCT (°)	310	70	80	70	70	90	100	110	110	100
SKNT (kt)	8	27	24	19	32	25	19	29	28	47

R_h = Relative humidity, T_d = Dewpoint temperature, θ_{se}=Pseudo-equivalent temperature, DRCT = Wind direction, SKNT = Wind speed.

A great deal of latent heat was released due to the condensation of water vapour. This led to the warming of the upper part of the air column, although most of the heat was transported from the disturbance to the outside circulation. It can be revealed from the temperature field, for example, that there was a value of –29.7°C at 300 hPa at 0000 UTC 21 November, which went up to –27.6°C at 300 hPa at 0000 UTC 22 November, and warmed by 2.1°C in one day. Then, the warm tendency decreased and it was –28.4°C at 300 hPa at 0000 UTC 23 November. Finally, it reached down to –29.9°C at 300 hPa at 0000 UTC 24 November. The diurnal variation is not a factor because the temperature measurements occur at the same time (0000 UTC).

For evaluating the heat amount budget, the probable precipitation amount was calculated by using observed temperature change data at Songkhla station in the vertical column during 21–22 November. The results show the local heat amount can produce only a precipitation amount of 40.98 mm during 24 hours whereas the observational precipitation at Songkhla station was 150.2 mm during the same period. This means a greater heat amount than the local observation was released, among which only a part of it heated

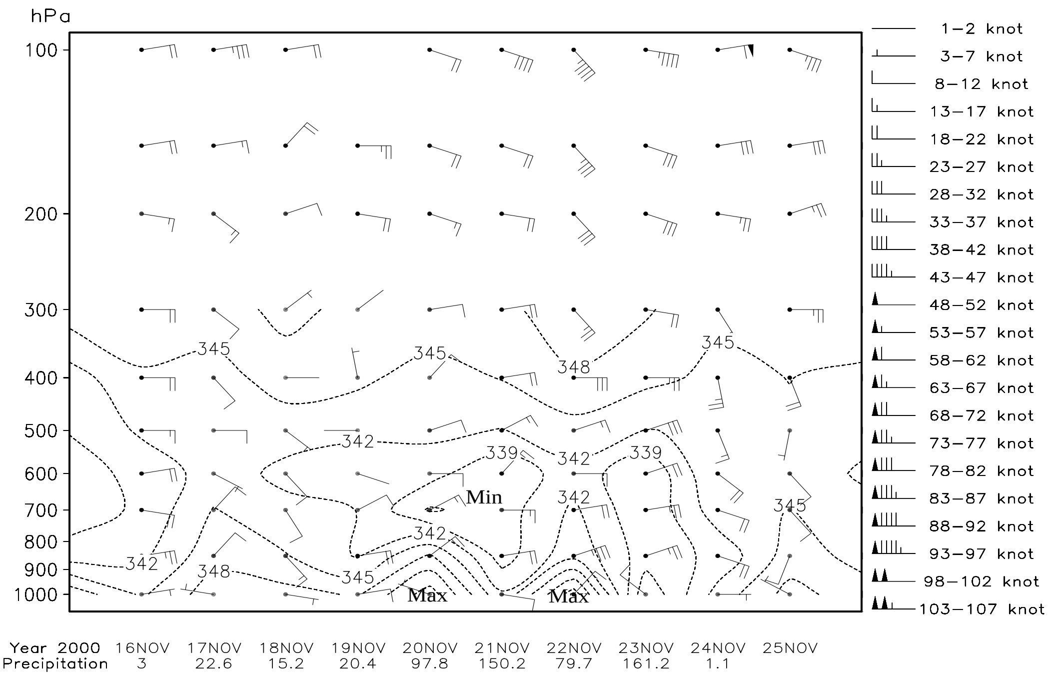

Fig. 16. 0000 UTC winds and vertical distribution of pseudo-equivalent temperature ($\theta_{\rm se}$) at Songkhla station.

the air in the lower latitude area and the majority of it was transported to the middle latitude region by the Hadley Circulation to maintain the normal running of the general circulation.

7. An analysis of the cloud clusters

In addition, the other important factor, namely, instability in the atmospheric stratification, is shown in Fig. 16. It can be found that there is a close relationship between heavy rainfall in Hat Yai and the $\theta_{\rm se}$ vertical distribution, for example on 22 November. Below 600 hPa, $\theta_{\rm se}$ decreased from 355.2 K at 1000 hPa to 340.9 K at 600 hPa. The pseudo-equivalent temperature difference in the layer was about 14.3 K. Above 600 hPa, θ_{se} increased and it reached to 351 K at 300 hPa. This implies that there existed an unstable layer from 1000 to 600 hPa. Warm and moist air was lifted, unstable energy was released and convective activities were triggered as soon as strong convergence existed in the lower troposphere. The phenomenon can also be revealed from the upper air sounding data (Table 1).

To further analyze the convective development, hourly GMS infrared cloud images were analysed. From Fig. 17a, it can be detected that the free-cloud areas are, respectively, in the South China Sea in the Northern Hemisphere and in the Southern Indian Ocean west to Australia, which were covered by two different high pressure systems. The main cloud clusters were concentrated in the west of Malaysia and Sumatra, and may be related with the systems in the Southern Hemisphere. At the same time, some smaller cloud clusters formed in the south part of the South China Sea, even though they were scattered. It can also be seen that one cloud cluster was just located near Hat Yai, which may be associated with the strong heavy rainfalls in southern Thailand. At 1800 UTC 21 November 2000 (Fig. 17b), the cloud clusters were still in south Thailand; the other significant phenomenon is that the cloud clusters in the south part of the South China Sea developed further. At 1000 UTC 22 November 2000, the cloud clusters from India and the South China Sea merged near southern Thailand, Malaysia and Sumatra (Fig. 17c). At 0300 UTC 23 November 2000, the above-mentioned big cloud area developed further and there existed an obvious vortex structure, and a bright and deep cloud cluster was just located in southern Thailand next to Malaysia (Fig. 17d). The satellite images prove that the convective activities were very strong during the heavy rainfalls in Hat Yai, South Thailand. This clearly shows that the severe

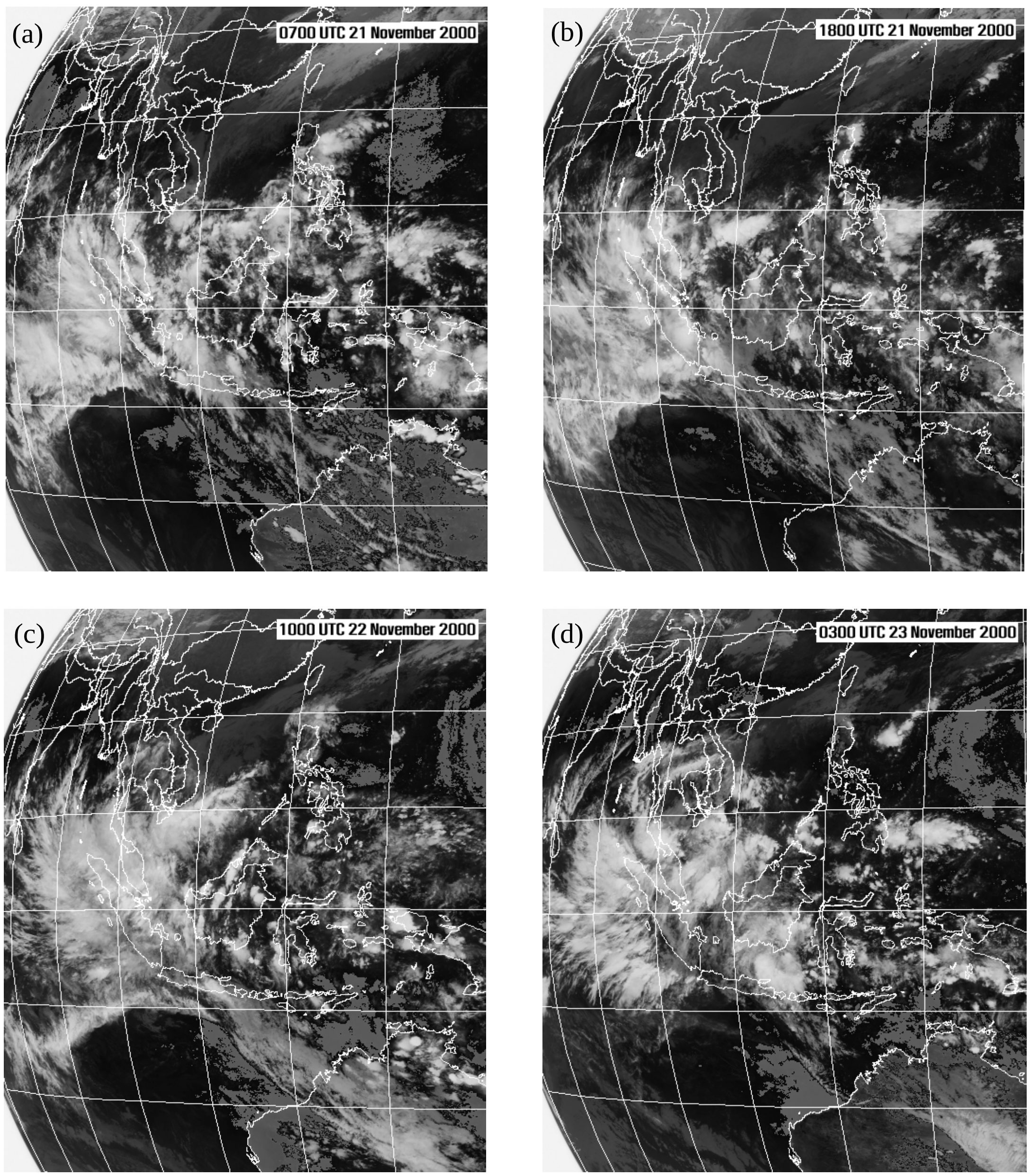

Fig. 17. GMS satellite imagery at (a) 0700 UTC 21 November 2000; (b) 1800 UTC 21 November 2000; (c) 1000 UTC 22 November 2000; (d) 0300 UTC 23 November 2000.

weather systems as well as the associated convection activities were triggered by the interaction between the different currents from both hemispheres.

8. Conclusions and discussions

Based on the above, the following conclusions can be drawn:

(1) Cold surge outbreaks: In the cold season, the cold air outbreaks over East Asia are one of the most significant weather events of winter over the Northern Hemisphere, and extremely dry and cold air invades from Siberia to Mongolia, North China, Korea, even to Southeast Asia.

(2) Strong heavy rainfalls during the winter monsoon: During the winter monsoon, rainfall amounts are substantially larger over southern Thailand, Malaysia and Indonesia, as compared to other tropical regions. This may be associated with winter monsoonal surges bursting out of the Siberian high, and occasionally

reaching as far south as the equator and possibly beyond.

(3) Tropical disturbances: The majority of occasions of heavy rainfall over South Thailand, Malaysia and the South China Sea is due to the developing of tropical disturbances and small vortexes along the low level near the equatorial trough around 5°–10°N. These South China Sea disturbances are possible when the northeast trades are sufficiently deep and broad, surging south-southwestward from north of the South China Sea and eventually merging with the near-equatorial trough and equatorial westerlies. The rainfall associated with the South China Sea disturbances is substantial and occasionally exceeds 200 mm per day.

(4) Strong convective activities: The convergence zone of total moisture flux was south of 10°N, with the maximum in South Thailand and Malaysia. There also existed an upward motion area south of 10°N, and the maximum of the upward motion was very close to the maximum of the convergence of total moisture flux. Therefore, much moisture was concentrated in the above-mentioned area, and was lifted upward, which produced was very favorable conditions for the occurrence of the strong convective cloud clusters.

(5) Latent heat: It can be found from the temporal vertical cross section of θ_{se} that there existed a potential unstable zone in the mid-lower troposphere at Songkhla station (near Hat Yai) before the occurrence of the heavy rainfalls. The warmer zone in the upper-middle troposphere was detected, and it may have been due to the release of the latent heat. In the winter monsoon, there may have existed pronounced interactions between the multi-scale systems and also between the systems of both hemispheres.

(6) Interaction: The strong convective activities in the lower latitude area triggered by the small vortex related both with the northeast current from the North Hemisphere and the cross-equatorial southeast current from the South Hemisphere, influence not only the local weather in the tropical region, but also give feedback to the atmospheric general circulation, and this probably enhanced significantly the Hadley circulation.

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REFERENCES

Chang, C.-P., and K.-M. Lau, 1980: Northeasterly cold surges and near-equatorial disturbances over the winter MONEX area during December 1974. Part II: Planetary-scale aspects. *Mon. Wea. Rev.*, **108**, 298–312.

Chen, T. C., M. C. Yen, W. R. Huang, and W. A. Gallus Jr., 2002: An East Asian cold surge: Case study. *Mon. Wea. Rev.*, **130**, 2271–2290.

Chu, C. C., 1934: Southeast monsoon and precipitation in China. *J. Chinese Geogr. Soc.*, **1**, 1–27.

Ding, Y. H., and T. N. Krishnamurti, 1987: Heat budget of the Siberian High and the winter monsoon. *Mon. Wea. Rev.*, **115**, 2428–2449.

Ding, Y. H., 1994: *Monsoon over China.* Kluwer Academic Publishers, 550pp.

Greenfield, R. S., and T. N. Krishnamurti, 1979: The Winter Monsoon Experiment – Report of December 1978 field phase. *Bull. Amer. Meteor. Soc.*, **60**(5), 439–444.

Huang, S. S., and M. M. Tang, 1987: On Structure of East Asian Monsoon System. *Meteorological Science,* **7**, 1–16.

Lau, K.-M., C. P. Chang, and P. H. Chan, 1983: Short-term planetary-scale interactions over the Tropics and midlatitudes II: Winter-MONEX period. *Mon. Wea. Rev.*, **111**, 1372–1388.

Lau, K.-M., and C.-P. Chang, 1987: Planetary scale aspects of the winter monsoon and atmospheric teleconnection. *Monsoon Meteorology*, C.-P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 161–202.

Lau, N.-C., and K.-M. Lau, 1984: The structure and energetics of midlatitude disturbances accompanying cold-air outbreaks over East Asia. *Mon. Wea. Rev.*, **112**, 1309–1327.

Li, S. Z., 1936: Untersuchungen unber Taifune, Veroeffentlichungen des Meterologischen. Instituts der Universitaet Berlin, Bd1, Ht5. (in German)

Li Zhenjun, and Zhao Sixiong, 1996: Structure and dynamics of cold fronts observed in East Asia in spring, Part I: Structure of strong spring cold fronts. *Chinese J. Atmos. Sci.*, **20**(6), 662–672. (in Chinese)

Murakami, T., 1979: Winter monsoonal surges over East and Southeast Asia. *J. Meteor. Soc. Japan*, **57**(2), 133–158.

Pearce, R. P., 1988: The Asian winter (Australian summer) monsoon contrasted with the summer monsoon. *WMO Meteorology Research Programme*, 71–80.

Ramage, C. S., 1971: *Monsoon Meteorology.* Academic Press, 296pp.

Sumi, A., and T. Murakami, 1981: Large-scale aspects of the 1978–79 winter circulation over the greater WMONEX region. *J. Meteor. Soc. Japan*, **59**(5), 625–645.

Tao, S. Y., and L. X. Chen, 1988: 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.

Tu, C. W., and S. S. Huang, 1944: The advance and retreat of the summer monsoon in China. *Meteorological Magazine*, **18**, 81–92.

Yen, M. C., and T.-C. Chen, 2002: A revisit of the tropical-midlatitude interaction in East Asia caused by cold surge. *J. Meteor. Soc. Japan*, **80**(5), 1115–1128.

Zeng, Q. C., B. L. Zhang, Y. L. Liang and S. X. Zhao, 1994: East Asian summer monsoon —A case study. *Proc. Indian Nat. Sci. Acad.*, **60A**(1), 81–96.

Zeng, Q. C., and J. P. Li, 2002: On the interaction between northern and southern hemispheric atmospheres and the essence of tropical monsoon. *Chinese J. Atmos. Sci.*, **26**(3), 207–226.

Zhang, Y., K. R. Sperber, and J. S. Boyler, 1997: Climatology and interannual variation of the East Asian winter monsoon: Results from the 1979-95 NCEP/NCAR reanalysis. *Mon. Wea. Rev.*, **125**, 2605–2619.

Zhao, Sixiong, Sun Jianhua, Chen Hong, Qi Linlin, Zhao Yijun, Li Aiguo, and Li Yunyun, 2002: A study of snowfall in Beijing on 7 December 2001. *Climatic and Environmental Research*, **7**(1), 7–21. (in Chinese)

Zhao Sixiong, Tao Zuyu, Sun Jianhua, and Bei Naifang, 2004: *Study on Mechanism of Heavy Rainfalls on Meiyu (Baiu) Front in Changjiang (Yangtze) River Valley*. Meteorological Press, Beijing, 282pp.