The onset mechanism of the East-Asian summer monsoon and its local impact

by

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ABSTRACT

A new perspective in identifying the onset mechanism of the East-Asian summer monsoon and its local impact is provided in this study. Recently, in May and June 2002, the Taiwan Monsoon Experiment (TMEX) was conducted to analyze the onset mechanism over East Asia. An effort is made here to compare the characteristics of the onset circulations between TMEX, MONEX (summer Monsoon Experiment), and SCSEX (South China Sea Monsoon Experiment).

The major findings for the onset mechanism over East Asia include: 1) The formation of the low-level Meiyu trough is highly related to the onset of the summer monsoon. The interaction between the subtropical high and cold-core anticyclone behind the front generates the low-level Meiyu trough. 2) The enhanced upper-level trough system and the associated jet stream over East Asia maintain the active low-level front, while the jet stream is enhanced by the split flow from another jet stream over Iran. 3) The development of upper-level trough systems indicates that the low-level front interacts with the midlatitude and tropical systems.

During May 15 to May 18, 2002, a frontal system was passing Taiwan. The major features that occurred during frontal passage include: 1) The frontal system was too shallow (~1 km) to cause a significant pressure or wind field change in the high mountains. However, the temperature decrease was observed in the stations at both the lower-plains and the higher mountains. 2) The northern and eastern stations had more clear pressure and temperature changes with the frontal passage. Due to the leeward pressure trough located in East Taiwan, the wind direction change in the eastern stations was earlier than the western stations. Trapped by the Central Mountain ranges, heavy rainfall was observed in western, but not eastern Taiwan. 3) The interesting feature of a sudden moisture buildup and extension to the upper troposphere after the summer monsoon onset were found in the analysis of sounding data. This result not only demonstrated that the Meiyu frontal system
was associated with a higher moisture gradient, but also indicated the higher likelihood of precipitation after the Meiyu onset.
CHAPTER 1: INTRODUCTION

The Meiyü/Baiu rainband is a significant weather system over East Asia in the late spring to early summer seasons. After a dry and cold winter, the onset of the Meiyü season brings rainfall, which is important for people’s lives and agriculture, creating a number of economic benefits. On the other hand, heavy rainfall within the Meiyü rainbelts can cause flash floods in the local region and result in substantial economic losses. This special precipitation characteristic can be used to distinguish the winter and summer seasons. Thus, traditionally people define the East-Asian summer monsoon as beginning after the Meiyü onset.

East Asia is one of the major monsoon regions (Ramage, 1971). It covers areas including the South China Sea, Taiwan, Mainland China, to Japan and Korea. Chen and Weng (1997) presented the major elements of the summer monsoon over South China Sea, while some of the features of the East-Asia summer monsoon are included (see Appendix, Fig. A-1). The East-Asian summer monsoon rainfall, associated with the Meiyü rainband, takes about two months to move from southeast Asia to northeast China and Japan, while the India monsoon rainfall takes only about two weeks to reach north India from southern India (Sikka and Gadgil, 1980). Many studies mentioned that the East-Asian summer monsoon rainfall within the mean position of the Meiyü rainbelt has a northward migrating behavior, following the movement of the subtropical high system over the western Pacific Ocean (e.g., Lau and Li, 1984; Chen et al., 2002b). The early East-Asian summer monsoon onset of the South China Sea and Taiwan is around mid-May. With the northward migration of the Meiyü rainbelt, the monsoon onset over the Yangtz-River Valley is around mid-June and arrives in Japan in mid or late June to form the Baiu onset (the same as Meiyü onset in China) (Rao, 1976; Tao and Chen, 1987; Lau et al., 1998).
I. Motivation for the Study

A number of experiments were conducted to analyze the Asia summer monsoon. Observational data was collected by the summer Monsoon Experiment (MONEX) (Fein and Kuettner, 1980) and the South China Sea Monsoon Experiment (Lau et al., 2000) in 1979 and 1998, respectively. Based on these two datasets, the possible onset mechanisms have been widely discussed. Recently, the Taiwan Monsoon Experiment (TMEX) was conducted in May and June 2002 to gather data for the study of the summer monsoon onset over Taiwan. This data was used to investigate the onset mechanism of the East-Asian summer monsoon over Taiwan and was used to make a comparison with the former two experiments.

Since the onset of the monsoon rainfall over East Asia is facilitated by the Meiyu frontal system, the higher density of observational stations in Taiwan gives us a good opportunity to examine the local impacts of the Meiyu frontal system. Therefore, it is worth providing a new perspective for the onset mechanism over East Asia by discussing the large-scale circulation changes in the onset time step of 2002, and to explore the local impacts of the onset Meiyu frontal system in 2002.

II. Literature Review

a. The characteristics of the Asian summer monsoon

- Interannual and intraseasonal variation

Both the summer monsoon onset date and the monsoon rainfall undergo an interannual variation. The possible mechanisms, which cause the interannual variation of the Asian summer monsoon, have been discussed by many studies. Rao and Goswami (1988) analyzed the interannual variation of the Indian monsoon. They pointed out that the amount of monsoon rainfall is associated with the sea surface temperature change over the northern portion of the Indian Ocean. Recently, Li and Yanai (1996) examined the onset
and interannual variability of the Asian summer monsoon. Using the strength of the summer mean vertical wind shear of zonal wind over the Indian Ocean as an index, they found the interannual variation of the Asian monsoon is associated with the upper troposphere temperature change, sea surface temperature variation, and the strength of heating and cumulus convection.

Chen and Yoon (2000) discussed the possible mechanism of the interannual variation in the Indochina summer monsoon rainfall. They found that the summer monsoon rainfall over this area is modulated by the occurrence frequency of a westward propagating weather disturbance over the South China Sea to the western tropical Pacific region and by the east-west interannual seesaw of global divergent water vapor flux. Chang et al. (2000) discussed the interannual variation of the summer monsoon over the Yangtze River Valley. They argued that the sea surface temperature, over the equatorial eastern Pacific, plays an important role in determining the amount of precipitation during the pre-Meiyū or the Meiyū season (May and June). Their result shows that a wet monsoon year is related to a stronger subtropical high; an enhanced pressure gradient could cause a more intense front. Later, Wang et al. (2001) analyzed 50 years of NCEP/NCAR data. They pointed out that the enhanced rainfall along the Meiyū front is linked with a weak western North Pacific summer monsoon circulation. Since the variation of SST could affect the Asia summer monsoon, some researchers also pay attention to the possible relationship between ENSO and the Asia summer monsoon, especially the Indian monsoon (e.g., Chang et al., 2001; Krishnamurty and Goswami, 2000; Shukla and Paolino, 1983).

Besides the interannual variation, the East-Asian summer monsoon also undergoes intraseasonal oscillations: the 30-60 day oscillations and the 10-20 day oscillations. The zonal wind field in the tropics exhibits a 40-50 day oscillation first found by Madden and Julian (1971, 1972). This oscillation is a global-scale feature and was amplified over the Asian summer monsoon region (Krishnamurti et al., 1985; Lorence, 1984). Not only are the
30-60 day oscillations important, the 10-20 day oscillations are also important in the Asian summer monsoon region. Krishnamurti and Ardanuy (1980) explored the propagation of the 10-20 day mode. They indicated that the 10-20 day surface pressure mode has westward propagating characteristics between 20° and 30°N over the Asian monsoon region. Later, Krishnamurti et al. (1985) showed that the life cycle of the 1979 Indian monsoon resulted from the interaction of the 30-60 day global-scale intraseasonal mode and the 10-20 day westward propagating monsoon mode over central India. Chen and Chen (1993) explored the synoptic structure of the 10-20 day intraseasonal monsoon mode and its relationship with the time variation of monsoon rainfall. They suggested the Indian monsoon rainfall is modulated by this westward propagating 10-20 day monsoon mode.

As located in the root of the East-Asian summer monsoon, the onset of the South China Sea (SCS) monsoon is suggested to result from the interaction between a westward migrating 10-20 day oscillation and a northward migrating 30-60 day oscillation (Chen and Chen, 1995; Chen and Weng, 1997). Chen and Chen (1995) analyzed the onset and life cycle of the South China Sea summer monsoon in 1979. They mentioned that the major rainbelt over the SCS coincided with the ITCZ and was sensitive to the 30-60 day oscillation of the sea surface temperature and global divergent circulation. In addition, they also demonstrated that phase locking between the 12-24 day monsoon low and the 30-60 day monsoon trough might be a possible reason to cause the onset in 1979 over the SCS. A similar feature of phase locking also appears in the 1979-1993 SCS monsoon onset (Chen and Weng, 1997).

The phase locking effect is also found over China and Japan. Lau et al. (1988) used the Empirical Orthogonal Function (EOF) method to discuss the characteristics of the summer rainfall pattern in central China. They indicated that the summer monsoon in China is modulated by the 20-day (Meiyu mode) and the 40-day mode oscillation, which is related to the Madden and Julian Oscillation. The Meiyu season onset/summer monsoon
onset over central China takes place when the 20-day Meiyū mode becomes significant. Using the GMS high cloud amount data for looking at the circulation change of the East-Asian summer monsoon, Tanaka (1992) showed that the similar phase locking feature between the 30-60 day and the 10-20 day intraseasonal mode was found over Japan and its surrounding area. Furthermore, he suggested that this phase locking feature was a possible mechanism to form the Baiu season onset in Japan.

It is necessary to note that the 10-20 day oscillations mentioned by previous studies are dominated by different weather systems over the South China Sea (the monsoon low propagating from tropics) and central China or Japan (the Meiyū frontal zone at the lower level). As a part of the East-Asian summer monsoon region, Taiwan also undergoes the 30-60 day and 10-20 day oscillations in the summer season. Its rainfall in early summer is mainly contributed by the Meiyū rainbelt. A more comprehensive study of the variations of the summer monsoon rainfall in Taiwan is found in Chen et al.'s (2002b) study. Since the discussion of the intraseasonal mode is with the time filter process, it cannot present the detailed interaction process between the synoptic-scale midlatitude front and the large-scale circulation, as mentioned earlier.

- **The possible influences from Tibetan Plateau**

Besides the possible interaction between intraseasonal modes, the heating effect of the Tibetan Plateau is suggested as a mechanism to establish and maintain the summer circulation in central China (He et al., 1987; Luo and Yanai, 1983, 1984; Murakami and Huang, 1984). Both observational and numerical analysis of moisture, temperature, and precipitation around the Tibetan Plateau have been directed to understanding the possible linkage between the summer monsoon onset and the possible influence from the Tibetan Plateau. Luo and Yanai (1983) pointed out that the southern and eastern Plateaus are more moist and wet than the western Plateau during the Meiyū season period. In their further
study (Luo and Yanai, 1984), the higher temperature in the eastern Plateau was believed to be a strong heat source in central China during the Meiyü season to maintain the Meiyü rainbelt. On the other hand, Tao and Chen (1987) discussed the distribution of the heat source; they indicated that the Bay of Bengal, not the Plateau, is the major heat source in May for the early Asian summer monsoon onset.

To examine the original source of active rain over China, Tao and Ding (1981) show that the most severe convective rainstorms over the Yangtz River Basin often come from the area near the Plateau. This huge latent heat release, related to a heavy rainfall along the Meiyü rainbelt, could form the Asian summer monsoon onset (Luo and Yanai, 1983). To look at the South China Sea monsoon onset mechanism, Yanai et al. (1992) mentioned that the diabatic heating over the eastern Tibetan Plateau is an important factor to stimulate the onset over Southeast Asia. Recently, Ueda and Yasunari (1998) analyzed the land-sea thermal contrast between the Tibetan Plateau and the adjacent ocean. They argued that the thermal contrast between the former and the latter is a possible mechanism for inducing and enhancing the eastward extension of the low-level monsoon flow to trigger the SCS monsoon onset.

- **The water vapor support of monsoon rainfall**

  Significant rainfall marks the importance of the Meiyü rainbelt for the East-Asian summer monsoon. The characteristics of the water vapor transport for maintaining the active Meiyü rainbelt during the Meiyü season have been widely discussed in the past (e.g., Chen and Murakami, 1988; Chen et al., 1988). Comparing the monthly averaged streamfunction and the velocity potential function at 200-mb, Lau et al. (1988) showed that both of these global circulations have the behavior of northwestward migrations. Lau et al. suggested that the pre-monsoon rainfall in Indochina is possibly associated with this shift of large-scale circulation.
Cadet and Greco (1987a, 1987b) investigated the water vapor transport over the Indian Ocean by using the water vapor flux and water vapor budgets. They mentioned that the water vapor used for supplying the Indian monsoon rainfall is mainly from the Southern Hemisphere. Different from the Indian monsoon, the moisture in the Bay of Bengal is transported from the western coast of India by the monsoon circulation.

Chen and Murakami (1988) examined the convective activities and its related divergent circulation over the northwestern Pacific Ocean in the summer season. Using the monthly mean values of the convective index (Ic), they argued that the two active convective zones (ITCZ and Meiyū rainband) existed in June 1979 over East Asia. In their discussion, the maintenance of these two convective zones from the regional divergent circulation undergoes a 30-50 day oscillation in Japan. Chen et al. (1988) suggested that the water vapor associated with Meiyū/Baiu rainbelt was transported from the South China Sea region.

- **The variation of low-level jet stream and upper-level jet stream**

  The enhanced low-level southwesterly flow toward the Meiyū front is also seen as a possible mechanism to establish and maintain the Meiyū/Baiu onset. By examining the moisture transporting process, Murakami (1959) pointed out that the southwesterly or the low-level southerly trades transport the most moisture from tropical western Pacific to the Baiu frontal zone. Kato (1989) showed the evolutionary development of the Meiyū frontal system in 1979 in three different time stages; May, early June, and late June-early July. He indicated that the Baiu season onset in Japan was happening when the low-level southerly winds rapidly increased from mid-June to early July. The enhanced southwesterly flow brings the warm and moist air from the lower latitude to the higher latitude and provides a good environment to maintain the development of the Meiyū frontal system (Ninomiya, 1978, 1980).

  The development of the low-level Meiyū/Baiu front is suggested in association with
the middle level or upper level trough over East Asia (Ninomiya and Muraki, 1986; Kato, 1989). Based on 10-day averaged wind fields, Ninomiya and Muraki (1986) subdivided the Baiu season of 1979 into four stages; pre-, early-, peak-, and post-Baiu. They pointed out that the well-developed upper level trough and ridge (in their study as Baiu trough and ridge) were intensified in the most active period of Baiu. In addition, a double jet stream at 300-mb was observed in the northern and southern parts of the upper level ridge around 85°~120°E during the peak period of Baiu in 1979. The wind field evolution at 500-mb in the same year was described by Kato (1989). These results showed that the upper level trough was developing in early June and a double jet stream structure was revealed in May.

b. The characteristics of the Meiyu/Baiu cloud band

Limited by the data sources and the resolution in both time and space, before 1980 most studies of the East-Asian summer monsoon area usually paid more attention to the relationship between large-scale circulation variation and the climatological precipitation change. In order to break out of this gap, many local experiments have been conducted to gather more high-resolution data for the understanding of a detailed structure of the Meiyu frontal system and its local impact.

It is now known that Meiyu/Baiu cloud band is made up of a train of several cyclones. The general characteristics of Meiyu/Baiu cloud band includes: the synoptic-scale frontal zone (~6000 km), medium-scale cyclones (~1000 km), and the mesoscale-disturbances (~100 km) embedded in the medium-scale cyclone with heavy rains (Ninomiya and Murakami, 1987; Matsumoto et al., 1971). This complex structure and mixed scale characteristics of Meiyu rainbelts are discussed by many observational and numerical modeling studies (e.g., Trier et al., 1990; Matsumoto et al., 1971; Chen et al., 1998).

Ninomiya (1984) analyzed the characteristics of the Meiyu/Baiu cloud band in the summer of the Northern Hemisphere by comparing the basic structure of polar fronts and
Baiu fronts during 19-26 June 1975. He pointed out that the Baiu front has a weaker temperature gradient than the typical polar front, but its associated moisture gradient and equivalent temperature gradient were stronger. Based on this, they concluded that the Meiyu frontal band is not a typical polar frontal band, but is an important subtropical frontal zone in Asia.

Trier et al. (1990) did a case study of the Meiyu frontal zone over the northern region of Taiwan. They pointed out this Meiyu frontal zone is a subtropical cold front. Ninomiya and Murakami (1987) discussed the variation of the five-day mean of the water vapor mixing ratio at the surface and at 500-mb during June 16 to July 25, 1968. In their results, the value of the water vapor mixing ratio along the Baiu front was close to the typical value for a tropical air mass. The horizontal gradient of the mixing ratio in this period was more significant than the thermal gradient with the Baiu frontal zone. In addition, they suggested that in 1968 during the Meiıyı/Baiu season the middle troposphere was moist and after the Baiu season the middle troposphere became significantly drier.

The major rain producer in the Meiyu season is the medium-scale cyclone with the mesoscale disturbances (Matsumoto et al., 1971). Numerous numerical studies are used to understand the structure of these heavy rainstorms and their relationship with the Meiyu front. Chen et al. (1998) used the MM5 model to examine a Meiyu frontal case over eastern China on 12-13 June 1991. Based on the modeling results, they suggested that the mesoscale convective complex associated with the Meiyu frontal system can be intensified by the front; on the other hand, the intense moist front provides a good environment for the generation of rainstorms.

Beside the mesoscale convective systems, the frequent occurrence of the low-level jet (hereafter: LLJ) structure related to the generation of the Meiyu frontal system is also widely discussed in the East Asian society. Ninomiya and Murakami (1987) constructed a time-averaged vertical structure of the Baiu front by the vertical cross-section at 130°E.
their figure, a LLJ stream is located at 850~700 mb around 33°N and the major jet stream is located 300 mb north of the LLJ (around 35°N). Comparing the vertical distribution of the LLJ and the equivalent potential temperature, they mentioned that the unstable area is located south of the LLJ in association with dry air above the Meiyü front, while the moist tropical air exists below the inversion layer. A similar low-level jet stream structure associated with the Meiyü rainbelts was also noted over China (Tao and Chen, 1987). Several numerical studies focus on this topic and their results suggest the LLJ is important and highly correlated with the development of heavy rainfall in the Meiyü frontal zone through the condensation heating process (e.g., Chou et al., 1990; Nagata and Ogura, 1991).

Kato and Kodama (1992) explored the formation of the Baiu front in southern Japan in early May 1979. They mentioned that the distribution of the frontal zone in mid-April to May is consistent with a development of anticyclones in the back of the frontal zone, due to the baroclinic instability and the frontal zone being a quasi-stationary system. Summarizing previous studies’ (Kato and Kodama, 1992; Ninomiya, 1984; Ninomiya and Murakami, 1987) findings, the common characteristics of the Meiyü frontal system includes:

1) The Meiyü/Baiu rainbelts are quasi-stationary. In the upper-levels, there is usually a cutoff low related to the slower moving Meiyü/Baiu cloud band.

2) The moisture gradient and horizontal wind shear are important in locating the Meiyü/Baiu rainbelt. The temperature gradient associated with the Meiyü frontal zone is weaker than the typical polar front.

3) The Meiyü cloud band is a multi-scale weather system, while the mesoscale convection systems are embedded in the synoptic frontal zone. The existence of the LLJ south of the Meiyü front is important for the development of active rainstorms along the Meiyü front.
c. The local impacts of the passage of frontal system during Meiyü season

Taiwan is located in East Asia and undergoes two major monsoon features: the summer monsoon and the winter monsoon. The major phenomenon in the winter monsoon period is the cold surges associated with the cold front. The strong cold air advection results in a sudden temperature drop (Lau and Li, 1984; Chen et al., 2002a). Unlike the winter monsoon, the summer monsoon in Taiwan is characterized by moist and warm southwesterly flow. During the late spring to early summer, the Meiyü rainbelts are the major weather systems that affect the rainfall over Taiwan.

The Central Mountain Range is oriented from northern to southern Taiwan and separates it into eastern and western areas. This special topography causes variations in the distribution of precipitation. In winter, northern and northeastern Taiwan, located on the windward side, have more precipitation than other places. In contrast, southwestern Taiwan is a wet region in summer (Chen et al., 1999). In addition, Taiwan is a small island; the east-west width is about 150 km, and the north-south length is about 400 km. Unlike the other areas around East Asia, Taiwan has a high-density network of observation stations that covers the whole island. The unique topography and high density of observation stations allows for a detailed study of the structure of the Meiyü front and its local impact.

Trier et al. (1990) analyzed a subtropical cold front case from 8 June 1987. They examined the vertical structure of the Meiyü cloud band based on the rawinsonde ascents and the Doppler radar measurements in northern Taiwan, and showed that the leading edge of the cloud band was shallow and about 1 to 2 km deep. The thermal structure of the subtropical cold front was regulated by the air-sea interaction, especially on the post-frontal system, which moves to the southwestern coast and meets the much warmer air over the water. Part of the major features of this case described in their study include:

1) The Meiyü cloud band is shallow and is split by the Central Mountain Range in Taiwan caused by the deceleration of the low-level pre-frontal westerlies.
2) The temperature contrast along this Meiyū frontal zone is about 5~7°C, the wind direction has a clear change after the front passes, and the moisture contrast calculated by the dew point depression is about 3~4°C.

Ray et al. (1991) presented the detailed Doppler radar analysis of the same case. They pointed out that the southerly wind speed (~10 m s\(^{-1}\)) ahead of this front is weaker than the northeasterly wind speed (~17 m s\(^{-1}\)) behind the front. In addition, a weak convergence system was observed with the fronts passing; after the front passed, a general divergence was found. It was shown in their results that the frontal zone was marked by several squall line systems. Furthermore, a numerical simulation of the subtropical squall line over the Taiwan Strait had been noted (Tao et al. 1991). The characteristics of precipitation systems over Taiwan during May ~ June 1987 was shown by Johnson and Bresch (1991). By discussing the time series of vertical moist static energy distribution at a northern station of Taiwan, they pointed out that the unstable period is related to the passage of the Meiyū front, and the air becomes more stable after the Meiyū front passes.

III. Limitation of Previous Studies and Purpose for Present Study

Although the summer monsoon onset is highly related to the generation and the propagation of the midlatitude front, not any frontal system during the early summer season can cause the onset of the East-Asian monsoon. Previous studies (e.g., Tao and Ding, 1981; Luo and Yanai, 1984) suggest the general conditions for the generation of a midlatitude front during the summer season, but they do not explore how the large-scale circulations correspond with the onset frontal system. How the East-Asian summer monsoon becomes established and is maintained by the large-scale circulation, through the process of the generation and the propagation of onset front will be investigated in this study.

Unlike the widely discussed maintenance of the Meiyū frontal system from the lower level circulation, the upper level variation has received less attention. It is worth making
more efforts to discuss the upper level driving force and its association with the Meiyū onset. These salient features of the East-Asian summer monsoon onset ignored by previous studies raise the following questions:

1) As revealed in Lau and Chan’s (1986; Fig. 10) study, a Meiyū trough identified by a band of minimum OLR can extend from the Bay of Bengal, South China along the eastern coast of Mainland China to southern Japan. How is this low-level Meiyū trough line formed? How do the upper level circulations maintain the huge extension of the low-level Meiyū rainbelt?

2) It is now known that the Meiyū rainbelt is an interaction between the midlatitude fronts and the tropical monsoon systems (Lau and Li, 1984). The detailed coupling process and the possible coupling mechanism of these two different systems have not been explored in previous studies by examining the variations in the upper level circulation. Do the upper level circulations show the coupling process?

3) The double jet stream structure in the upper-levels is pointed out by previous studies. Where do the double jet streams come from? How is the low-level front maintained by the upper level jet stream?

Besides analyzing the necessary environmental conditions of large-scale circulation for the generation and maintenance of Meiyū rainbelts, another purpose of this study is to research the local impacts as the Meiyū frontal zone passes. The study of the Meiyū cloud band is very complex since it mixes synoptic and mesoscale characteristics. The environmental modulations by topography, air-sea interaction, and the significant diurnal cycle effect in the summer seasons possibly affect the development of the Meiyū cloud band. By increasing data sources and resolution, it is necessary to do more case studies and make comparisons with previous studies. Thus, the following questions are carried out.

1) As revealed in previous studies, most studies use radar images, IR and VIS cloud images or numerical modeling to determine the vertical structure of the Meiyū frontal
zone. However, the different local impacts between the lower plains and higher mountains during the Meiyü frontal system passage have not been presented by previous studies. Can the surface stations in the lower plains and higher mountains show the vertical structure of the Meiyü frontal system? What are the different local impacts of the Meiyü frontal system in eastern and western Taiwan?

2) The Meiyü frontal zone has a strong moisture contrast as already demonstrated by many studies mentioned earlier. Limited by the availability of the surface observational data, most studies use the grid point data to analyze the vertical moisture structure. Since the multi-level observational data by sounding is available now, it is interesting to look at the variation of moisture during the Meiyü season in the sounding data. Is the abrupt moisture change shown by sounding data when the Meiyü cloud band is passing? Can the time series of vertical moisture distribution indicate the onset of the Meiyü season?

3) It is generally believed that the large-scale circulation modulates the local weather conditions. Can the modulation process be shown by the local surface observational data?

IV. Topics of Intent

In this study, we investigate the possible onset mechanism for the East-Asian summer monsoon over Taiwan and its surrounding areas. In addition, the local impact caused by the Meiyü frontal system’s passage is another topic in this study. The uniform datasets from NCEP will be adopted for the analysis of the large-scale and regional circulations. A new perspective for the coupling process between middle latitude and tropical systems by examining the variation of the upper level circulation is presented in the later discussion. The maintenance of the lower level Meiyü frontal system will be explored by the analysis of the vorticity budget, water vapor budget, and the divergence field. Also, the propagating
characteristics of the Meiyū frontal system, the different local impacts in the higher mountains and the lower plains, the different reactions in eastern and western Taiwan for the passages of the Meiyū frontal system, and the modulation between local and large-scale circulation will be discussed later.

V. Thesis Organization

Data and methodology adopted in this study are described in Chapter 2. In Chapter 3, the synoptic overview, the characteristic of the Meiyū onset in 2002, and its onset mechanism will be discussed. A more detailed observational analysis for the local impact in Taiwan is shown in Chapter 4. Concluding remarks and future works are described in Chapter 5.
CHAPTER 2: DATA and METHODOLOGY

I. Data Sources

a. NCEP reanalysis datasets

The dataset used for analyzing large-scale environmental conditions is provided by NCEP (National Center for Environmental Prediction), which is available at ftp://ftp.cdc.noaa.gov. The time resolution of this data is in four time steps per day at 0000, 0600, 1200, and 1800 UTC. The horizontal resolution is 2.5° (longitude) × 2.5° (latitude), and 17-pressure levels are available (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 mb). The zonal wind, meridional wind, vertical wind, moisture, and air temperature at pressure levels during 1996-2002 from May to June are derived from this dataset. In addition, the sea level pressure, surface temperature, and surface wind field at the lowest sigma level from the NCEP reanalysis-I with the same horizontal and temporal resolution over the same period are also used here. The total T62 Gaussian grid points of the precipitation rate are 192x94 and it covers range from 88.542°N to 88.542°S, 0°E to 358.125°E.

Kalnay et al. (1996) documented the nature and reliability of the reanalysis data generated by the NCEP/NCAR 40-year reanalysis project in detail. In their study, they classified the output reanalysis data as four different types based on the degree of the influence from the observations. The zonal wind, meridional wind and air temperature at 17 levels and the sea level pressure used in the current study are classified as type A, which are strongly influenced by the observations and the NCEP reanalysis data can provide a better estimate of the state of the atmosphere. For the relative humidity at 8 levels, the vertical velocity at 12 levels, the temperature at lowest sigma level and the horizontal wind field (u, v)
at the lowest sigma level are defined as type B. Type B indicates that the analysis value can be strongly affected by both the observational data and the model. The precipitation used in the current study is derived from the model fields and there is no direct influence from the observational data (type C in Kalnay et al., 1996).

b. GPCP satellite-derived (IR) GPI daily rainfall

The precipitation data produced by GPCP (Global Precipitation Climatology Project; home page is located in http://orbit-net.nesdis.noaa.gov/arad/gpcp/) used in the current study are a daily dataset with 1°x1° resolution grid, available from ftp://ftp.ncep.noaa.gov. The total grid resolution of this data is 360x80; each grid value represents an area average for the 1x1 degree box. The data cover the area from 0°E~360°E, 40°S~40°N, and there is no serious problems for the data boundaries at 40°N and 40°S (Huffman and Bolvin, 2003). The time period from 1996 to 2002 is used later for discussion.

The estimated precipitation from GPCP was merged with multiple of data types including infrared data, microwave data, and rain gauge observations (Huffman et al., 1997). The unit of the GPCP satellite-derived (IR) GPI daily rainfall data is mm day⁻¹. Three-hourly infrared (IR) imagery is accumulated by the geostationary-satellite operator and forwarded to Geostationary Satellite Precipitation Data Centre (GSPDC) of the GPCP. There, the data is averaged to produce daily records and merged on a global grid (Huffman and Bolvin, 2003). The microwave data is based on the observations made by low-orbit-satellite. Error fields for the precipitation estimates are also available in Huffman and Bolvin (2003).

c. Surface synoptic maps, cloud images, and radar images

The surface synoptic charts, issued by the Japan Meteorological Agency (JMA), include 4 time steps (0000, 0600, 1200, 1800 UTC). The per-hour GMS (Geostationary Meteorological Satellite of Japan) infrared cloud images are also adopted in this study.
radar images are issued by the CWB (Central Weather Bureau) in Taiwan, where the
time-resolution is in units of per-hour.

d. The observational data from surface stations

The observational data is mainly taken/derived from the more than 300 surface
stations of ARMTS (Automatic Rainfall and Meteorological Telemetry System) and 25
conventional surface stations of CWB in Taiwan. In this study, we examine the variation of
various weather parameters per-hour including surface pressure, temperature, dew-point
temperature, surface wind, and precipitation.

Sounding data taken twice a day (00UTC and 12UTC) in May 2002 were used from
the stations in Taipei (WMO-46692), Hualien (WMO-46699), and Ping-Nan (WMO-46780).
The information contained in the sounding data included details regarding temperature, dew
point, wind speed, and wind direction. In order to get uniform vertical resolution, this study
interpolates the variables to standard pressure-levels (1000, 925, 850, 700, 600, 500, 400, 300,
250, 200, 150, and 100 mb).

II. Methodology

a. Area average and time average

In order to get the time series of climatological GPCP data around Taiwan, the
area-average value of GPCP over a box (120°-122.5°E; 20°-25°N) is used here. Because the
entire data from 2002 is not available at the current time, we only compute the time-average
from 1996 to 2001 to obtain the climatological histogram of the daily GPCP. The same
time-averaged method is adopted to get the histogram of daily surface observational
precipitation data in Taiwan.

b. Selected criteria of the onset date of East-Asian summer monsoon
Since the precipitation during the Meiyu season undergoes an interannual variation, it is not reasonable to set an exact threshold of the precipitation for selecting the onset date. Therefore, this study is mainly based on the change in the large-scale circulation and precipitation data to select the East Asia summer monsoon onset date (Meiyu onset) in Taiwan. The criteria includes:

- The precipitation associated with the Meiyu frontal zone is significant and can continue for several days in Taiwan and its surrounding areas.
- The onset front defined by the JMA chart must pass East Asia.
- The monsoon’s southwesterly winds enhance and dominate the low-level circulation over East Asia.

c. Vorticity budget analysis

The vorticity budget equation in the quasi-geostrophic state can be written as

$$\frac{\partial \zeta}{\partial t} = -\nabla \cdot (\zeta + f) - (\zeta + f) \nabla \cdot \tilde{V},$$

where $\zeta$ and $f$ are the relative vorticity and planetary vorticity, respectively. The relative vorticity can be obtained from $\zeta = \hat{k} \cdot \nabla \times \tilde{V}$ and $f = 2\Omega \sin \phi$, where $\phi$ is the latitude. The vorticity budget equation can be used to discuss the frontal genesis ($\frac{\partial \zeta}{\partial t} > 0$).

The maintenance mechanism of the vorticity tendency ($\frac{\partial \zeta}{\partial t}$) is through the vorticity advection [$-\nabla \cdot (\zeta + f)$] and the vortex stretching ($-(\zeta + f) \nabla \cdot \tilde{V}$). According to the continuity equation ($\nabla \cdot \tilde{V} + \frac{\partial \omega}{\partial p} = 0$), the vortex stretching term is linked with the convergence or divergence field, while the lower-level convergence and upper level divergence will form upward vertical motion.
d. Water vapor budget analysis

The maintenance of the Meiyu frontal zone was explored by the vorticity budget and the water vapor budget analysis. The water vapor support through a large-scale circulation for the Meiyu front can be represented as

$$\frac{\partial W}{\partial t} + \nabla \cdot \bar{Q} = E - P,$$

where $W = -\frac{1}{g} \int_{\tau}^{\infty} q dp$ is the total precipitable water, $g$ is gravity, $q$ is the specific humidity, and $p_s$ is the surface pressure, where $p_T$ is generally taken as 300 mb. The second term, $- \nabla \cdot \bar{Q}$, indicates the convergence or the divergence of the vertical-integrated vapor flux $(\bar{Q} = \frac{1}{g} \int_{\tau}^{\infty} \bar{V} q dp)$; where $\bar{V}$ is the horizontal wind field. $P$ and $E$ indicate the precipitation and the evaporation, respectively.

In this study, the modified equation for the water vapor budget is adopted instead of the original equation. The water vapor transport can be represented by the rotational and divergent components, $\bar{Q} = \bar{Q}_R + \bar{Q}_D$ (Chen, 1985), where

$$\bar{Q}_R = \hat{k} \times \nabla \psi_Q$$

and

$$\bar{Q}_D = \hat{k} \times \nabla \chi_Q.$$

The $\psi_Q$ and $\chi_Q$ are calculated by solving Poisson’s equation with the T31 spherical harmonic method. Since $\nabla \cdot \bar{Q}_R = 0$, the water vapor budget can be represented as

$$\frac{\partial W}{\partial t} + \nabla^2 \chi_Q = E - P.$$

It is clearly shown by this equation that the maintenance of rainfall is dominated by the convergence or divergence of the water vapor flux.
e. The vertical cross-section of cross-jet stream front circulation

The direct north-south cross-section or east-west cross-section did not represent the vertical structure of the Meiyu cloud band well. The Meiyu frontal zone is oriented northeast to southwest. In order to get a more detailed vertical cross-front structure, three different cross-section areas along the north, middle, and south parts of the frontal zones have been chosen. Assume the new two-dimensional domain is cut by \( AB \), where \( A \) is the northern point, \( B \) is the southern point, and their locations in the original coordinate are \((x_A, y_A), (x_B, y_B)\). Thus, a new point \((x_C, y_C)\) along this cross-section line can be defined as

\[
y_C = y_A + \frac{y_B - y_A}{x_B - x_A} \times (x_C - x_A), \quad c = 1, 2, 3, \ldots, 144
\]

or

\[
x_C = x_A + \frac{x_B - x_A}{y_B - y_A} \times (y_C - y_A), \quad c = 1, 2, 3, \ldots, 73.
\]

In this study, three northwest-southeast cross-sections were selected and the resolution of data has been interpreted to become 73 grids (2.5° between two grids in the horizontal axis from north to south) \( \times \) 19 grids (19 levels in the vertical axis). In other words, the second formulation is adopted in the later discussion.

Since the horizontal divergence wind fields include two components \((u, v)\), we re-constructed it along the cross-section component \((v_D)\) and the cross cross-section component \((u_D)\). Therefore,

\[
v_D = -u \cos \theta + v \sin \theta
\]

and

\[
u_D = u \sin \theta + v \cos \theta,
\]

where \( \theta = \tan^{-1} \left( \frac{y_B - y_A}{x_B - x_A} \right) \). On the other hand, the vertical motions \((w)\) in this cross-section are linear interpolated to the 19 pressure levels (1000, 950, 900, 850, 800, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 200, 150, and 100 mb). Finally, a new two-dimensional wind field \((v_D, w)\) is generated.
CHAPTER 3: THE ONSET MECHANISM OF THE EAST-ASIAN SUMMER MONSOON

Introduction

Because the Asian summer monsoon onset is highly related to the large-scale circulation change, most researchers focus on their relationship to study the onset mechanism of the East-Asian summer monsoon. The most common analyzing method adopted in previous studies is to discuss the time averaged large-scale circulation change in the summer season (June to August) or pre-summer season (April to May). For example, He et al. (1987) discussed the upper level circulation change at 200 mb in 1979 by using 25-day averaged streamline charts from mid May to early June. Luo and Yanai (1983) used 40-day mean circulation patterns to examine the East-Asian monsoon onset mechanism. Later, Luo and Yanai (1984) used 10-day averaged method to discuss temperature and wind field change in the Meiyü season. These methods give us good indications for understanding the variations in the summer circulation. However, the time-filtered processes cannot show the detailed interaction between the synoptic-scale Meiyü frontal system and the large-scale circulation. In order to understand what kind of large-scale circulation can stimulate the East-Asian summer monsoon onset by the process of the generation and the propagation of the Meiyü frontal system, this study used 6-hour NCEP reanalysis data instead of the time-averaged process to explore possible onset mechanisms.

In the following discussion, the climatological features of onset of the East-Asian summer monsoon will be discussed first. Later, the synoptic structure of the onset time step in 2002 will be explored. The possible onset mechanism of the East-Asian summer monsoon in 2002 will be suggested later by the discussion of the time evolution of the large-scale circulation. More evidence from a comparison between the three international
experimental years: 1979 (MONEX year), 1998 (SCSMEX year), and 2002 (TMEX year) will also be used to support our findings. Finally, the maintenance mechanisms of the Meiyu frontal system are examined.

I. Climatological Features

a. Interannual and intraseasonal oscillations

Based on the selection criteria in Chapter 2, the East-Asian summer monsoon onset date during 1996 to 2002 is defined in Fig. 3.1a. The different onset date between each year indicates that the East-Asian summer monsoon undergoes an interannual variation. A possible reason for the interannual variation is related to the sea surface temperature change and the variation of the global divergent water vapor flux (e.g., Li and Yanai, 1996; Chen and Yoon, 2000).

Besides the interannual variations, the summer monsoon rainfalls are modulated by the 30-60 day and the 10-20 day intraseasonal modes (Chen and Chen, 1993; Chen and Weng, 1997; Lau et al., 1988). These two intraseasonal oscillations can be well depicted in the global grid-point data (e.g., Chen et al. 1995a) and in the regional observational data (e.g., Tanaka 1992; Chen et al., 2002b). Figures 3.1b and 3.1c show the composite chart of daily precipitation over six year (1996-2001). They are calculated through regional observational data from stations instrumental with ARMTS (Automatic Rainfall and Meteorological Telemetry System) in Taiwan and by the grid point data of GPCP satellite-derived (IR) GPI daily rainfall, respectively. As shown in Figs. 3.1b and 3.1c, the 10-20 day oscillations are embedded in the 30-60 day mode during the early summer season. The life cycle of the summer monsoon rainfall shown in Fig. 3.1b can be subdivided into active (20 May ~ 20 June), break (20 June ~ 20 July), and retreat (20 July ~ 20 August) stages. In the current study, we focus on the first stage of the onset of summer monsoon.
Fig. 3.1 The Meiyu onset dates from 1996 to 2002 are defined and marked as closed circles in (a). The average of these onset dates (5/17) is plotted as a solid line in (a). (b) and (c) are the histograms of the climatological daily precipitation from the surface stations of ARMTS and from the IR satellite data of GPCP, respectively. The unit of the precipitation in (b) and (c) is mm day$^{-1}$. 
b. The characteristics of the large-scale circulations at onset time step

The early summer monsoon rainfall is attributed to the Meiyu rainbelts (Chen et al., 2002). Therefore, the formation of the Meiyu rainbelts and the associated large-scale circulation change is important for the discussion of the onset mechanism. Based on the daily variation of GPCP data, the climatological onset date during 1996-2002 is defined as 5/19.

• The upper troposphere circulation: 300-mb

The upper level flow at the time of the climatological East-Asian summer monsoon onset date during 1996 to 2002 is illustrated in Fig. 3.2a. The salient features at 300-mb include:

1) Two major jet streams are revealed in Fig. 3.2a. One is located around 30°N-40°N over East Asia (J₁), and the other is located around Iran (J₂), south of the Caspian Sea and southwest of the Mediterranean Sea.

2) A midlatitude trough (T₁) is observed over northeastern China and Korea, and the corresponding midlatitude ridge over Mongolia (R).

3) Two major anticyclones in the tropics are noted. One anticyclone lies east-west in the area between 90°E and 150°E, while the second is located over the Arabian Sea.

4) A tropical trough line (T₂) is sandwiched between two major anticyclonic patterns over the tropics and is highly related to the southern branch of the split flow from the jet stream over Iran (J₂).

5) A developing mid-Pacific trough is located around (15°N, 160°E).

• The lower troposphere circulation: 925-mb

1) The Meiyu rainband exists over East Asia, and is regulated by a warm subtropical high over the western Pacific Ocean and a cold anticyclone behind the front (Fig. 3.2b).
Fig. 3.2 The daily-mean 300-mb, 925-mb streamline charts of the climatological onset date (5/19) during 1996 to 2002 are shown in (a), (b), respectively. The horizontal wind speeds are superimposed in (a) and the precipitations from GPCP are superimposed in (b).
2) The monsoon circulation is caused by the land-sea thermal contrast (Ramage, 1971). Following the development of the Asian summer monsoon, the monsoon westerlies form over India, the Bay of Bengal, and Indochina, becoming stronger and stronger.

3) The trough line extending from northern Indochina, trough the central portion of the South China Sea, and down trough the Philippines to western Pacific Ocean is referred to as the monsoon trough line (Cheang, 1987).

4) As mentioned in Chen and Chen's (1995) study, three trough lines related to the Indian monsoon are revealed in the time-average chart from May-August. Since the Indian monsoon is not yet well developed in May, there is only one developing trough line over eastern India as shown in Fig. 3.2b.

The climatological circulations indicate the major characteristics of the Asian summer monsoon. However, the climate field is too smooth to represent the onset mechanism well. Because of the interannual variation, it is necessary to use the individual year to do a more detailed discussion of the onset mechanism of the East-Asian summer monsoon. In this present study, we use 2002 as an example to discuss in detail the variation of the large-scale environment during the onset period and the time-evolution of the onset front.

II. Synoptic Overview — The Onset Time Step In 2002

a. The upper troposphere circulations

Using the observational rainfall data in Taiwan and the large-scale circulation change as an index, the East-Asian summer monsoon onset in 2002 occurred on 05/15 at 06Z. Unlike the climatological structure, the midlatitude trough ($T_1$) and ridge ($R_1$) in the upper level is clearer at the onset time step in 2002 (Fig. 3.3a). Several salient features mark the characteristics of upper troposphere at this time:
Fig. 3.3 (a) depicts the \( V_{300\text{mb}} \) Jet at the 2002 onset time step (05/15/06Z). (b) combines the surface wind, surface pressure and the GMS IR cloud images. The values of pressure larger than 1008.8-mb are shaded as blue color in (b). The cloud images are shaded as pink colors. The darker pink colors indicate a more active upward motion in (b). Precipitations from NCEP reanalysis data are shaded with pink colors in (c). The mountain is marked with a green color line.
1) A midlatitude jet stream (Jl) southwest-northeast extends from eastern China to the Sea of Japan. A second jet stream (J2) is located over Iran. These patterns are similar to the climatological onset features shown in Fig. 3.2a.

2) The split flow dominates the upper level circulation over China. This flow originates from the jet stream over Iran (J2). The northern branch of the split flow extends eastward from Iran into western China and then separates again over the area around (50°N, 100°E). Its southern branch enhances the jet stream over East Asia (Jl) and its northern branch enhances the jet stream over eastern Japan (J3).

3) The tropical trough T2 is sandwiched between two major tropical high systems (H1 and H2). Observing the southern branches of J2, the airflow moves southeastward and turns northeastward when it becomes blocked by the H1 system. The northeastward flow also intensifies the strength of the jet stream over East Asia (J1).

4) A large trough line, combined with T1 and T2, southwest-northeast extends from central China to the Bay of Bengal.

5) A cutoff low over the east side of L. Baykal (110°E, 55°N) implies slower movement of the low-level midlatitude frontal system.

Comparing with Fig. 3.3a and Fig. 3.3b, the most active convection along the low-level front is highly related to the large upper-level trough system (T1+T2). The upper level jet stream (J1) is maintained by the low-level onset front (e.g., Ninomiya and Muraki 1986; Kato, 1989). However, the enhancement of the jet stream over East Asia (J1) from the split flow over Iran (J2) was not mentioned by the previous studies. Besides this, the existence of the tropical trough (T2) at 300-mb was also ignored by previous studies. How does the jet stream over Iran (J2) enhance the jet stream over East Asia (J1)? How was T2 generated and what is the importance of the existence of T2 for the onset of the East-Asian summer monsoon? These interesting questions will be discussed later through the examination of the time evolutions in the upper level circulation.
b. The surface circulations

At 0600UTC on 15 May 2002, a midlatitude frontal zone was oriented from northeast to southwest over the eastern coast of China (Fig. 3.3b). This frontal system north-south extends more than 2000 km and affects the regional weather from 40°N to 15°N over East Asia. Unlike the huge north-south extension along the front, the width of the major cloud band is only several hundred kilometers. By observing the weather system behind the major frontal zone, several mesoscale squall line systems are found over south-central China. These squall line systems with the midlatitude front during the early summer season have also been observed by many other studies.

The local high-low coupling system in association with the Meiyi frontal zone is the basic frontal structure. This frontal structure is similar to the winter cold surge case (featured in Chen et al. 2002a; Fig. 5). The most different characteristic between the former and the latter is that a well developed, low-level trough line appears in the former (Fig. 3.3b), but not in latter. This low-level trough line coincides with the active cloud band and the location of the surface lower pressure zone. The process of the formation of the low-level trough triggers the onset of the East-Asian summer monsoon.

The large-scale circulation regulates the moving speed of the Meiyi frontal system. The movement of the frontal system at 05/15/06Z in 2002 was regulated by a train of anticyclones over the western Pacific. A zone of lower pressure at the surface is embedded in the subtropical high over the western Pacific and the anticyclone behind the front. Figure 3.3c shows the distribution of the precipitation from NCEP reanalysis data. The active rainfall along the frontal system is evidence to support that the East-Asian summer monsoon onset was at this time step. Additional, evidence of Meiyi onset (or summer monsoon onset) includes the development of the enhanced southwesterly wind and the development of monsoon surface lower pressure zone. Lau and Chan (1986) indicated the existence of a
low-level Meiýü trough line during summer season, but the detailed circulation structure and
the process of the formation of the low-level Meiyu trough line did not appear in their study.
How did the low-level Meiýü trough line form and how did it facilitate the onset of
East-Asian summer monsoon? How did the lower pressure zone develop? These
questions will be examined by the time evolution of the surface circulation.

III. The Time Evolutions of Lower and Upper Troposphere Circulations

a. The surface circulations

Figure 3.4 shows a time series of surface synoptic weather maps issued by JMA
(Japan Meteorology Agency) during the onset time of East-Asian summer monsoon in 2002.
The front affects East Asia for three to four days. With the eastward movement of the
low-level front, the lower pressure at the surface also propagates eastward. The high
pressure system over East Asia (Fig. 3.4a) before the monsoon onset is replaced by lower
pressure (Fig. 3.4d) after the monsoon onset. In order to understand the development of the
lower surface pressure, the sea level pressure from the NCEP reanalysis data was
superimposed with the surface streamline chart in Fig. 3.5. The location of the surface front
shown in Fig. 3.4 was marked with a dash line in Fig. 3.5.

• The initial stage: Day -3 ~ Day -1

At 0600 UTC on 12 May 2002 (Day -3), a convergence center was first found around
the eastern Tibetan Plateau (marked as A) (Fig. 3.5a). Another convergence center was also
located over eastern India with lower pressure smaller than 1008.8-mb (marked as B).
Compared with Lau and Chang’s (1986) study (their Fig. 10), this developing Indian
monsoon low is similar to the onset vortex mentioned in their study, and can facilitate the
onset of the Indian monsoon (Krishnamurti et al., 1981). Unlike the lower surface pressure
Fig. 3.4 A time series of surface synoptic weather maps issued by Japan Meteorological Agency. The values of $p$ larger than 1012-mb and smaller than 1008-mb are shaded in blue and pink, respectively.
Fig. 3.5 The time-evolutions of surface wind ($V_{sfc}$) superimposed with surface pressure ($p_s$). The values of $p_s$ larger than 1009.8-mb and smaller than 1008.8-mb are heavily and lightly stippled, respectively. The developing onset front and Indian monsoon low are marked as A and B. The low-level trough lines associated with Meiyu frontal zone are plotted as dash lines.
over India, East Asia is dominated by a high-pressure system (Figs. 3.5a, 3.5b). This high pressure system over East Asia and the western Pacific Ocean implies a less likelihood of precipitation.

One day later, the convergence center over central China (A) propagated easterly to the area around 100°E~110°E, 25°~30°N, resulting in the decrease of pressure in the surrounding area (Fig. 3.5b). Unlike this eastward moving midlatitude weather system, the cyclonic flow over eastern India (B) remains almost steady in the same position (20°N, 85°E). Observing the development of the surface pressure zone, the lower pressure zone associated with the frontal system is embedded in between two different high-pressure systems, the subtropical high over western Pacific and the high-pressure system behind the front.

The cyclonic flow related to the front at 05/14/06Z (Day –1) is clearly depicted on the streamline chart, but the anticyclonic flow behind the front is not capable of being observed (Fig. 3.5c). In addition, a short low-level trough line related to the front can be found over East China. Ahead of this trough line, the enhanced southerly wind comes from both the monsoon westerlies crossing Indochina and the developing subtropical anticyclonic flow. The flows are combined together to support the southerly winds and are important for the maintenance of the frontal system.

• **The onset stage: Day 0 ~ Day +2**

The midlatitude cyclonic flow is continuously developing and moving eastward from China. Unlike in the previous stages, the cold-core anticyclonic flow behind the front is well depicted in Fig. 3.5d. When the cold air is pushed out, the airflow is blocked by the subtropical anticyclonic flow over the western Pacific. Since the cold air cannot be directly pushed out, the northeasterly winds must change direction to move along the subtropical anticyclonic flow. Therefore, the low-level Meiyu trough line is formed and covers the whole area around the east coastline of China. The East-Asian summer monsoon in 2002 is
then onset at 0600UTC on May 15, due to the active convection associated with the low-level trough line.

As the major frontal system moves out, several medium scale cyclones were generated and connected as a train to form the active Meiyu rainbelt and provided heavy rainfall to East Asia. It is necessary to note that the major cloud belt is quasi-stationary over Southeast Asia for about three days (from Day +0 to Day +2). This quasi-stationary feature matches findings in Kato and Kordama’s (1992) study. The characteristics of the continuing rainfall lasting several days also matches the criteria for defining the onset of the summer monsoon. Lau and Chan (1986) suggested that the East Asian summer monsoon onset is triggered by the onset of the Indian monsoon. However, during the onset period in 2002, the continental thermal low over India was almost located in a similar position. It is not likely that the East Asian summer monsoon onset is related to the Indian monsoon onset in 2002.

- **The decay stage: Day +3**

The decay stage is defined as no rainfall recorded after the frontal system’s passage over Taiwan. Using the precipitation data from Taiwan, 06UTC on 18 May marks the beginning of the decay stage of the monsoon rainfall in 2002. At this time step, the surface frontal system moves away from East Asia. However, the monsoon surface pressure is already well developed. Comparing with Fig. 3.5a and Fig. 3.5f, the high pressure system over East Asia is revised by the monsoon lower pressure after monsoon onset.

b. The upper-level circulations: 300-mb

Figure. 3.6 shows the characteristics of the upper-level system during the onset period. To more clearly understand the relationship between upper-level circulation and the low-level frontal system, the location of the front was marked with a red dash line in Fig. 3.5 and 3.6.
Fig. 3.6  The time-evolutions of the upper level streamlines and the jet streams at 300mb are plotted. The location of the low-level Meiyu troughs defined in Fig. 3.5 is marked with a red dashed line.
The later discussions will focus on the development of the jet streams (J₁, J₂ and J₃), regional troughs (T₁ and T₂), and the anticyclonic systems (H₁ and H₂).

- **The initial stages: Day -3 ~ Day -1**

  As observed in Fig. 3.6a, a regional trough (T₁) is located over (30°N, 100°E). A low-level convergence center (A in Fig. 3.5) is located under the downstream side of the upper level trough T₁. Different from A, the low-level Indian monsoon low (B in Fig. 3.5) is under the closed anticyclonic flow (H₂). This feature indicates that A and B have different developing processes through different maintenance mechanisms in the upper level systems.

  Comparing Day -3 to Day -1, the clear movement and enhancement of T₁ and its associated jet stream (J₁) explains the possible maintenance of the eastward propagating low-level front (red dash line). As shown in Fig. 3.6, the enhancement of J₁ is supported by the split flow from the jet stream over Iran (J₂), south of the Caspian Sea. Since three seas (Caspian Sea, Black Sea, and Mediterranean Sea) are located north of this jet stream, the increase of land-sea thermal contrast over this area may cause the generation of the jet stream.

  Along with the northeastward migrating regional trough (T₁), a corresponding upper level anticyclone (H₁) propagated northeastward. Chen et al. (2002a) pointed out that the movement and development of T₁ and H₁ are well coincident. Comparing the movement between H₁ and H₂, H₁ moved from (15°N, 110°E) to (22.5°N to 130°E) during 0600 UTC May 12 to 0600 UTC May 14, while the high system over India (H₂) was slowly moving out to the Arabian Sea. The different in direction and propagating speed between H₁ and H₂ resulted in the generation of another regional tropical trough (T₂).

- **The onset and active stages: Day 0 ~ Day+2**

  The upper level jet stream J₁ moves to East Asia at the onset time stage (Fig. 3.6d). The deepening of the upper level midlatitude trough (T₁) is caused by the cold air outbreak
behind the front in the low-levels (Fig. 3.5d). The north and south branch of the split flow combine together to enhance the jet stream over East Asia ($J_1$). On the east side of $T_1$, the closed anticyclonic flow over western Pacific extend from the lower levels (subtropical high) to the upper levels ($H_1$) and slow down the moving speed of the low-level frontal system.

Comparing Figs. 3.6c and 3.6d, the upper level tropical trough ($T_2$) is well developed at the onset time step (05/15/06Z). The most interesting and salient feature shown by Fig. 3.6d is the coupling process of two different regional troughs: the midlatitude trough ($T_1$) and the tropical trough ($T_2$). A southwesterly flow at 300-mb was extended and covered an extensive area over the Bay of Bengal, Indochina, and eastern Asia to Korea. The existence of this large trough ($T_1+T_2$) pointed out a higher likelihood for the development of the active convection system at the low-level.

- **The decay stages: Day +3**

This large upper level trough system ($T_1+T_2$) still dominates and maintains the low-level Meiyu rainbelt on Day +1 and Day +2. After Day 2, not only did the connection of these two trough systems become weaker due to the different propagating speeds and directions, but it also lead to the enhancement of the jet stream over East Asia ($J_1$) from the jet stream over Iran ($J_2$) disappear. At 05/18/06Z, the connection between $T_1$ and $T_2$ disappeared and the low-level Meiyu rainbelt moved out away from East Asia.

Lau and Li (1984) mentioned that the Meiyu rainbelt interacts between the midlatitude polar fronts and the tropical monsoon system. However, the interaction of the low-level systems with the development of the upper level systems has not been shown in pervious studies. It is clearly shown in our discussion that the large trough combined with the midlatitude upper level trough ($T_1$) and tropical upper level trough ($T_2$) is highly correlated with the development of the low-level Meiyu frontal system (red dash line).
c. The analysis of the longitude-time (x-t) diagram

The coupling process of upper-level midlatitude trough (T1) with the upper level tropical trough (T2) triggers the onset of the East-Asian summer monsoon. The longitude (x) – time (t) diagrams of ψ (300mb) and p, during April 16 to June 15, 2002 were used to examine the coupling process between the midlatitude system and the tropical systems (Fig. 3.7). The position of low-level frontal systems issued by the Japan Meteorological Agency over the area between (100°E~180°E, 22.5°N~27.5°N) are marked with closed circles in Fig. 3.7a.

The summer monsoon of 2002 began after the frontal system passage over East Asia as the continental low was developing (Fig. 3.7a). The eastward propagation of the monsoon surface low is carried out by the eastward propagation of the frontal system. In the upper levels, the upper-level trough (T1) and ridge (R1) are enhanced and are advected eastward to maintain the low-level onset front (Fig. 3.7c). Differing with the other frontal systems shown in Fig. 3.7a, the location of the onset front in the lower-levels is well coincident with the upper level trough over East Asia (T1). This relationship helps the onset front develop further than other frontal systems.

The development of the Indian monsoon low (at 85°E) is different from the development of the monsoon surface low over East Asia (at 120°E) (Fig. 3.7b). The developing Indian monsoon low almost stays in the same position during the early summer season, but the monsoon surface lower pressure system extends further eastward between 5/16 and 5/23 in Fig. 3.7a and b. The eastward extension of the lower pressure shown in Fig. 3.7b is carried out by the southern part of the onset front and is coincident with the development of monsoon surface low over East Asia (shown in Fig. 3.7a).

Figure 3.7d presents the development and the movement of the upper level trough over the tropics. The upper-level tropical trough shown in Fig. 3.7a (T2) at 90°E is slower moving than the midlatitude trough (T1) at 120°E shown in Fig. 3.7c. The different
Fig. 3.7 Longitude (x) - time (t) diagrams of surface pressure at (a) 25°N ± 2.5 and (b) 17.5°N ± 2.5; values of $p_s < 1010$ and ≤ 1008 mb are lightly and heavily stippled. The contour interval of $p_s$ is 1mb. The x-t diagrams of 300-mb streamfunction $\psi$ (300mb) at (c) 35°N ± 2.5 and (d) 20°N ± 2.5; the values of $\psi$ (300mb) ≤ -3.5x10^7 m^2 s^-1 and ≤ -5x10^7 m^2 s^-1 are lightly and heavily stippled at (c), while the values of $\psi$ (300mb) ≤ -0.5x10^7 m^2 s^-1 and ≤ -2x10^7 m^2 s^-1 are lightly and heavily stippled at (d). The location of front in JMA is marked by closed circle in (a). The upper level trough and ridge the same with Fig. 3.6 are marked in (c) and (d).
propagating speeds between the former and the latter indicate that it is not possible for the upper-level midlatitude trough to always be connected with upper-level tropical trough. The major difference between the onset front and other front is that both the midlatitude and tropical trough systems in the upper levels are enhanced at the time of the onset, but not at other time period. The well connecting feature between the upper-level midlatitude trough ($T_1$) and upper-level tropical trough ($T_2$) and its associated enhanced jet stream over East Asia can be seen in two stimulators of the onset of the East-Asian summer monsoon.

**IV. The Comparison Between 1979, 1998, 2002 Onset Case**

**a. The characteristic of onset circulations in the MONEX year**

During the period of May-July in 1979, the summer Monsoon Experiment (MONEX) was conducted over India to understand the large-scale circulation change associated with the summer monsoon (Fein and Kuettner, 1980). Based on the variations of the large-scale circulations, the JMA charts, and the local precipitation record in Taiwan, the early East-Asian summer monsoon onset of 1979 is defined as 12UTC on May 15 (Fig. 3.8a).

Observing the upper level structure, a cutoff low over Korea is shown in the 300-mb streamline chart (Fig. 3.8a). An upper-level tropical trough ($T_2$), which formed between the two tropical anticyclones, was observed at (70°E, 30°N). Although $T_2$ did not couple with $T_1$ this year, the jet stream over East Asia was enhanced by the downstream side of the trough related to $T_2$. The trough line over East Asia ($T_1$) extends southwesterly and reaches to the north of the South China Sea. In comparing Fig. 3.8a with Fig. 3.8c, the active convection appears to develop along the downstream side of this upper level trough ($T_1$). It is evident that the enhanced jet stream over East Asia ($J_1$) maintains the development of the low-level onset front.
Fig. 3.8 (a) depicts \( V_{300mb} \) (Jet) on the 1979 onset time step (05/16/12Z). The values of \( p_s \leq 1009.8\) mb and \( \leq 1008.8\) mb are shaded by blue and pink colors and are superimposed with surface streamline charts in (b). The precipitation from NCEP (\( P_{NCEP} \)) is superimposed with the surface streamline in (c). The front location defined by JMA and surface streamline charts is marked with a red line in (b). The movement of the surface cyclone related to the rainbelt is marked in (c). \( +1, +0, -1, \) and \( -2 \) means day +1, day0, day-1, and day-2, respectively.
An active Meiyu rainbelt oriented east-west over the western Pacific generated a monsoon low pressure zone which was sandwiched in between the subtropical high and the anticyclone behind the frontal system (Figs. 3.8b and 3.8c). This huge extended rainbelt is composed of the eastward propagating polar front (low center was plotted with blue dot in Fig. 3.8c) and the northeastward propagating tropical cyclone from the equator (low center was plotted with red dot in Fig. 3.8c). It was suggested by Chen and Chen (1995), that the tropical cyclone, which is regulated by the northward migration of the 30-60 day oscillation, facilitated the onset of the South China Sea monsoon rainfalls of 1979. When this tropical cyclone catches up with the south part of the midlatitude front, the longer and enhanced Meiyu rainbelt is observed over East Asia. At this stage, the monsoon westerlies develop over the southern part of the South China Sea which maintain the southwesterly winds ahead of the rainbelt.

Associated with this active rainbelt, the low-level Meiyu trough line is clearly revealed in the surface streamline chart (Fig. 3.8c). Since the low-level Meiyu trough is well coincident with the monsoon surface lower pressure and the active monsoon rainbelt, the development of this low-level trough facilitated the onset of the East-Asian summer monsoon in 1979. In Fig. 3.8c, the most active rainfall is located west of the South China Sea. The water vapor support of the onset front in 1979 mainly came from the South China Sea, not the Bay of Bengal as in 2002.

b. The characteristics of onset circulations in the SCSMEX year

In May and June of 1998, the South China Sea Monsoon Experiment (SCSMEX) was conducted to explore the possible onset mechanism of the SCS. Later, more studies made efforts to understand the characteristics and the onset mechanism of the SCS in 1998 (e.g., Johnson and Ciesielski, 2002; Ding and Liu, 2001; Lau et al., 2000). By examining the distribution of the OLR, Ding and Liu suggested that the monsoon onset of 1998 over the
Fig. 3.9 Similar to Fig. 3.8, but in 1998/05/18/00Z. The value of $p_s \geq 1013$-mb are blue shaded in (b). The front location defined by JMA and surface streamline charts are marked with red lines in (c).
northern portion of the SCS and East Asia is in the fourth pentad of May (5/15 ~ 5/20). Comparing the time-evolution of the 5-day mean OLR, Ding and Liu suggested that the onset rainbelt is affected by the interaction between the midlatitude weather systems and the tropical monsoon air current. However, a detailed discussion of the mechanism for the monsoon onset and its maintenance was not presented in their study.

In this study, the onset time over East Asia is defined as 00UTC on May 18 in 1998 by using the selection criteria mentioned in Chapter 2. Similar to 2002, the upper level midlatitude trough (T1) extends over East Asia and is coupled with the tropical trough over western India and the Bay of Bengal (T2 in Fig. 3.9a). The jet stream over East Asia (J1) at 300-mb enhanced by the confluence of the split flow from the jet stream over Iran (J2). Under this jet stream, an active cloud band (Fig. 3.9b) and rainbelt (Fig. 3.9c) was present. The coupling process of upper level midlatitude trough (T1) and tropical trough (T2) indicates that the low-level active rainbelt interacted with the midlatitude and tropical weather systems. Without this coupling process (e.g. the onset time step of 1998 and 2002; Figs. 3.9a and 3.3a) or the enhancement of the jet stream over East Asia (e.g. the onset time step of 1979, 1998 and 2002; Figs. 3.8a, 3.9a and 3.3a), the low-level active rainbelt cannot become well developed.

Fig. 3.9c shows this rainbelt combined with two cyclonic flows associated with the midlatitude front. The first is located over Japan, while the second is located north of the SCS. Unlike the 1979 onset case, the cyclonic flow north of the SCS does not propagate from the equator. Instead, this cyclonic flow is generated when the southward propagating cold airflow behind the front meets the moist warm air north of the SCS. Similar with the 2002 onset case, the water vapor support of this rainbelt comes from the Bay of Bengal. The intensified monsoon westerlies do not extend to the South China Sea and East Asia (Figs. 3.8b, 3.8c). The major southerly wind ahead of the rainbelt over East Asia comes from the west branches of the subtropical anticyclonic flow over the western Pacific, while during the
onset period the western Pacific subtropical high rapidly retreats (Johnson and Ciesielski, 2002).

c. The common or different features of 1979, 1998, and 2002 onset cases

The Years of 1979, 1998, and 2002 show the existence of split flow over Central China. This split flow comes from the jet stream over Iran and surrounding areas. The importance of this split flow is not mentioned in previous studies. Shown in our discussion, the northern and southern branch of the split flow enhances the upper-level jet stream over East Asia. The detailed interaction between the two jet streams over Iran and East Asia is not clear and therefore needs more study.

The upper-level tropical trough (T2) is related to the southern branches of the split flow. The moving speed of the upper-level tropical trough is generally slower than the midlatitude trough. Due to the interannual variation of the summer monsoon, not every onset case (e.g. 1979 onset case) shows the perfect connection process between the upper-level tropical trough and the midlatitude trough as well as the onset case in 2002. However, it is true that the interaction between the jet streams with these two systems exists every year during the onset period and triggers the onset of the East-Asian summer monsoon.

Under the enhanced jet stream over East Asia, the Meiyu rainbelt is modulated by: the monsoon westerlies, the subtropical anticyclone over the western Pacific Ocean, and the anticyclonic flow behind the front. The formation of the low-level Meiyu trough implies the generation of active monsoon rainfall and facilitates the onset of East-Asian summer monsoon. The midlatitude front is not always the only cause of the onset of the rainbelt. In some years, the onset rainbelt is combined with the midlatitude front and the tropical cyclone (e.g., 1979 onset case). The zone of lower surface pressure associated with the eastward propagating low-level front extends eastward to East Asia.

The East-Asian summer monsoon onset is highly related to the Meiyu onset. Some
studies suggest the development of the upper level Tibetan high is a possible onset mechanism of the East-Asian summer monsoon (e.g., Tao and Ding, 1981). However, it is not possible for the midlatitude onset front to be maintained by the upper level high system. Instead, it is more reasonable to show the development of the low-level frontal zone is associated with the development of an upper level trough and the associated jet stream. The current study indicates that the onset mechanism of the East-Asian summer monsoon is related to the split flow from the jet stream over Iran, whose northern branch enhances the midlatitude trough (T₁), and the southern branch contributes to the tropical trough (T₂). In addition, when these two systems are well connected, it can stimulate and maintain the East Asia summer monsoon.

V. The Maintenance of the Meiyū Rainbelt

a. The water vapor budget analysis

The Meiyū rainbelt is an important index for searching for the onset of the East-Asian summer monsoon. Using 2002 onset cases (06Z May 15, 2002) as an example, the maintenance of the precipitation of the onset front was shown in Fig. 3.10. Over East Asia, the flow in the low-level converges (χ₁₀₀₀ₘ₉ > 0; Fig. 3.10b), while the flow in the upper-levels diverges (χ₂₀₀ₘ₉ < 0; Fig. 3.10a). The two major convergence centers are revealed in low-levels (marked as C in Fig. 3.10b) match up well with the upper-level divergent center (marked as D in Fig. 3.10a). A low-level convergence line related to the frontal system oriented from northeast to southwest lies over East Asia. Corresponding with this convergence line, a divergence line was observed at 200-mb. The low-level convergence and the upper-level divergence introduce the upward motions along the front over East Asia. Therefore, the most active rainfall was observed along this low-level convergence line.
Fig. 3.10 (a) ($\chi_{200\text{mb}}$, $P_{\text{NCEP}}$), (b) ($\chi_{1000\text{mb}}$, $P_{\text{NCEP}}$), and (c) ($\chi_Q$, $P_{\text{NCEP}}$) at 2002/05/15 06Z. The values of $P_{\text{NCEP}} \geq 3$ mm day$^{-1}$ are lightly shaded in (b), (c) and (d). The interval values of $\chi_{200\text{mb}}$ and $\chi_{1000\text{mb}}$ are $5 \times 10^7$ m$^2$ s$^{-1}$. The convergence line along the front at 1000-mb is marked as a red dash line, while the associated upper-level divergence line at 200-mb is marked as a blue dash line in (a). The convergence center and divergence center over East Asia are indicated by C and D, respectively.
To examine the transporting process of the water vapor along the front, the divergence/convergence field of water vapor $\chi_Q$ was plotted (Fig. 3.10c). Corresponding with the low-level $\chi$ field (Fig. 3.10b), two convergence centers of $\chi_Q$ were observed in Fig. 3.10c. Based on the water vapor budget equation $\left( \frac{\partial W}{\partial t} + \nabla^2 \chi_Q = E - P \right)$, the divergence field of water vapor ($\chi_Q$), the evaporation ($E$), and the precipitation ($P$) can affect the local water vapor change ($\frac{\partial W}{\partial t}$). As shown in Figs. 3.10b and 3.10c, the water vapor convergence ($\chi_Q > 0$) couples with the active upward motion along the front and provides a good environment for the generation of rain.

b. The vertical cross-section along the front

In order to more clearly understand the maintenance of the Meiyu frontal zone and the relationship between the vertical motion along the frontal system and the upper-level jet stream, three vertical cross-sections across the front over East Asia at 06UTC on May 15 of 2002 have been selected for discussion (Figs. 3.11 d-f). The related locations are presented as lines A, B, and C in the horizontal charts (Figs. 3.11 a-c).

It is clearly depicted by Fig. 3.11c, that the cold air is located well behind the front, while the higher temperatures, caused by the enhanced southwesterly wind, existed ahead of the front. The same features are shown in the vertical cross-sections of potential temperature (solid line in Fig. 3.11d-f). The cold core air is trapped below 700 mb between 30°N—40°N. Cross-section C in the southern part of this front has the weaker horizontal temperature gradient than cross-section A and B (Fig. 3.11c). The weaker horizontal temperature gradient implies that the weather system is less baroclinic (similar as the characteristic of the tropical system) in the southern part of the front, while cross-sections A and B are more baroclinic. The different horizontal temperature gradients between the three
Fig. 3.11 (a) \((V_{300\text{mb}}, \text{Jet})\), (b) \((V_{500\text{mb}}, -\omega_{700\text{mb}})\), and (c) \((V_{1000\text{mb}}, T_{1000\text{mb}})\) depict the horizontal characteristics in lower levels and upper levels. Three cross-front sections are selected as A, B, and C in the horizontal charts. (d), (e) and (f) are \([(v_D, -\omega), \text{jet}, \theta]\) at cross-sections A, B, and C, respectively. The location of the front is marked with a triangle in (d), (e), and (f).
vertical cross-sections indicate that the characteristics of the cloud system along the front are different. This difference also gives a good indication that the Meiyu frontal system is combined with the characteristics of midlatitude and tropical features.

Using the streamlines and the distribution of temperature at 1000-mb as a reference, the locations of this front in cross-sections A, B, and C are at 27.5 °N, 22.5 °N and 20 °N, respectively. The related locations are marked as triangles in the corresponding vertical cross-sections in Fig. 3.11 d-f. The more active upward motion along the front is found in cross-section C, as it is closer to the original sources of the water vapor support for the frontal system. Examining the relative location of the upper level jet streams and the vertical motion, the upward motion exist on the east side of the upper level jet stream. In contrast, the stronger downward motions are observed under the jet core. The increase horizontal temperature gradient at the lower level enhances the upper level jet stream, and the upper level jet stream provides a good environment to maintain the development and movement of the low-level frontal system.

c. The vorticity budget analysis

Shown by our previous discussion, the onset front propagates eastward. The maintenance of the eastward propagation of low-level frontal system can be examined by the analysis of the vorticity budget equation as follows:

\[
\frac{\partial \zeta}{\partial t} = -\nabla \cdot \nabla (\zeta + f) - (\zeta + f) \nabla \cdot \nabla \tilde{V},
\]

where the local vorticity change (\(\frac{\partial \zeta}{\partial t}\)) is caused by the vorticity advection \((-\nabla \cdot \nabla (\zeta + f))\) and the vortex stretching \(-(\zeta + f) \nabla \cdot \nabla \tilde{V})\). Fig. 3.12b shows the positive vorticity advection dominates the greater part of the downstream side of the major trough line at 300-mb over East Asia. The upper level midlatitude trough propagates eastward through
Fig. 3.12  The distributions of streamfunction superimposed with vorticity ($\psi$, $\zeta$) at 300-mb and 850-mb in 2002/05/15/06Z are depicted in (a) and (d). The corresponding vorticity advection \([\psi - \nabla \cdot (\xi + f)](300\text{-mb})\) and vorticity stretching \([\nabla \cdot V](300\text{-mb})\) superimposed with $\psi$ (300-mb) are shown in (b) and (c), while (e) and (f) show the same fields at 850-mb as (b) and (c), respectively. The contour interval of $\psi$ (300-mb) and $\psi$ (850-mb) are $5 \times 10^6$ m$^2$ s$^{-1}$ and $1.5 \times 10^6$ m$^2$ s$^{-1}$, respectively.
the process of the redistribution of the vorticity by the vorticity advection term. The linkage of upper and lower levels is not only shown by the divergence field, but can be also shown by the vorticity budget equation. Since the enhanced upper level trough \( \left( \frac{\partial \zeta}{\partial t} > 0 \right) \text{ at 300-mb} \) can induce the low-level cyclonic flow \( \left( \frac{\partial \zeta}{\partial t} > 0 \right) \text{ at 850-mb} \) through the rotating process, the eastward propagating upper level trough will lead the low-level front eastward and maintain the low-level midlatitude front.

The vortex stretching term is more important in the lower-levels than in the upper levels. Relating to the cyclonic flow \( (\zeta > 0) \) at 850-mb, the positive vortex stretching exists over the convergence area (Fig. 3.12f). The distribution of the vorticity stretching term is coincident with the upward motion shown in Fig. 3.11b. The vorticity stretching term dominates the variation of the vorticity tendency ahead of the front at 850-mb. The low-level cyclonic flow develops \( \left( \frac{\partial \zeta}{\partial t} > 0 \right) \) and moves eastward to the area, where the positive vortex stretching exists. The developing cyclonic flow in the lower-levels indicates the formation of the onset front in 2002.
CHAPTER 4: THE LOCAL IMPACTS OF MEIYÜ FRONTAL ZONE IN TAIWAN

Introduction

The Meiyū frontal system is mixed with the characteristics from the synoptic-scale front, medium-scale cyclones, and mesoscale disturbances (Ninomiya and Murakami, 1987; Matsumato et al., 1971). Its associated rainfall can last for several days and plays an important role in the economic benefits of agriculture and human life over East Asia. Therefore, the discussion of the local impacts from the Meiyū frontal system becomes complex, but necessary. The detailed structure of the convective systems associated with the frontal system has been widely discussed by several numerical modeling studies (e.g., Chen et al., 1998; Chou et al., 1990; Nagata and Ogura, 1991). In contrast, most of the observational studies focus on the discussion of the synoptic frontal structure and its local impact (e.g., Trier et al., 1990; Ray et al., 1991). Our present study will focus on the synoptic frontal structure, while a brief discussion is made on the local impacts of the mesoscale convective systems embedded in the frontal system.

Taiwan is a small island with a unique topography and a high-density network of observational stations. Without any weather systems passing, the land-sea breeze is the major feature of the daily wind field change. Not only the wind field, but other weather factors also undergo a clear diurnal (e.g. $T_S$) or semi-diurnal (e.g. $p_S$) variation. How is the Meiyū frontal zone modulated by the local topography? How are the diurnal variations of the local weather changes regulated with the large-scale circulation while the Meiyū frontal system is passing? These two are interesting topics for discussion. Previous studies (e.g., Trier et al., 1990; Ray et al., 1991) made an effort to analyze the vertical structure of the Meiyū frontal system through the use of radar or cloud images. Due to the
limitation of surface observational data, they were not able to examine the local impacts of the Meiyu rainbelt at different altitudes. With the increasing number of surface data sources, more detailed observational studies in Taiwan are now been made.

The following discussion is based on the data gathered from the TMEX (Taiwan Monsoon Experiment) in 2002. The time period studied between May 15 and May 18 of 2002 was during the onset of the Meiyu frontal systems passage in Taiwan. First, the details of the progression of this frontal zone will be examined through the GMS infrared (IR) cloud images and local radar images. Some effort is made to discuss the characteristics of the cloud pattern associated with the front and the change of the weather factors in Taiwan during the frontal passage. After this, the vertical structure and the local impacts of this front will be discussed by using the surface observational data. Finally, the analysis of sounding data, the discussion of the modulations between the large-scale circulations and the local weather changes are investigated.

I. The Progression of the Meiyu Cloud Band and Its Associated Weather System over Taiwan

a. The characteristics of cloud patterns and radar images

Figure 4.1 shows the characteristics of the propagation and the development of the cloud band over East Asia. The surface wind field of the NCEP reanalysis data and the location of the front as defined on the surface weather map issued by the Japan Meteorological Agency (JMA) are superimposed on the IR cloud images. This frontal system affected the local weather over Taiwan for about three to four days during 15 May to 18 May in 2002. The most salient feature was the generation of the mesoscale convective systems associated with the front (Figs. 4.1c-e). It is interesting to see that the local weather in Taiwan is affected by both of these two major cloud systems, the synoptic frontal zone and the mesoscale convective systems. The development of cumulus convection systems over
Fig. 4.1 A time series of surface streamline superimposed over IR cloud images at six different time steps: (a) 2002/05/14 18Z, (b) 2002/05/15 06Z, (c) 2002/05/16 06Z, (d) 2002/05/16 18Z, (e) 2002/05/17 06Z, and (f) 2002/05/17 12Z.
the northern part of the South China Sea ahead of the southern part of the front implies that different characteristics exist between the middle- and the southern part of the front as mentioned in Chapter 3.

The frontal passages over Taiwan are also shown by the radar images (Fig. 4.2). On 2002/05/14 at 18Z the enhanced cloud band is located over the east coastline of China (Fig. 4.2a). As the front propagates southeastward, the frontal system starts to affect the local weather in Taiwan at 06Z on 5/15. Comparing Figs. 4.2b and 4.2c, the structure of this front becomes weaker at 06Z on 5/16. Later on, it re-intensifies again when the mesoscale convective system moves northward and combines with the major frontal system (Fig. 4.1 and 4.2d). The possible enhancement of the Meiıyü frontal zone by the developing mesoscale convective system is suggested in Chen et al.'s (1998) study.

b. Distinguish major rainy period over Taiwan

Figure 4.3a shows the corresponding time-evolution and distribution of the cloud systems over Taiwan. The higher values of color (dark shaded areas) imply the more active upward motion. The time-evolution of the per-hour precipitation observed by the ARMTS and CWB stations in Taiwan during this period are shown as a histogram in Fig. 4.3b. The variation of surface pressure, surface temperature, and the surface wind field in Tanshui (located in northern Taiwan) are presented as a solid line with closed circles, a solid line with open circles, and the wind vector, respectively. Several short-rain cycles are observed during this period. Based on the different characteristics of the cloud patterns, three major rainy periods are defined. They are:

(1) the first rainy period from 00Z on 5/15 to 18Z on 5/15, caused by the passage of the leading edge of the front.

(2) the second rainy period is caused by the active mesoscale convective system associated with the front, which started at 15Z on 5/15 and ended at 00Z on 5/17.
Fig. 4.2 A time series of regional radar images at six time steps in 2002: (a) 05/14/18Z, (b) 05/15/06Z, (c) 05/16/06Z, (d) 05/16/18Z, (e) 05/17/06Z, and (f) 05/17/12Z. The red dotted line represents the surface front defined by JMA chart.
Fig. 4.3  
(a) The latitude (y) – time (t) diagram of GMS IR cloud images over Taiwan during 5/14/18Z (5/15/02L) to 5/18/00Z (5/18/08L). $p_s$, $T_s$, and $V_s$ in Tanshui are plotted as a solid line with closed circles, a solid line with open circles, and a wind vector in (b), respectively. The accumulated precipitation from ARMTS is presented in a histogram in (b).
(3) the third rainy period is due to the re-enhanced frontal system’s passage after 00Z on 5/17.

Examining the variations of the surface temperature and the surface pressure observed in Tanshui, a clear temperature decrease is found to coincide with the wind direction change from the southeast to the northwest at the beginning of the first rainy period. Beginning with the rapid temperature drop and the suppression of the diurnal variation of temperature, the surface pressure slowly increases with the semi-diurnal variation after the arrival of the frontal cloud band. The first rainy period ends when the cloud band becomes weaker over Taiwan. Associated with the short break period of rainfall between the first and second rainy periods, the surface temperature increases again because of the diurnal solar heating process. However, the magnitude of this increase is smaller because the cold air advection associated with the northerly wind modulates the regular diurnal solar heating effect. Later on, the surface temperature drops again and reaches the lowest value during the second rainy period due to the heavy rainfall in Taiwan.

II. The Altitude of the Frontal Zone

It is mentioned by many studies that the Meiyy fronts is very shallow. The shallow frontal system discussed by previous studies has mainly focused on the altitude of the frontal leading edge, but does not include the mesoscale convective systems generated along the front (e.g., Trier et al., 1990; Johnson and Bresch, 1991). For serving our purpose to understand the altitude of this front and its associated local weather change, seven stations with different elevations along the Central Mountain Range in Taiwan were selected to be analyzed. Their related locations are shown in the right bottom of Fig. 4.4. From northern to southern Taiwan, stations one to seven are Tanshui (19 m), TaTunShan (1099 m), Hsinchu (32.8 m), Taichung (83.8 m), Jihyuetan (1014.8 m), Alishan (2406 m), and Yushan (3850 m).
Fig. 4.4  (a) Time series of surface pressure ($P_s$, solid line), surface wind vector ($V_s$) observed at seven stations; their relative locations are shown in the map. (b) shows the corresponding time series of surface temperature ($T_s$, solid line), dew point depression ($\Delta T_d$, dash line) and precipitation (P-bar). The arrival time of front is indicated by the yellow downward vector. The green downward vector indicates the front away from Taiwan.
a. The variation of surface pressure and wind field

The front arrived northern Taiwan at 06Z on 5/15 in 2002 (yellow downward arrow in Fig. 4.4). Shown in Fig. 4.4a, before the front passes the enhanced southerly winds can be observed in northern Taiwan (stations 1~4). The clear wind shift from southerly to northerly is revealed in the higher mountains areas of northern Taiwan (station 2), but is not observed in the higher mountains of central Taiwan (stations 5~7). Above the altitude of 1000 m in the central part of Taiwan, there is no clear surface winds change during the passage of the low-level frontal system. Comparing the wind directions in Yushan (station 7, the tallest mountain over East Asia) and in the other six stations, it is interesting to see that the wind direction is more uniform in Yushan.

Unlike the sudden pressure jumps after the cold front's passage (Chen et al., 2002a), the surface pressure changes caused by the passage of the Meiyu frontal system during the summer season increase slower than the surface pressure changes caused by the typical cold front. Also the increase of the surface pressure associated with the passage of the Meiyu frontal system is regulated by the semi-diurnal variation. The phenomena of the slower pressure increase after the Meiyu frontal system passed is mainly observed in northern Taiwan (stations 1~3 in Fig. 4.3a). Not only the northern stations located over the lower plains (e.g., Tanshui and Hsinchu) show the slower pressure increase, the stations in the higher mountains in northern Taiwan (e.g., TaTunShan) also experiences a similar feature after the frontal system passed.

With the southward propagating frontal system moving into Taiwan, the high-pressure system behind the front is modulated by the local topography. The variations of surface pressure in both the lower plain and the higher mountain stations in central Taiwan do not show a clear increase in surface pressure related to the frontal passage. Previous studies usually defined the highest altitude of the clear horizontal wind shift as the altitude of the front (e.g., Trier et al., 1990; Chen et al., 2002a). Adopting a similar definition, this front
can reach up to 1 km in northern Taiwan, but is shallower than 1 km after it moves into Taiwan since the more uniform wind direction is observed in the higher mountains of central Taiwan.

b. The variation of temperature, dew point depression, and precipitation

Not only the temperature change shows a clear diurnal variation, the dew point depression ($\Delta T_d = T - T_d$) also shows clear diurnal variations during 10 May to 28 May in 2002 (Fig. 4.4b). Observing the temperature change in northern Taiwan (stations 1~3), besides the regular diurnal variation a clear temperature increase was revealed during 5/14/18Z to around 5/15/00Z before the front arrived to northern Taiwan. This temperature increase is caused by the enhanced southerly winds advecting the warm and moist air into Taiwan. Although the southerly wind is also observed in Taichung, the temperature variations do not show a noticeable increase with the exception of the diurnal variation. The smaller magnitude of the warm air advection caused by the weaker latitudinal temperature gradient in the southern Taiwan is a possible explanation.

The wind shifting from southerly to northerly indicates the arrival of cold air behind the front. The cold air advection suppressed the diurnal variation of temperature on May 15, 2002. The suppression of temperatures is not only shown in the lower-plains stations, but also observed in the higher mountain stations, including both Alishan and Yushan (Fig. 4.4b). It is generally believed that the diurnal cycle is more significant in the areas under clear skies. Although the cold air mass is trapped and may not reach the upper levels, the cloud cover over mountains can result in the suppression of the diurnal variation of temperature.

When the warm and moist air from the south meets the cold and dry air from the north, the process of condensation begins. Associated with the decreasing temperature, the dew point depression is also decreasing. This feature indicates the increase of the water vapor to saturation. The increase (decrease) of precipitation is highly correlated with the
decrease (increase) of the dew point depression. Trier et al. (1990) studied a case of the Meiyū frontal zone and pointed out its moisture content calculated by the dew point depression is about 3~4°C. Observing Fig. 4.4b, the dew point depression with the smaller value than 2°C lasts for several days in both the lower plains and higher mountain stations after the frontal passage. This result suggests that the dew point depression is a good variable to indicate the onset of the Meiyū season.

It is worthwhile to summarize the characteristics of the variation of the weather during the first rainy period and make a brief comparison with the influence of the mesoscale convective systems. The results show:

1) The surface pressure increase and the surface wind direction change during the first rainy period are not revealed in the stations in the taller mountains in central Taiwan. In contrast, on 5/17/2002 the lower pressure system associated with the passage of the convective systems suppressed the semi-diurnal cycle of pressure change (Fig. 4.4a).

2) Three major effects caused the suppression of the diurnal temperature variation during the frontal passage. They are the cold air advection, the cloud cover, and the precipitation in Taiwan.

3) Due to the cloud cover over Taiwan, the suppression of the diurnal temperature variation can reach Yushan during the first leading edge of the frontal passage and the convective system’s passage. The associated smaller value of dew point depression (< 2°C) and the heavy rainfall depict the onset of the Meiyū season.

III. The Different Local Impact Between Eastern and Western Taiwan

Taiwan undergoes two different monsoon seasons, the winter monsoon and the summer monsoon. The northeasterly wind dominates the low-level circulation over Taiwan during the winter season, while the southwesterly wind dominates the low-level circulation over Taiwan during the summer season. The interaction between the local topography and
the seasonal circulation change causes the northeastern station to be moister and have more precipitation than other stations in Taiwan during the winter season. In contrast, more summer monsoon rainfall is observed in southwestern Taiwan (Chen et al., 1999). Undoubtedly, the Central Mountain Range in Taiwan, which is oriented from north-south separating Taiwan into two major areas, plays an important role in modulating the local weather systems which results in different local impacts between eastern and western Taiwan.

The Meiyū frontal systems and cold surges are the major weather systems over Taiwan in the early summer season and winter season, respectively. Chen et al. (2002a) analyzed the local impact of a cold front’s passage in Taiwan during winter season. Their results show:

1) A significant pressure jump is observed in northern and eastern Taiwan after the cold front passes. In contrast, southwestern Taiwan does not experience the sudden pressure jump.

2) Related to the pressure change, the diurnal cycle of the temperature variation is dissipated or suppressed in northern and eastern Taiwan, while southwestern Taiwan has a more distinct diurnal cycle.

3) All of the CWB (Central weather Bureau in Taiwan) stations in the lower plains undergo a distinct wind direction change when the cold front passes.

The Meiyū frontal system is made up by a weaker temperature gradient than the typical cold front (Ninomiya, 1984). Comparing the local impacts between the passages of the former and the latter, the smaller magnitude of the surface pressure increases are revealed in the northwestern stations after the Meiyū frontal system’s passage as discussed earlier. However, the local weather change during this time period in the eastern stations has yet to be examined. Thus, two interesting questions are raised.

1) What is the different reaction in eastern and western Taiwan during the Meiyū frontal
system's passage?

2) Are the variations in the surface wind field coincident with the passages of the Meiyu frontal zone as well as the passages of the cold front in both western and eastern stations?

To answer these questions, two stations: Chiayi (at an altitude of 26.8 m in western Taiwan) and Hsinkang (at an altitude of 32.7 m in eastern Taiwan) were selected to do the detailed comparison. Later on, the time departure of the surface pressure, surface temperature, and surface wind fields in Taiwan between 02Z on 5/15 (before the frontal passage) and 02Z on 5/16 (after the frontal passage) were used to compare the local impacts in eastern and western Taiwan.

a. The comparison between Chiayi and Hsinkang

- The variations of pressure and wind field

Shown in the time evolution of cloud and radar images, the frontal zone propagates eastward passing over Taiwan from northwest to southeast. In other words, Chiayi (the western station) is affected by this frontal system earlier than Hsinkang (the eastern station) as revealed in Fig. 4.5c. Based on this feature, one may simply guess that the corresponding change in wind direction and surface pressure in the western station (Chiayi) should be earlier and more significant than in the eastern station (Hsinkang). However, different results are shown in Fig. 4.5a. The pressure change between 5/14 and 5/15 in Hsinkang is larger than in Chiayi, and the surface wind field change in Hsinkang is earlier than in Chiayi.

What causes a smaller pressure change in Chiayi than in Hsinkang? To answer this question, the relative locations of the eastern and western stations must be considered with the variation of the large-scale circulation associated with the frontal system. Before the frontal passage, enhanced large-scale southwesterly winds ahead of the front are observed (Fig. 4.5c). The southwesterly airflow, blocked by the central mountain range in Taiwan, accumulates along the west side of the mountains. In contrast, eastern Taiwan is located
Fig. 4.5  Time series of surface pressure ($p_s$, solid line in (a)), surface temperature ($T_s$, solid line in (b)) and surface wind vector at Chiayi (western station) and Hsinkang (eastern station). (c) (IR, $V_s$, P) at 05/15/06Z in Taiwan are presented with gray color, wind vector, and open circle, respectively. The same time step with (c) is indicated by a downward vector in (a) and (b).
along the leeward side of the mountains and the original air masses have been taken away from eastern Taiwan by the large-scale circulation. Due to this reason, the pressure drops are clearer in Hsinkang before the frontal passage (Fig. 4.5a). The features of the leeside pressure trough and windward pressure ridge before the frontal passage in Taiwan was similar with the results shown in Trier et al.'s (1990) study. However, they did not discuss the pressure change after the frontal passage. When the anticyclonic flow behind the front arrived to Taiwan, the large-scaled wind change from southwesterly to northeasterly. Thus, the eastern stations are located on the windward side with enhanced northeasterly wind and western Taiwan is located on the leeward side at that time. Based on a similar reason as discussed earlier, the pressure will increase more in the eastern stations than in the western stations after the frontal passage. Combining the effect from before and after the frontal passage, the pressure variation in Hsinkang (the eastern station) is larger than in Chiayi (the western station).

How does one explain the earlier wind change in Hsinkang than in Chiayi? The reason is highly related to the distribution of the surface pressure. When the frontal zone arrives in northeastern Taiwan, the local wind direction starts to become more northeasterly (Fig. 4.5c). This is caused by the lower pressure zone in Hsinkang, and the northeasterly winds observed in northeastern Taiwan are able to extend more southerly along this lower pressure zone. Therefore, although Hsinkang is under a clear sky at that time, the wind direction has already changed to northerly. In contrast, the high-pressure zone located in Chiayi blocks the northerly wind behind the front. Thus, the wind direction change associated with this front is later in Chiayi than in Hsinkang.

- The variation of temperature

Ahead of the front, the enhanced southerly wind, which can increase the local temperature, was observed in both Chiayi and Hsinkang. Besides the regular variation of diurnal cycle revealed in Fig. 4.5b, the temperature is rapidly increasing in Hsinkang before
the arrival of the front, but not in Chiayi. A possible explanation for this feature is the presence of cloud cover over Chiayi prior to that in Hsinkang. The opposite influence between the warm air advection (causes the temperature increase) and the cloud cover (causes the temperature decrease) resulted in a smaller temperature increase in Chiayi. In contrast, there was no cloud cover in Hsinkang between 18Z on 5/14 to 06Z on 5/15. The diurnal solar heating and the warm air advection caused a larger temperature increase in Hsinkang than in Chiayi. Not only is a larger increase in temperature observed in Hsinkang, the decrease in temperature is also more significant there than in Chiayi. Because of the earlier wind direction change to northeasterly, Hsinkang is affected by the cold air advection earlier. Therefore, the temperature decrease in Hsinkang is larger than in Chiayi.

b. The local impacts during the Meiyü frontal passage

The weather conditions in Hsinkang (located in eastern Taiwan) and in Chiayi (located in western Taiwan) behave differently during a frontal system’s passage. However, one may question if other stations in western and eastern Taiwan show this difference? In order to take out the possible influence from the regular diurnal cycle and semi-diurnal cycle, the same time step at 02Z between 5/15 and 5/16 were selected to be analyzed. Figures 4.6a, 4.6b, and 4.6d show the difference in the surface pressure, the temperature, and wind field at 02Z on 5/16 (after the frontal system passing) from 02Z on 5/15 (before the frontal system passing).

As shown in Fig. 4.6a after the frontal passage, the surface pressure increase is greater in northern and eastern Taiwan than in southwestern Taiwan. This distribution of local pressure change has a similar result as the cold front passes through Taiwan (feature in Chen et al., 2002a; Fig. 13), although the value is smaller. It is not surprising to see the temperature decrease in areas where the pressure increases. The most salient feature is the surface temperature decrease found in the southwestern areas. Since the diurnal solar heating
The different local impacts caused by the frontal passage in Taiwan is presented, while $\Delta p_s (T_s, V_s) = p_s (T_s, V_s)$ at 05/16/02Z;10L subtract $p_s (T_s, V_s)$ at 05/15/02Z;10L. (a), (b), and (d) are the changes of surface pressure, surface temperature, and surface wind field, respectively. (c) is the accumulated rainfall during 05/15/02Z to 05/16/02Z. The contour intervals of (a), (b), and (c) are 1-mb, 1°C and 2.5 mm·day$^{-1}$, respectively. The values of $P < 2.5$ mm·day$^{-1}$ in (c) are not plotted.
effect is already filtered out, the temperature decrease over southwestern Taiwan might be caused by the cloud cover and the related precipitation (Fig. 4.6c).

Unlike the temperature decrease over the lower plains, the temperature increases over the Central Mountain Range (Fig. 4.6b). In addition, a corresponding heavy rain area is found over the mountains in central Taiwan (Fig. 4.6c). Since the frontal zone is very shallow from 02Z on 5/15 to 02Z on 5/16, the local warming process might be a possible mechanism to induce the local convective system and generate the heavy rainfall there. This suggestion needs to be demonstrated by the further numerical modeling studies.

By examining the variation of surface wind, it is seen that the western stations have a clearer wind variation than the eastern stations. Since the wind direction changes in eastern Taiwan earlier than in western Taiwan, the more uniform wind field is revealed in the eastern stations during the first rainy period. In addition, the enhanced northerly wind shown in western stations might be caused by the down slope wind generated by the heavy rainfall. Therefore, it is expected to see the results shown in Fig. 4.6d.

IV. The Analysis of Sounding Data

a. The variation of moisture

Since the onset of the East-Asian summer monsoon is highly related to the activity of the Meiyū frontal system, which is marked by the significant moisture gradient, it is worthwhile to examine the variations of moisture during the summer season. Using sounding data twice a day from 1 May to 30 May 2002, the vertical time-evolution of wind field and the dew point depression \( \Delta T_d = T - T_d \) in Taipei (north of Taiwan), Hualien (northeast of Taiwan), and Ping-Nan (southwest of Taiwan) are presented in Figs. 4.7a, 4.7b and 4.7c, respectively. Their locations are shown in the map at the bottom of Fig. 4.8. The lower values of the dew point depression, stippled with the darker color, indicate a higher moisture content and thus a higher likelihood of precipitation.
Fig. 4.7  The altitude (z) – time (t) diagrams of wind field (V) and dew point depression ($\Delta T_d = T - T_d$) plotted by the sounding data at Taipei, Hualien, and Ping-Nan are shown in (a), (b) and (c), respectively. (d) represents the same variables (V, $\Delta T_d$) at (120°E, 22.5°N) by NCEP reanalysis data. The values of $\Delta T_d \leq 6$ and $\Delta T_d \leq 3$ °C are lightly and heavily stippled at (a), (b) and (c), while the values of $\Delta T_d \leq 8$ and $\Delta T_d \leq 6$ °C are lightly and heavily stippled at (d). The downward vectors indicate the onset time step: 05/15/06Z in 2002.
The altitude (z) – time (t) diagrams of zonal wind (U; contour) and time departure of temperature \( \Delta T \) at three same stations with Fig. 4.7. The values of \( \Delta T \geq 0.5^\circ C \) and \( \Delta T \leq -0.5^\circ C \) are heavily and lightly stippled.
It is surprising to see all of these three local observational sounding data showing that the moisture suddenly builds up and extends into the upper-troposphere after the summer monsoon onset of 2002. Before the Meiyu onset, the moisture is trapped in the lower level while smaller values of $\Delta T_d (< 6^\circ \text{C})$ are observed below 700-mb. During the Meiyu onset, the higher moisture as indicated by the areas of $\Delta T_d < 6^\circ \text{C}$ can reach into the upper troposphere around 400 to 300-mb. Previous studies (e.g. Ninomiya, 1984; Johnson and Bresch, 1991) mentioned that the moisture gradient is a significant factor for the generation of the Meiyu frontal system. However, this interesting phenomenon where the moisture suddenly builds up and reaches into the upper levels after the Meiyu onset has not been clearly presented in previous studies by examining the time-evolution of the dew point depression.

Is 2002 a special, individual case? Do other years show the phenomenon of moisture builds up after the Meiyu onset? Luo and Yanai (1984) mentioned that the higher moisture was revealed at the eastern Tibetan Plateau in the 1979 summer monsoon onset over China. Johnson and Bresch (1991) pointed out that the higher moisture is in association with the unstable Meiyu frontal system during the Meiyu season in 1987. In addition, Ninomiya and Murakami (1987) mentioned that the higher values of the water vapor mixing ratio were observed in the middle of the troposphere (500-mb) during the Japanese Baiu season in 1968. These findings suggested by the previous studies imply that a similar phenomenon may have occurred in the other years. Once the sounding data in Taipei and Hualien was verified from 1979 to 2002 (not shown), while a similar feature of the moisture buildup after the Meiyu onset are found every year.

The analysis of the variation of moisture based on the sounding data indicates the onset of Meiyu season in Taiwan and surrounding areas. Kalnay et al. (1996) classified the moisture of the NCEP reanalysis data as type B, which can be strongly affected by both the observations and model. Is the re-analysis data from NCEP able to show a similar local
phenomenon? Observing Fig. 4.7d, the dew-point depression analyzed by the NCEP reanalysis data in the area (120°E, 22.5°N) also shows the moisture buildup after the Meiyü onset. The higher similarity between the NCEP reanalysis data and the sounding data enable us to research the relationship between the summer monsoon onset and the process of the moisture increase by the former instead of using the latter.

As mentioned before, the lower value of the dew point depression associated with the frontal passage in Taiwan is not only shown in the surface stations in the lower plains, but also in the higher mountains. Comparing Figs. 4.7a-c, this feature is coherent with the results shown by the sounding data. During the summer season, the enhanced low-level southwesterly winds cause the air over southwestern Taiwan to become more moist and wetter than northeastern Taiwan. Therefore, it is likely to see higher moisture in the middle and upper troposphere over Ping-Nan (southwestern station) than the moisture over Hualien and Taipei (northern stations) after the Meiyü onset.

b. The vertical structure of the frontal system

In our previous discussion, seven different altitude stations were selected to examine the vertical evolution of the frontal zone. Does the sounding data depict a similar vertical structure of the frontal zone as our previous discussion? In order to answer this question, the temperature anomalies (taken out the monthly mean of May in 2002) are superimposed with the zonal wind field observed in the sounding data in Fig. 4.8. The major features shown in Fig. 4.8 are summarized as follows:

1) Two well-depicted thermal dipole structures (warm-cold) were observed between 5/14 to 5/18 and between 5/21 to 5/25. Before the front arrived, the temperature increased (heavy shaded areas in Fig. 4.8). After this period, the temperature decreased (light shaded areas in Fig. 4.8). This feature is observed in both the lower and upper troposphere.
2) The feature of clear zonal wind direction change associated with the passage of the frontal system is trapped in the lower level (< 800-mb) during the Meiyū onset of 2002. Before the front arrived, the westerly wind \((u > 0)\) dominated the low-level circulation in Taipei and Hualien. Until the cold airs reach the north of Taiwan, the wind starts to change from westerly \((u > 0)\) to easterly \((u < 0)\). As comparing Fig. 4.7c and Fig. 4.8c, the local wind field in Ping-Nan did not show the easterly wind clearly \((u < 0)\) after the passage of the frontal system between 5/14 to 5/18, but did undergo a wind direction change from southerly (before the front passes) to northerly (after the front passes).

3) The intensified upper level jet stream is well coupled with the cold air in the lower levels. The increase of the horizontal temperature gradient in the lower levels can enhance the upper level jet stream. Besides this, the westerly wind in the lower troposphere is also intensified. The possible maintenance mechanism of the Meiyū frontal zone is the low-level jet stream as suggested by previous studies (e.g., Ninomiya and Murakami, 1986).

V. The Comparison Between a Large-scale Circulation and the Regional Weather Condition

In order to analyze the modulation process, three different stages—before, during, and after frontal passage, the dates at 00Z on 5/15, at 00Z on 5/17, and at 00Z on 5/18 in 2002—were selected to represent the three different stages, respectively. The local surface wind field (vector), surface temperature (triangle), and the precipitation (open circle) observed by the surface stations in Taiwan are superimposed with the large-scale surface wind field (Fig. 4.9). On the other hand, the corresponding local vertical Hadley cell circulations (averaged between 120°~122.5°E) are used to describe the variation of the vertical motion (Fig. 4.10).
Fig. 4.9 Three time steps at 05/15/00Z, 05/17/00Z, and 05/18/00Z are selected to present the characteristics of surface wind ($V_s$; vector), surface temperature ($T_s$; triangle), precipitation (P; open circle) and IR (gray colors) before, during, and after the passing front in Taiwan. The surface streamline charts of large-scale circulation are superimposed with those local weather factors.
Fig. 4.10 Mass flux functions \( (\psi_m, P_{\text{NCEP}}) \) and precipitation \( (P_{\text{NCEP}}) \) between \( (120\text{°}\text{E} - 122.5\text{°}\text{E}) \) at the same three time steps with Fig. 4.9. The positive values of \( \psi_m \) are lightly stippled. The location of Taiwan is marked with a thick line.
a. Before the frontal system passes

At 00Z (08LST) on 5/15/2002, the enhanced southwesterly wind dominates the low-level circulation over Taiwan and the surrounding areas (Fig. 4.9a). Climatologically, the daily variations of local wind field in Taiwan are dominated by land breeze or sea breeze, which is related to the diurnal variation. However, it is shown by Fig. 4.9a that the local wind field has a stronger component as opposed to that of the land breeze or sea breeze, which have a more easterly/westerly component, especially in the western stations of Taiwan. The enhanced southerly wind in the lower troposphere can also be found by examining the circulation of the mass flux function (Fig. 4.10a). Associated with the southerly wind, the warm and moist air is advected from south to north. When the warm moist air meets the cold and dry air from the north, upward motion results in a heavy rainfall over the area around 35°N ~ 40°N.

b. During the frontal system passes

Later on, the frontal system propagates eastward and starts to generate rainfall in northwestern Taiwan. A number of medium or small-scale cloud systems pass and affect the local weather conditions in Taiwan during the second and third rainy periods. The process of the enhancement or the weakening process of these medium or small-scale disturbances is not clear and needs more numerical modeling studies. Figure 4.9b shows a squall line, which was located over the western coastline of Taiwan at 00Z on 5/17/2002, and the mesoscale convective systems observed east of Taiwan at the same time. These two weather features affect the distribution of precipitation. The life cycles of these small or medium-scale patterns are shorter than the major synoptic front. In addition, the faster enhancing or weakening processes of these patterns cause the local wind directions to change more frequently. Therefore, the predictions for the local wind field become more difficult during the frontal passage.
Only with the passages of the leading edge of the front and of the active mesoscale convective systems over Taiwan have the more clear temperature and pressure changes. In contrast, the other small weather systems do not have a significant influence on the local pressure and temperature variations. The eastern stations experienced precipitation during the second and third rainy periods due to the mesoscale or small-scale convective systems embedded in the major frontal system. The cloud cover and the heavy rainfall cause a local temperature decrease during the frontal passage. When the frontal system moves into Taiwan, the local Hadley cell circulation also moves southward. It is revealed in Fig. 4.10b that the active upward motion is located over Taiwan at 06Z on 5/17/2002. The cold and dry northerly wind start to dominate the large-scale circulation around Taiwan after the frontal system's passage over Taiwan (Fig. 4.10c).

c. After the frontal system passes

Not only the large-scale circulation, but also the local surface wind field clearly shows the northerly wind after the frontal passage during the onset of the East-Asian summer monsoon (Fig. 4.9c). In other words, the large-scale circulation at 00Z on 5/18/2002 plays a more important role than the land-sea breeze effect. Comparing Fig. 4.9a and Fig. 4.9c, the wind direction change from southwesterly to northerly causes the temperature change from warmer to cooler. After the frontal passage, the downward motion dominates the vertical circulation over Taiwan and the surrounding areas at 00Z on 5/18/2002 (Fig. 4.10c). The southward movement of the mass flux function indicates that the cold air advection affects the weather in northern Taiwan earlier than in southern Taiwan.
CHAPTER 5: CONCLUDING REMARKS AND FUTURE STUDIES

The summer monsoon rainfall has a significant impact on the Asian society. The Asian summer monsoon includes two major monsoon areas, the Indian monsoon and the East-Asian monsoon. After the summer Monsoon Experiment (MONEX) was conducted in 1979, the onset mechanisms of the Indian summer monsoon have been widely discussed. Later on, the East-Asian summer monsoon and the South China Sea summer monsoon were also investigated by many studies. In 1998, the South China Sea Monsoon Experiment (SCSMEX) was conducted for a more detailed analysis for understanding the SCS monsoon. Possible mechanisms, which trigger the onset of the East-Asian summer monsoon suggested by previous studies, include Tibetan heating (e.g., He et al., 1987; Luo and Yanai, 1983, 1984) and the phase locking feature between 10-20 day and 30-60 day monsoon mode (e.g., Lau et al., 1988; Tananka, 1992; Chen and Chen, 1995).

In May and June of 2002, the Taiwan Monsoon Experiment (TMEX) was conducted to gather data for study the onset mechanism of the East-Asian summer monsoon. The local observational datasets gathered by the TMEX provides an opportunity to investigate the local impacts caused by the passage of the frontal system during the onset period. This study focused on researching the onset mechanism of the East-Asian summer monsoon and its local impacts.

I. The Onset Mechanism of the East-Asian Summer Monsoon

The East-Asian summer monsoon covers a large area. The summer monsoon onset is defined by the formation of significant rainfall generated by the Meiyü rainbelts (the so-call Meiyü onset). The climatological Meiyü onset date varies with the northward
migrating subtropical high. In the present study, the first transition period (onset period) of the East-Asian summer monsoon after May is investigated. First, the comparison of the circulation change between climate and individual year (2002) was discussed. Second, the time evolution of the large-scale circulation during the onset period in 2002 in the upper and lower troposphere was described and used to determine the necessary environmental condition, which can trigger the summer monsoon. Third, the discussion of the onset of the East-Asian summer monsoon in 1979 (MONEX year) and 1998 (SCSMEX year) were made to compare with the onset circulation in 2002 (TMEX year). Finally, the maintenance mechanism of the Meiyü rainbelt was examined. The major findings in this study are summarized as follows.

a. The comparison between climatological onset date and the onset date of 2002

The East-Asian summer monsoon undergoes interannual and intraseasonal oscillations. Based on the GPCP satellite-derived (IR) GPI daily rainfall data and the rainfall record in Taiwan, the climatological onset date of the East-Asian summer monsoon during 1996 to 2002 was defined as 5/19. The features of the large-scale circulation change at this time include:

1. The upper level Meiyü trough, Meiyü ridge, subtropical jet, and northern branches of the split flow, which comes from the jet stream over Iran, characterized the climatological midlatitude upper level circulation over East Asia. On the other hand, the tropical upper level circulation was marked by two anticyclonic flows; one over the Arabian Sea and another over South China. The southern branch of the split flow from Iran interacts with two upper level tropical anticyclones to form an upper level tropical trough between them. The role played by this tropical trough and the importance of the split flow for the onset of the East-Asian summer monsoon were
2. Under the enhanced jet stream over East Asia, an active rainbelt was observed in the lower-levels. The climatological low-level circulation at 925-mb is regulated by the subtropical high, the cold-core anticyclone behind the front, the monsoon westerlies, the midlatitude front, and the tropical Indian monsoon low.

The 2002 summer circulation onset is at 06Z on 5/15. The major feature in both the lower and upper levels is similar with the climatological onset circulation. Two interesting features are shown in the large-scale circulation of the onset case of 2002.

- A large upper level trough combined with a midlatitude Meiyu trough and tropical regional trough are shown in the onset case of 2002. An enhanced jet stream associated with the large upper level trough over East Asia is suggested as a possible maintenance mechanism of the low-level Meiyu rainbelts.

- A well developed low-level trough line over the East China Sea was observed under the jet stream over East Asia. The low-level trough was highly coincidental with the active Meiyu cloud band and the distribution of active rainfall. The formation of the low-level trough is suggested to trigger the onset of the East-Asian summer monsoon.

How is the upper-level tropical trough formed? How much does the jet stream over East Asia enhance the front? The upper-level tropical trough is generated by the interaction between two tropical anticyclones. Since these two tropical anticyclones have opposite propagating directions, the regional tropical trough is formed between them. Shown in our discussion, the tropical trough system is highly related to the southern branches of the split flow from the jet stream over Iran. On the other hand, when the split flow from the jet stream over Iran converges together, it can enhance the jet stream over East Asia.

The well developed low-level trough over the East China Sea was formed by the interaction between the subtropical flow, the monsoon westerlies, and the cold-core anticyclonic flow behind the low-level front. After the onset of the summer monsoon, the
lower pressure at the surface associated with the low-level Meiyū trough covers the entire East Asia region. The significant rainfall related to the Meiyū cloud band indicates the onset of the East-Asian summer monsoon.

b. The analysis of longitude (x) -time (t) diagram

The upper level trough system is the maintenance mechanism of the low-level Meiyū frontal zone. The coupling processes between the midlatitude and tropical regional trough systems are important for the formation of the upper-level trough system. By examining the time series of the upper level circulation and the longitude (x) -time (t) diagram of \( \psi (300 \text{ mb}) \), the coupling process of these two upper level troughs was presented in the onset case of 2002. Shown in our previous discussion, the coupling process facilitates the onset of the East-Asian summer monsoon.

The most different characteristic between the upper-level midlatitude and upper-level tropical trough systems is that the midlatitude trough moves faster than the tropical trough system. Therefore, the eastward propagating midlatitude trough will not always connect with the tropical trough system. When the troughs connect, the upper level trough becomes extended from north-south, and more active cumulus convection related to the low-level Meiyū frontal zone is observed. The length of time which two upper level troughs are connected determines the life of the low-level frontal zone.

Lau and Li (1984) mentioned that the Meiyū frontal system is influenced by the midlatitude and tropical weather systems. Ding and Liu (2001) showed this interaction during the onset time of the SCS monsoon in 1998 by using the five-day mean streamline chart at 850-mb and OLR data. However, these studies did not examine the interaction process between the midlatitudes and tropical systems by discussing the variation of the upper level large-scale circulation. Shown in the previous discussion, the upper level circulation of the onset case in 2002 indicates the existence of the coupling process between
the midlatitude and tropical upper level troughs. This feature is evidence of that the Meiyu frontal system is influenced by the midlatitude and tropical weather systems.

In the lower-levels, the longitude-time diagram of $p_s$ depicts the development and movement of the tropical and midlatitude weather systems. Associated with the generation and the movement of lower level Meiyu front, a well-developed surface lower pressure zone, which extended into East Asia, was observed after the monsoon onset.

c. The comparison between MONEX, SCSMEX, and TMEX years

In our present study, the coupling process between the midlatitude and the tropical trough systems is suggested as a necessary condition for the enhancement of the upper level jet stream over East Asia, which is a maintenance mechanism of the lower-level active Meiyu frontal system. More evidence to support our finding is made by the analysis of the summer monsoon circulation in the other two years, the MONEX year (1979) and the SCSMEX year (1998).

The onset of the East-Asian summer monsoon in 1979 was at 12Z on 5/15. The related Meiyu rainbelt is composed of two different weather systems, the northward propagating tropical system from the western tropical Pacific and the eastward propagating midlatitude front from central China. A similar coupling process of the upper level midlatitude trough and the tropical trough systems is observed in 1979. However, different from the onset time step of 2002, the upper level midlatitude system is coupled with the upper level tropical trough system over the northern South China Sea in the onset time step of 1979, not over the Bay of Bengal.

The Meiyu onset over East Asia in 1998 was at 00Z on 5/18. The active Meiyu rainbelt extended from the Bay of Bengal across Indochina, Taiwan to south of Japan. The upper level Meiyu trough and the tropical trough over the Bay of Bengal maintain the active lower-level front at the onset time step of 1998, while the upper level jet stream over East
Asia is maintained by the split flow over China. The original source of this split flow is the upper level jet stream over Iran. Similar with the onset case of 2002, in 1998 the water vapor support for the onset case of low-level Meiyü rainbelt originated in the Bay of Bengal. However, the water vapor support for the onset case of 1979 came from the South China Sea.

The common features of the onset case from these three years include:

- The upper level split flow from the jet stream over Iran enhances the jet stream over East Asia. The jet stream over East Asia maintains the low-level active Meiyü rainbelts.
- The connection between the regional upper-level trough and the upper-level tropical trough forms a large upper level trough over East Asia.
- The subtropical high over the western Pacific Ocean modulates the cold-core anticyclonic flow behind the front and forms a low-level Meiyü trough line to stimulate the generation of active rainfall.

d. The maintenance of the Meiyü frontal system

The divergence field, the water vapor budget, and the vorticity budget have been used in a more detailed discussion for the maintenance mechanism of the low-level Meiyü rainbelt. At 06Z on 5/15/2002, a convergence line associated with the active Meiyü rainbelt was found at $\chi_{1000mb}$ over East Asia. At the same time, another convergence line was found over South China. These two convergence lines connected together to form a longer convergence zone, which coincide with the distribution of precipitation. Corresponding to the low-level convergence lines, the upper levels show a large zone of divergence. This divergence zone combines with two major divergence areas; one over the East China Sea and another over South China. As shown in the distribution of $\chi_0$, two convergent centers of water vapor are found and coincident with the low-level convergent centers of $\chi_{1000mb}$. The lower-level convergence and the upper-level divergence indicate active upward motion over
East Asia. Associated with this upward motion, the convergence of the water vapor introduces the precipitation along the frontal zone.

Three cross-sections along the front were selected to search for the interaction between the upper-level jet stream and the upward motion related to the front. These cross-sections show that the upward motion exists in front of the upper level jet stream and the downward motion exists under the jet core. The cold air outbreak behind the front increases the horizontal temperature gradient and enhances the upper level jet stream, while the upper level jet stream maintains the low-level front. In the southern part of the frontal zone, the upward motion is less baroclinic since the horizontal temperature gradient is weaker. However, the middle and northern part of the front is more baroclinic since a stronger temperature gradient exists there.

Associated with the upward motion, the positive vortex stretching term at the lower level intensifies the low-level cyclonic flow and helps the development of midlatitude cyclone. On the other hand, the positive vorticity advection dominates the downstream side of the upper-level trough. This positive vorticity advection maintains the low-level front and causes the low-level front propagating eastward.

II. The Impact of the Meiyü Frontal Zone for the Regional Weather Change

The onset mechanism of the East-Asian summer monsoon was demonstrated by the variation of large-scale circulation in this study. Since the Meiyü onset is important for the East-Asian society, a downscale analysis was made for the study of the regional impact of passage of the Meiyü frontal zone.

Taiwan has a high-density network of observational data, which is helpful because of its unique topography. The Central Mountain Range oriented north-south with the highest mountain Yushan (~4 km) separates Taiwan into two areas. During the winter, eastern
Taiwan is on the windward side with the northeasterly wind. In contrast, southwesterly wind in the summer monsoon indicates that western Taiwan is on the windward side during the summer season. It is now generally believed that the Meiyu front is a shallow front with a significant moisture gradient. Thus, other questions are raised in this study:

1) What is the influence of the front at different altitudes? Is this front a shallow front?
2) What are the different local impacts shown in eastern and western Taiwan?
3) Can sounding data indicate the onset of the summer monsoon over Taiwan?
4) How can the large-scale circulation regulate the local weather conditions? What are the variations of weather conditions before and after the frontal passage in the onset case of 2002?

a. The characteristics of the propagation of Meiyu frontal zone across Taiwan

The Meiyu front starts to affect the local weather in Taiwan after 06Z on 5/15/2002. Its propagating process is from west to east and from north to south, and it moves out away from Taiwan after 12Z on 5/17/2002. The cloud band is combined with several characteristics. Behind the major frontal zone several squall line systems caused by the density current are revealed. The mesoscale rainstorms associated with the front are observed at 06Z on 5/16 in the southern part of the front. The mixed synoptic scale and mesoscale systems are the special characteristics of the Meiyu cloud band.

Three major rainy short periods are observed during the frontal passage. Before 18Z on 5/16, the shallow frontal zone causes the rainfall. After this, the front with embedded active convection starts to affect Taiwan and results in the second and third rainy periods until the frontal system is away from Taiwan.
b. The different local impacts between high mountains and lower plains

Examining seven stations with different altitudes from the lower-plains to higher mountains in Taiwan, a clear pressure and wind direction change can reach up to 1 km (TaTunShan; 1099 m) when the front first touches northern Taiwan. Within the southward movement, the front becomes weaker and is shallower than 1 km over central Taiwan since both of the time series for $p_s$ and $V_s$ do not show an abrupt change in high mountains stations. Therefore, the modulations of the Meiyu frontal zone due to the regional topography are demonstrated by the surface observational data.

Unlike the clear variation of wind field and pressure field trapped in the lower levels, the thermal structure associated with the frontal passage can reach into the upper levels. Related to the southerly wind, the lower plains show a temperature increase before the frontal passage. When the front arrives, the cloud cover over Taiwan results in the suppression of the diurnal variation of the surface temperature. This feature also cloud be observed in the higher mountains stations. However, unlike the typical cold front, the Meiyu frontal zone has weaker temperature gradients. In addition, the diurnal cycle of temperature is suppressed by the frontal passage, but is not as significant as the cold front passing. As shown in our discussion, the variation of precipitation was highly correlated with the variation of dew point depression ($\Delta T_d = T - T_d$). The precipitation and the higher moisture values (smaller value of dew point depression) can also be observed in the stations at the higher altitudes.

c. The different local impacts between eastern and western Taiwan

The enhanced southwesterly winds ahead of this front intensify the effect of the windward pressure ridge in western Taiwan and the leeward pressure trough in eastern Taiwan. This result is similar to the results of Trier et al.'s (1990) study. However, in their study they did not pay attention to the pressure change after the frontal passage. Chen et al.
(2002a) analyzed cold surge cases passing over Taiwan, where they found northern and eastern Taiwan underwent more clear surface pressure changes than any other place. Effort was made in this study to find out what is the feature of the local weather change after a Meiyū frontal passage in the summer monsoon onset period.

It was mentioned in our previous discussion, after the frontal passage the southwesterly wind switches to the northeasterly wind and eastern Taiwan becomes on the windward side. The pressure increase in eastern stations is clearer than in the western stations. In addition, the pressure change during the frontal system’s passage is more observable in eastern Taiwan.

Western Taiwan was under a cloudy sky earlier than eastern Taiwan during this analysis period. Since the cloud cover suppressed the diurnal solar heating in western Taiwan, the temperature increase noted in the western stations during this period are mainly caused by the warm air advection. In contrast, under the clear sky, eastern stations have more clear temperature increase due to the diurnal heating combined with the warm air advection. Coherently with the surface pressure increase observed in eastern Taiwan, the surface temperature decrease is also observed in the eastern stations.

Comparing the weather conditions with more stations, the pressure and temperature variations are even smaller in southwestern Taiwan. The precipitation is located in northern and western Taiwan, but is not shown in eastern Taiwan during the shallow frontal system’s passage. The blocking effect of the Central Mountain Range in Taiwan is the possible explanation.

d. The analysis of sounding data

The analysis of the sounding data shows the sudden buildup of moisture can extend into the upper levels after the Meiyū onset. Not only the sounding data, but the NCEP reanalysis data also has a similar result. Therefore, the vertical time-evolution of the
variation of moisture is suggested as a good indicator for researching the onset of summer monsoon over East Asia. Comparing the vertical time evolution of the dew point depression in northern Taiwan (Hualien and Taipei) and southwestern Taiwan (Ping-Nan), the upper level moisture in southwestern Taiwan is higher than at the other stations after the Meiyū onset. This result is similar to Chen et al.'s (1999) study that southwestern Taiwan has more precipitation in the summer season.

As the frontal system passes, the temperature variations from warming and cooling can be observed in both the lower and upper troposphere. In contrast, the corresponding horizontal zonal wind direction changes from westerly to easterly become trapped in the lower troposphere below 800-mb. These results are coherent with the analysis of the surface observational data in high mountains and low plains.

Enhanced low-level westerly winds are found in the warm areas of the frontal system, while intensified jet streams in the upper levels are observed above the cold areas. As suggested by many studies, the low-level jet streams are also a possible maintenance mechanism of the Meiyū front (e.g., Ninomiya and Murakami 1986). In our present study, the influence of the low-level front from the upper level jet stream is shown and is demonstrated that the upper level jet stream is important for the onset of the East-Asian summer monsoon.

e. The comparison between large-scale circulation and local weather conditions

To examine the regulation between large-scale circulation and local observational weather conditions, three time stages, before (00Z on 5/15), during (00Z on 5/17), and after (00Z on 5/18) the frontal system's passage are selected for discussion.

The enhanced southerly wind shown at the local stations before the frontal passage demonstrates that the large-scale circulation is regulated by the local weather conditions. In
addition, the differences in the wind field between the former and the latter indicate that the large-scale circulation is modulated by the local topography. Before the frontal passage in Taiwan, the Hadley cell circulation depicts the upward motion located north of Taiwan.

As the front moves into Taiwan, the variation of the local wind fields become messy and is difficult to match with the large-scale circulation. It is caused by a number of passages of different small and medium scale weather patterns, such as squall lines or mesoscale convective systems. The temperature decrease during the front's passage is caused by three major effects: the cold air advection, the cloud cover and the precipitation in Taiwan. The Hadley cell circulation shows that the most active upward motion is located over Taiwan and surrounding areas as the front passes.

After the front is passing, the enhanced northerly wind dominates the variation of both the large-scale circulation and the local wind fields. The wind direction change before and after the frontal system's passage as revealed in this case is highly related to the variation of the large-scale circulation.

III. Recommendations for Future Study

1. It is shown in this study that the split flow is important for the enhancement of the jet stream over East Asia. Tracing the original source of the split flow, this study pointed out that the jet stream over Iran is the root of the split flow. However, why the jet stream splits into two parts over China is still unclear and needs further study.

2. It is now known that the East-Asian summer monsoon undergoes interannual and intraseasonal variations. Do the jet streams over northeastern Asia have the same interannual and intraseasonal variations as the monsoon rainfall? Are the variations of the East-Asian jet stream coincidental with the variations of the jet stream over Iran? If so, what is the possible influential effect for the jet stream over Iran?

3. The lower level Meiyü frontal zone was associated with the large upper level trough
system. As we mentioned earlier, the enhanced trough line was combined with the midlatitude and tropical regional trough systems. The tropical regional trough was found over South China Sea in 1979 and over the Bay of Bengal in 1998 and 2002. Do the different tropical trough systems explain that the East-Asian summer monsoon is related to the South China monsoon onset? What is the possible reason to explain the variation of the tropical trough system? Does it relate to the variation of a wet and dry summer year?

4. To define the climatological onset date, previous studies usually use the precipitation data as the index. Since the vertical time evolution of the dew point depression depicts the onset of Meiyu season, it would be interesting to see if other monsoon areas have similar results.

5. The monsoon onset date is modulated by the northward migrating subtropical high; do the moisture variations defined by $\Delta T_d$ also behave the same way? In addition, do they undergo the interannual and intraseasonal variations?
Fig. A-1 The major elements of the summer monsoon over South China Sea to western tropical Pacific. The thick solid line represents the major flow pattern of the summer monsoon, while the local Hadley circulation is represented by the dashed line (after Chen and Weng, 1997).
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