Revisiting the Structure and Characteristics of an Early Summer Monsoon Trough over South China in 1975

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Abstract

The ECMWF 2.5° gridded analysis was used to re-examine the evolution of the synoptic flow patterns and frontal structure of an early summer monsoon trough that occurred during 10−15 June 1975. A blocking pattern that began with an omega shape developed into a Rex pattern on 12 June. During 10−14 June, the blocking low pressure and associated trough axis were almost stagnant. As a result, the Mei-Yu front was quasi-stationary and affected the Taiwan area for more than four days.

Similar to other frontal systems during the early summer rainy season over southern China, this Mei-Yu front exhibited baroclinic characteristics in the upper troposphere. In the lower troposphere, appreciable temperature gradients and maximum frontogenesis due to horizontal deformation between the postfrontal northwesterlies and prefrontal southwesterlies were diagnosed. The western section (~115°E) of this frontal system exhibited a marked northward vertical tilt. An upper-level jet near the tropopause was also present. A moist tongue was located south of the surface cold front within the low-level southwesterlies and extended vertically upward. A thermally direct circulation across the front with ascending motion within the prefrontal warm, moist air and descending motion within the postfrontal cold, dry air underneath the upper-level jet was diagnosed.

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1. Introduction

Based on climatological rainfall observations over Taiwan, the summer monsoon rainfall shows two distinct seasonal maxima: 15 May to 15 June, the transition period from prevailing winter northeasterlies to summer southwesterlies; and July−August, the typhoon season (Wang et al. 1985). The early summer monsoon trough occurs in southern China in mid-May and migrates to central China and Japan in mid-June (Yoshino 1965; Wang and LinHo 2002).

Most of the Mei-Yu fronts during the early summer monsoon season over Taiwan (15 May−15 June) occur prior to or during the migration of the early summer monsoon trough from southern China to the Yangtze Valley basin and southwestern Japan (Yoshino, 1965). The passage of subtropical cold fronts is often accompanied by heavy rainfall (Trier et al. 1990; Chen 1993).

During 10−15 June 1975, a Mei-Yu frontal system affected the Taiwan area for more than four days with intermittent heavy rainfall periods with significant flooding. Chen and Chang (1980) used subjectively analyzed grid data to describe the structure of this Mei-Yu frontal system. The data were analyzed every 12 hours at only four levels (e.g., 850-hPa, 700-hPa, 500-hPa, and 400-hPa levels) with a horizontal grid of 240 km. Their gridded data was first subjected to a 25-point smoother. They then divided this frontal event into two stages based on the life cycle of this event and presented the composite frontal structure for both stages.

They found that the eastern and central sections of the Mei-Yu front were similar to the mid-latitude baroclinic fronts. However, they suggest that the western section (~115°E) in the subtropics resembled a tropical disturbance such as the intertropical convergence zone (ITCZ) with weak temperature gradients, little vertical tilt, slow southward movement, but with large moisture gradients in the lower troposphere. Furthermore, there was also intense cumulus convection and a thermally direct secondary circulation. Both of these features appeared to be induced by a conditional instability of second kind (CISK) process in the western section of the front (Chen and Chang 1980).

Recently, Chen (1993) studied the structure of all eight frontal systems during the Taiwan Area Mesoscale Experiment (TAMEX; Kuo and Chen 1990). Except for the last frontal system (IOP #13), which occurred during the northward seasonal migration of the early summer monsoon trough from the Taiwan area to the Yangzte River Valley (23−25 June), all the TAMEX fronts exhibited baroclinic characteristics that resemble a mid-latitude cold front. Chen et al. (1994) diagnosed a TAMEX front that affected Taiwan during 1−2 June 1987. They showed that the frontal system is characterized by tropopause folding and an upper-level jet at the 250-hPa level, large temperature gradients near the surface, a thermally direct circulation across the baroclinic zone, and a very weak thermally indirect circulation to its south. The baroclinic frontal characteristics diagnosed by Chen et al. (1994) are rather typical for surface fronts that affect the Taiwan area during the early summer rainy season (Chen et al. 1989; Chen and Hui 1990; Trier et al. 1990; Chen and Chen 2002; Tu et al. 2014; and others). Furthermore, all these fronts propagate southeastward from southern China to the Taiwan area bringing intermittent rainy periods that lasted only about one to two days.

In this study, the 10−15 June 1975 case is revisited using gridded global data that are readily available in recent years. Recent global gridded data sets have better spatial-temporal resolution with more vertical levels than the gridded data used by Chen and Chang (1980). The evolution of synoptic-scale patterns related to the slow-moving nature and structure of the frontal system over southern China (baroclinic vs. equivalent barotropic) is re-examined.

2. Data and methodology

The global data analyzed by European Centre for Medium-Range Weather Forecast (ECMWF) Re-Analysis (ERA-40) with a 2.5° spatial grid is used. The vertical levels of ERA-40 start from the 1000-hPa level to the 1-hPa level with 23 levels. Air temperature, horizontal wind field, geopotential height, vertical velocity, vorticity, humidity, and divergence are analyzed at 6-h intervals. The horizontal temperature gradients associated with a cold front are more significant near the tropopause and lower levels because the vertical motion associated with the geostrophic adjustment processes vanishes at the surface and tropopause. With only four levels between the 850-hPa and 400-hPa levels, the data set used by Chen and Chang (1980) is inadequate to delineate the relatively large temperature gradients below the 850-hPa level. 1

1 The ERA-40 data set has 23 levels, which are 1000-hPa, 925-hPa, 850-hPa, 775-hPa, 700-hPa, 600-hPa, 500-hPa, 400-hPa, 300-hPa, 250-hPa, 200-hPa, 150-hPa, 100-hPa, 70-hPa, 50-hPa, 30-hPa, 20-hPa, 10-hPa, 7-hPa, 5-hPa, 3-hPa, 2-hPa, and 1-hPa.
upper-level front, and upper-level jet found by recent studies. Furthermore, the horizontal gradients of the meteorological fields associated with the Mei-Yu front were compromised by their recent studies.

In this study, the ERA-40 analyses with 13 vertical levels from 1000-hPa to 100-hPa provide adequate vertical resolution to resolve these frontal features. Although only few remote sensing measurements are assimilated in the ERA-40 analyses prior to the satellite era in 1979, the sounding network is relatively dense over southern China. This network allows the subsynoptic-scale features of frontal structure to be resolved.

The time evolution of the synoptic omega (Summer 1954; Bluestein 1993) and Rex blocking patterns (Rex 1950) for this event is depicted by the 300-hPa charts. Next, the longitude-time Hovmöller diagrams along 115°E at the 925-hPa, 500-hPa and 300-hPa levels are constructed to show the gradual southward advance of the frontal features including the low-level windshift, thermodynamic gradients, vertical motion, and the upper-level jet.

Synoptic weather patterns at the mature stage and decaying stages are also examined. Frontogenesis due to horizontal deformations *F* (Miller 1948; Eq. (7) of Chen and Li 1995), which is defined as

\[
F = \frac{1}{V_n, \theta} \left[ \left( \frac{\partial \theta}{\partial x} - \frac{\partial u}{\partial x} \right) \left( \frac{\partial \theta}{\partial y} \right) - \left( \frac{\partial v}{\partial x} \right) \left( \frac{\partial \theta}{\partial y} \right) \right] + \frac{\partial \theta}{\partial y} \left( \frac{\partial \theta}{\partial x} \right),
\]

where \(\theta\) indicates potential temperature, \(u\) indicates zonal wind, \(v\) indicates meridional wind, and \(V_n, \theta\) indicates the horizontal gradient operator, is diagnosed for both stages at the 925-hPa level.

Finally, the vertical cross sections along 115°E were constructed to study the frontal structure in the subtropics and compare with recent studies.

### 3. Evolution of synoptic patterns

Figure 1 shows the evolution of the geopotential height and winds associated with this unusual blocking event at the 300-hPa level. At 1200 UTC 9 June (Fig. 1a), an anticyclone was located at 50°N, 118°E northwest of a low-pressure system around 39°N, 135°E. A shortwave trough extended southwestward from the center of the low-pressure system to the southeastern China coast. Another shortwave trough extended from 51°N, 95°E to 39°N, 85°E. A semi-permanent high-pressure cell was located over southwestern China with easterlies along the southern China coast. Twelve hours later (Fig. 1b), the ridge-trough pressure pattern continued to amplify and moved slowly eastward. Concurrently, the shortwave trough axis moved to 45°N, 100°E. The low-high pressure pattern indicated the presence of omega blocking.

At 1200 UTC 12 June (Fig. 1c), the eastern low-pressure center deepened with closed pressure contours and the anticyclone was located to north of this low-pressure system. The high-low pressure pattern oriented in the north-south direction resembled a Rex blocking pattern (Rex 1950). The blocking pattern occupied most of the area between 30°N to 55°N and 120°E to 150°E. The Asian jet split into subtropical and polar jets. During the next 60 hours, the trough axis extended from the blocking low-pressure center to 20°N, 115°E. The semi-permanent high-pressure system moved slightly westward to 93°E. Prior to the seasonal transition in mid-June, the semi-permanent high (or South Asian anticyclone) is over northern Vietnam with westerlies along the southern China coast (e.g., Chen et al. 1989; Chen and Hui 1990, 1992). Similar to the TAMEX IOP #13 case that also occurred during the seasonal transition (Li et al. 1997; Chen 1993), the semi-permanent high was over southwestern China with easterlies along the southern China coast. Furthermore, appreciable temperature gradients in the low levels were also found for the TAMEX IOP #13 case (Li et al. 1997). At 0000 UTC 14 June (Fig. 1d), the blocking high weakened and the blocking low moved eastward. The trough axis associated with the blocking low and split subtropical jet started to move southeastward and weakened. This Rex blocking pattern persisted until 12 UTC 14 June and dissipated during 15 June. Chen et al. (2007) studied an unusual omega blocking case during 8-13 June 2000 using ECMWF 1.125° gridded analysis data. They suggest that the low-level Mei-Yu front over southern China moved slowly southward as the blocking pattern developed (8–12 June) and that the front also possessed baroclinic characteristics.

From 0000 UTC 15 June, the Rex blocking pattern weakened and the blocking low-pressure center started to move eastward (Figs. 2a, c). Concurrently, at the 925-hPa level, the trough axis associated with the Mei-Yu front extending southwestward from the center of cyclonic circulation (~32°N, 134°E), started to propagate southeastward. At 0000 UTC 16 June, the trough axis over southern China moved eastward and dissipated (Figs. 2b, d).

To investigate the evolution and structure of the western section of the Mei-Yu front over southern China, latitude-time Hovmöller diagrams along 115°E are constructed. At the 925-hPa level, a cold pool north of the windshift line associated with the surface front is evident. The cold air moved southward from 30°N to 21°N during 10–14 June and weakened afterward. The low-level air temperature north of the cold pool behind the cold front exhibited significant diurnal variations over the China plain (Fig. 3a).

Large horizontal \(\theta\) gradients were present at the 500-hPa level between 30°N and 36°N where the northwesterlies converged with the westerlies ahead of the trough (Fig. 3c). The turning of winds from low-level southwesterlies to westerlies at the 500-hPa level (Figs. 3a, c) indicates the presence of warm advection in the prefrontal low-level southwesterly monsoon flow. After 14 June, the temperature contrast decreased as the northwesterlies behind the trough were replaced by westerlies. The axis of maximum equivalent potential temperature (\(\theta_e\)) was co-located with rising motions (Fig. 3b). This feature attests that the low-level warm, moist air was transported upward by rising motion in the frontal zone. Behind the windshift line associated with the trough axis, sinking motion within the cold, dry air is evident. The windshift line at the 500-hPa level was 3–4° north of the 925-hPa position (Figs. 3a, b). It is apparent that the frontal zone tilted northward with height.

At the 300-hPa level during 10–14 June, the upper-level jet moved southward and weakened as the Rex blocking dissipated...
The jet axis was north of the high $\theta_e$ region at the 500-hPa level. The intrusion of cold air from the north is clearly evident at all levels with the baroclinic zone tilted northward with respect to height as found in TAMEX studies (e.g., Chen 1993). The marked vertical tilt of the frontal structure in both the mature and decaying stages will be discussed further in the next section.

4. Frontal structure and diagnosis

In this section, 0000 UTC 10 June and 0000 UTC 14 June are selected to represent the mature stage and decaying stage, respectively. Figure 4 shows the synoptic-scale maps at the 500-hPa, 850-hPa, and 925-hPa levels at 0000 UTC 10 June. At the 500-hPa level (Fig. 4a), the geopotential height field shows similar patterns as compared to the 300-hPa chart (Fig. 1a) with an anticyclone at 45°N, 121°E and a cyclone at 36°N, 130°E in northeastern Asia. A trough extended from the cyclone over the Korean Peninsula to southeastern China. Note that a weak low-pressure center was located at 12°N, 110°E at the 500-hPa level. The horizontal distribution of vertical motion (Fig. 4a) shows rising (sinking) motion ahead (behind) of the 850-hPa windshift line (Fig. 4b). At the 850-hPa level, the axis of the maximum horizontal $\theta_e$ gradients occurred between the warm, moist southwesterlies and the cold, dry northeasterlies (Fig. 4b). At the 925-hPa level, the axis of maximum horizontal $\theta$ gradients and maximum frontogenesis were found along the windshift line (Figs. 4c, d). Furthermore, the subtropical jet over southern China and the presence of horizontal temperature gradients below the jet level are consistent with the thermal wind equation (Fig. 1).

In the decaying stage, at the 500-hPa level, the blocking low-pressure system moved to 45°N, 135°E and the weakening blocking high-pressure system was located at 50°N, 135°E (Fig. 5a). The windshift line at the 850-hPa level moved southward to 25°N (Fig. 5b). Behind the windshift line, the postfrontal cold, dry air advanced southward. At the 925-hPa level, the maximum $\theta$ gradients and frontogenesis along the windshift line were still present but weakened (Figs. 5c, d). The subtropical and polar jets associated with blocking persisted in the decaying stage (Figs. 1d, 5a).

Synoptic-scale vertical cross sections were constructed to depict the vertical structure of the front. In the mature stage, the rising motions occurred south of $\theta_e$ gradients with a warm, moist tongue ($\theta_e > 340$K) extending vertically upward (Fig. 6a). It is apparent that the low-level warm, moist air from the south was...
advected to the frontal zone and transported upward by the frontal circulation. The prefrontal rising motions were located above the surface cold front (~28°N), between the cold, dry polar air from the north and the warm, moist southwesterly monsoon flow from the south (Fig. 6). The temperature and $q$ gradients between the postfrontal cold, dry air and prefrontal warm, moist air exist throughout the entire troposphere and are greatest near the surface (~28°N). A low-level jet core was located south of the frontal surface with an upper-level (~150 hPa) jet farther to the north (~35°N) (Figs. 6c, d). The maximum thermal gradients associated with the upper-level front (~33°N) below the upper-level jet core are about 4–5 degrees north of the surface front. Thus, the frontal zone exhibits appreciable temperature and moisture gradients with a marked vertical tilt (Figs. 6a, b). The above frontal structure resembles a TAMEX front diagnosed by Chen et al. (1994) (their Fig. 22).

5. Summary

In this study, the ECMWF 2.5° gridded analysis (ERA-40) is used to study a Mei-Yu front that occurred during 10–15 June 1975. The ERA-40 data allows us to study the evolution of the synoptic patterns and diagnose the structure of this Mei-Yu frontal system in comparison with other cases reported in recent studies. A rare blocking pattern began as an omega blocking pattern and developed into a Rex blocking pattern on 12 June. In the meantime, the upper-level jet split into subtropical and polar jets. During 10–14 June 1975, the blocking low-pressure center was almost stagnant. The upper-level trough associated with the blocking low and the subtropical jet moved slowly from the Yangtze River Valley to southern China. The Mei-Yu front associated with the slow-moving low-pressure center lasted for more than four days until the blocking pattern dissipated. For this case, the Mei-Yu front started to propagate southeastward and dissipate as the mid-latitude blocking pattern disappeared.

The baroclinic characteristics are a common feature of Mei-Yu fronts, which affect southern China during the early summer rainy season. Similar to other Mei-Yu cases during the same period, the western section of this Mei-Yu front (~115°E) exhibited appreciable temperature gradients in the frontal zone with a marked veri-
cal tilt. The temperature gradients were the largest near the surface and above the 400-hPa levels, and an upper-level jet was also present. A warm, moist tongue was located south of the surface cold front within the low-level southwesterly monsoon flow and extended vertically upward. An axis of maximum frontogenesis due to horizontal deformation in the lower troposphere is found between the prefrontal warm, moist southwesterly monsoon flow and the postfrontal cold, dry northeasterlies. A thermally direct circulation across the front was diagnosed with ascending motion within the prefrontal warm, moist air and descending motion within the postfrontal cold, dry air.

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