Composite Structure of a Low-Level Jet over Southern China Observed during the TAMEX Period

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(Manuscript received 25 April 1995, in revised form 7 August 1997)

Abstract

Three cases of southwesterly low-level jet (LLJ) were selected during the 1987 TAMEX field phase (May–June) to reveal the structure and evolution of the LLJ. To suppress minor differences among different cases of LLJs, a composite technique was employed to obtain all the meteorological parameters with respect to the 700 hPa jet axis.

Results showed that the LLJ formed and intensified in association with a non-quasigeostrophic trough intensification process. It had a highly supergeostrophic nature. Warm advection prevailed over the jet region and moisture flux convergence occurred over the region downstream from the jet core. The distribution of divergence and vertical velocity was mainly characterized by an antisymmetrical pattern upstream and downstream with upward motion caused by the along-jet ageostrophic wind speed convergence over the exit region. It also showed an antisymmetrical pattern to a lesser degree on both the left and right sides. The characteristics of secondary circulations across the jet axis were quite different from those of the upper-level jet. A thermally indirect circulation across the jet axis was observed in the entrance and the jet core regions and a thermally direct circulation existed over the exit region.

1. Introduction

One of the very interesting features accompanying a Mei-Yu front is the existence of a low-level jet (LLJ) to the south or southeast of the 850/700 hPa trough (or shear line) (Matsumoto *et al.*, 1971; Chen, 1977b; 1978; Tao and Chen, 1987). A close relationship between extremely heavy rainfall or a mesoscale convective system (MCS) and an LLJ in the 850–700 hPa layer during the Mei-Yu season has been found in many observational case studies over various geographic locations (Matsumoto, 1972; Akiyama, 1973; Ninomiya and Akiyama, 1974; Chen and Chi, 1978; Chen, 1979; Chen, 1983; Tao and Chen, 1987; Tsay and Chain, 1987). Chen and Yu (1988) examined 35 heavy rainfall events over northern Taiwan in May and June during the years 1965–84. They found that in 84 % of the cases of heavy precipitation an LLJ with a maximum speed of at least 12.5 ms^{-1} would be present at 700 hPa 12 hours prior to the start of the heavy precipitation. Conversely, when an LLJ was present over northern Taiwan, there was a 91 % likelihood that heavy precipitation was in progress or would begin within 24 hours. The physical processes through which the existence of an LLJ leads to heavy rain-

fall have been proposed by various researchers. For example, Matsumoto (1972) suggested that the upward branch of the secondary circulation associated with the LLJ is responsible for the heavy rainfall. Chen's (1977a) study, on the other hand, suggested that the LLJ is the main mechanism for creating potential instability to the warm side of a Mei-Yu front and for generating the convective heavy rainfall by the associated convergence downstream. The existence of the LLJ was found to be essential for maintaining the pre-frontal squall line by providing the strong vertical shear in the lower troposphere (Jou *et al.*, 1990; Wang *et al.*, 1990; Chen and Chou, 1993). The horizontal vorticity existing in the vertical shear accompanying the LLJ tended to balance the horizontal vorticity produced by the cold pool near the leading edge in those squall line cases observed in the Taiwan Area Mesoscale Experiment (TAMEX).

The formation and maintenance of an LLJ to the south of an area of extremely heavy rainfall (or MCS) has also been documented both in theoretical study (Chen 1982) and numerical experiments (Ninomiya, 1980; Ninomiya and Tatsumi, 1980; Chou *et al.*, 1990). Results of Chen's study (1982) suggested that the existence of an unstable inertial-gravity wave in the ascending motion region

caused a thermally direct circulation beneath the upper-level jet to the north and a reversed circulation to the south through the geostrophic adjustment process. It was proposed that the LLJ forms through the Coriolis acceleration of northward flow in the lower branch of this reversed circulation. This Coriolis acceleration mechanism was substantiated by a numerical study of Chou *et al.*, (1990) who simulated the formation of an LLJ to the south of the area of strong convection in a two-dimensional frontogenesis model. In that study, the importance of cumulus convection and especially a slantwise structure in developing the reversed circulation and the LLJ was suggested. In addition, Ninomiya (1980) and Ninomiya and Tatsumi (1980) simulated the formation of an LLJ to the south of a convective heavy rainfall area in their primitive equation model with a convective adjustment process. They attributed the formation of LLJs to the increase of pressure gradient caused by convective warming to the north. Observational case studies (Lin and Chiou, 1985; Lin, 1988; Pu and Chen, 1988; Lin and Tsai, 1989) showed that an LLJ tends to form or to intensify to the south of an MCS in southern China. Thus, results of observational, theoretical, and numerical studies all suggested that an LLJ can form to the south of the convective heavy rainfall area, presumably through the Coriolis acceleration of the lower branch of an induced secondary circulation. Over southern China, large-scale forcing and lee cyclogenesis processes have also been suggested as possible mechanisms for the formation of LLJs in spring and Mei-Yu seasons (Chen and Pu, 1985; Pu and Chen, 1988). Composite results of Tsay and Kau (1989) indicated a strong vertical coupling between the upper-level jet and the LLJ. They suggested that the formation of an LLJ to the south of the entrance region of an upper-level jet was possibly caused by a process proposed by Chen (1982).

Ageostrophic characteristics of the LLJ over the Japan area (Matsumoto *et al.*, 1971) led to a hypothesis of downward momentum transport in the formation of an LLJ (Matsumoto and Ninomiya, 1969; Akiyama, 1973). Over the Taiwan area, on the other hand, an LLJ was usually observed prior to the major convection and decreased its intensity after the heavy rainfall (Chen and Chi, 1978; Chen and Yu, 1988). Also, the area of MCS formation was usually determined by the location and intensity of an LLJ (Chen, 1977a; Chiou and Liao, 1984; Chen and Pu, 1985). Therefore, it seems reasonable that at least some of the LLJs over the Taiwan area were the cause rather than the result of convection. The observational study of Chen and Yu (1988) showed that an LLJ may form to the south of the heavy rainfall area and suggested that the secondary circulation associated with the Mei-Yu front presumably driven by convective latent heating is a pos-

sible formation mechanism for an LLJ. Apparently, a reasonable explanation for the differences existing between the LLJs over southern China, and the Taiwan and Japan areas is not available at the present time. It is clear that the formation and maintenance mechanism of the LLJs over different geographic areas is a very interesting topic and deserves further studies.

One of the scientific objectives of TAMEX is to examine the structure of the LLJ and its relationship to MCSs. Several IOPs in TAMEX provided detailed data for this purpose (Kuo and Chen, 1990). Most of the LLJs observed in the TAMEX area had their origin in the upstream region of southern China. As the LLJ moved toward the Taiwan area, it appeared to be affected by the topography of Taiwan and intensified locally to the northwest of Taiwan. Analyses of TAMEX cases showed that the prevailing low-level southwesterly flows tended to be deflected upstream of the Central Mountain Range (CMR) due to the blocking effect of the mountain, and the LLJ appeared to form to the northwest and to the southern tip of Taiwan (Chen *et al.*, 1989; Kuo and Chen, 1990; Trier *et al.*, 1990; Chen and Hui, 1992; Chen, 1993). The purpose of this paper is to investigate the structure and evolution of those LLJs which passed the TAMEX area (20–26°N, 116–123°E) during the TAMEX period. Since southern China was the formation region of the LLJ as observed in TAMEX area, the effect of the Tibetan Plateau on the formation and evolution of an LLJ is also an important topic to be studied. However, this is not the main concern of the present paper and should be investigated in the near future.

2. Case selection

During the field phase of TAMEX in May–June 1987, there were a total of ten cases of frontal passages over the Taiwan area (Wu and Chen, 1987). Intensive observations were executed for eight out of these ten frontal cases (Kuo and Chen, 1990). Based on the LLJ criteria of Chen and Yu (1988), Chen (1993) identified six cases which had pre-frontal southwesterly flows reaching LLJ intensity. To study the structure and evolution of an LLJ, the following criteria were used for selecting the TAMEX cases.

- (a) The axis of an LLJ must pass over the TAMEX area (20–26°N, 116–123°E).
- (b) It must be a southwesterly jet with a maximum wind speed greater than 12.5 ms^{-1} (25 kt) for at least 36 h at 850 hPa and/or 700 hPa.
- (c) The level of maximum wind must be below 600 hPa.
- (d) The horizontal and vertical structure must satisfy the criteria used by Chen and Yu

Fig. 1. 700 hPa map analyses of geopotential height contours (solid, dam), isotherms (dotted, °C), and isotachs (dashed, kt) at 0000 UTC 15 May (upper panel) and 1200 UTC 16 May (lower panel) 1987. Heavy dashed lines and arrows indicate trough and LLJ positions, respectively.

(1988) with a horizontal shear greater than $7 \times 10^{-5} \text{ s}^{-1}$ and a vertical shear greater than $7 \times 10^{-3} \text{ s}^{-1}$.

There were three cases of LLJs in May 1987 which satisfied these criteria and thus were chosen in this study. All of these LLJs had their origin over southern China, propagated and intensified downstream and finally dissipated. The following definition was adopted for identifying the stages of an LLJ during its life cycle.

- (i) Formation stage: The time when an LLJ reached a wind speed of greater than 12.5 ms^{-1} (25 kt) at either 850 hPa or 700 hPa.
- (ii) Mature stage: The time when an LLJ reached its maximum intensity as shown in the 850 or

700 hPa map analysis outside the TAMEX region or indicated by the high resolution soundings within the TAMEX area.

- (iii) Dissipating stage: Twelve hours prior to the time when an LLJ wind speed became less than 12.5 ms^{-1} (25 kt) at either 850 hPa or 700 hPa.

Figures 1–3 present the 700 hPa map analyses at the formation and mature stages for the three selected cases. Case 1 LLJ (Fig. 1) with a maximum wind speed of 40 kt formed over southern China to the southeast of a short-wave trough at 0000 UTC 15 May. The short-wave trough then moved east-southeastward and merged with a deepening midlatitude trough over the East China Sea and southeastern China coast at 1200 UTC 16 May.

Fig. 2. As in Fig. 1, except at 1200 UTC 19 May (upper panel) and 1200 UTC 20 May (lower panel) 1987.

At the same time, the LLJ propagated eastward and reached the mature stage to the southeast of major trough to the northeast of Taiwan near 125°E . Upstream from this LLJ, another jet (which was not analyzed in the composite study) formed over southern China coast near 114°E . Case 2 LLJ (Fig. 2) with a maximum wind speed of 30 kt formed over southern China in a large-scale trough area between an east-west and a north-south oriented short-wave trough at 1200 UTC 19 May. It intensified and propagated eastward along with the eastward development of the east-west oriented quasi-stationary short-wave trough and reached its mature stage over the southeastern China coast at 1200 UTC 20 May. Case 3 LLJ (Fig. 3) with a maximum wind speed of 30 kt formed to the southeast of an ENE-WSW short-wave trough over southern China at 0000 UTC 21 May. It remained quasi-stationary and intensi-

fied along with the deepening of the quasi-stationary trough and reached the mature stage at 0000 UTC 22 May. For all three cases selected in this study, the LLJs tended to strengthen concurrently with the intensification of the slowly eastward moving or quasi-stationary short-wave trough. The wind speed was greater than the movement speed of the jet system ($\bar{V} > \bar{C}_J$) even between May 15 and 16 when the movement was fastest. At the same time, the horizontal length as indicated by the 30 kt isotach for each individual LLJ case tended to double between the formation stage and the mature stage. Also, the temperature gradient over an LLJ area was mainly along the jet axis at the formation stage. It became mainly across the jet axis as the LLJ intensified to the southeast of the deepening short-wave trough at the mature stage.

Fig. 3. As in Fig. 1, except at 0000 UTC 21 May (upper panel) and 0000 UTC 22 May (lower panel) 1987.

3. Data and analyses

The general characteristics of three LLJs selected are presented in Table 1. The durations were 48 h, 36 h, and 36 h for Cases 1, 2, and 3, respectively. The averaged duration for 3 cases was 28 h from the formation to the mature stage and 12 h from the mature to the dissipating stage. The averaged orientations of jet axes with respect to the north for the three cases were 70°, 73°, and 70° for the formation, mature, and dissipating stages, respectively. A composite technique was employed on these three cases to obtain the structure of the LLJ. Data at different levels were composited with respect to the 700 hPa jet axis and jet core at each different life stage of the LLJ. This is because 700 hPa was close to the maximum wind level at the mature stage and also because the jet axis at 700 hPa appeared to be nearly straight. In other words, the composite was

derived by superimposing the jet core at 700 hPa for each case, regardless of differences in geographical location. The grid of the jet core center point at the 700 hPa level was used as the coordinate origin for other levels.

Data, as obtained from the ROC TAMEX Data Management Center (now the Subtropical Data Center of the National Science Council), were analyzed and digitized subjectively. Rawinsonde data over the TAMEX area were very helpful in locating the three-dimensional position of the jet axis and in identifying jet intensity. Meteorological parameters such as geopotential heights, temperatures, dew-point temperatures, wind speeds, and wind directions at 850, 700, 500, and 300 hPa were obtained with a horizontal grid distance of 1° latitude (~111 km) over an area of 11 by 5 grids in the x and y directions. The x-direction was chosen along

Table 1. The general characteristics of three cases of LLJs selected during the 1987 TAMEX field phase.

Life stage		Formation stage	Mature stage	Dissipating stage
Case items				
1	Time	0000 UTC 15 May	1200 UTC 16 May	0000 UTC 17 May
	Intensity and altitude	43 kt at 850 hPa 42 kt at 700 hPa	45 kt at 700 hPa	35 kt at 850 hPa 32 kt at 700 hPa
	jet core position	106.0°E 24.5°N	124.7°E 26.0°N	127.0°E 27.4°N
2	Time	1200 UTC 19 May	1200 UTC 20 May	0000 UTC 21 May
	Intensity and altitude	32 kt at 700 hPa	42 kt at 700 hPa	44 kt at 850 hPa 32 kt at 700 hPa
	jet core position	112.0°E 24.2°N	116.6°E 24.0°N	119.2°E 26.0°N
3	Time	0000 UTC 21 May	0000 UTC 22 May	1200 UTC 22 May
	Intensity and altitude	37 kt at 850 hPa 33 kt at 700 hPa	43 kt at 700 hPa	31 kt at 850 hPa 33 kt at 700 hPa
	jet core position	117.0°E 25.3°N	117.0°E 26.1°N	118.4°E 24.0°N

the 700 hPa jet axis and was on the center line over the analyzed area. In the formation stage of Case 1, the center of 700 hPa was located over relatively high topography. Therefore, there were two stations without observed data at 850 hPa over the north-western quadrant of the composite region. Horizontal and vertical extrapolations were applied in the analysis to fill the data gap for this case. Hopefully, this will not result in a distortion in the composite field in the formation stage. Also, station coverage was reasonably uniform on both sides of jet axis in the formation stage. In the mature stage, it was also true for Case 3. However, there were fewer stations on the north side for Case 1 and on the south side for Case 2. The positions of all stations used on the composite maps for the formation and mature stages are presented in Fig. 4.

The stations locate reasonably uniformly and densely on both sides of the jet axis. The kinematic method was used to compute the vertical velocity at 800, 600, and 400 hPa with the boundary condition assumed to be zero at 1000 hPa and 200 hPa. The adjustment scheme of O' Brien (1970) was employed to suppress the accumulated errors in the divergence to obtain the corrected vertical motion and divergence fields. It would be interesting to compare the composite precipitation map with the composite map of vertical motion. However, only the 24 h-accumulated precipitation data were available from the ROC TAMEX Data Center at some selected stations over the composite area. Therefore, composite precipitation was not obtained. Since the jet core position was at most 2° latitude different in the north-south direction among different life stages in each case (Table 1), the mean latitude of the jet core can be taken as the average for different life stages in each case in the discussion. The difference

Fig. 4. Positions of all used stations on the composite maps for the (a) formation stage and (b) mature stage. Abscissa and ordinate are along and across the jet axis in degrees of latitude. (0,0) is the center of jet core.

of latitude among the analyzed stations for each individual case can be as large as $\pm 4^\circ$; therefore, the geostrophic winds were computed for each individual case locally. The ageostrophic winds were then obtained for the composite. Since the LLJ at the dissipating stage was mainly over the oceanic area where the problem of data sparsity would lead to an unreliable composite, only the results at the formation and mature stages are presented and discussed.

Fig. 5. Composite structure of wind and geopotential height at 850 hPa (a, b), 700 hPa (c, d) and 500 hPa (e, f) with respect to the axis of the low-level jet at 700 hPa (center line in each panel) during its formation stage (left panel) and mature stage (right panel). Geopotential heights (Z) are analyzed at 5 m intervals (solid; dam) and isotachs (dashed) at 5 kt (2.5 ms^{-1}) intervals. Wind plots with full barb and half barb represent 10 kt (5 ms^{-1}) and 5 kt (2.5 ms^{-1}), respectively.

4. Composite structure

4.1 Wind field

Figure 5 presents the composite geopotential and wind fields for the formation and mature stages at 850, 700, and 500 hPa. Note that the 700 hPa jet axis was oriented approximately 70° from the north for both stages. Therefore, the wind direction in the x direction towards the right is about 250° . At 700 hPa, the jet axis was along the center line and the winds were parallel to the jet axis as the present cases are the nearly straight jets. The maximum wind was near 35 kt at formation stage and intensified to 45 kt with the deepening trough at mature stage. At the same time, the horizontal shear also increased with the cyclonic shear on the left-hand side (NW side) greater than the anticyclonic shear on the right-hand side (SE side). The horizontal length of the LLJ, as indicated by the 30 kt isotach, was about doubled from 500–600 km at the formation stage to greater than 1000 km at the mature stage. At 850 hPa, a southwesterly jet core of greater than

30 kt was located about 300 km downstream from the 700 hPa jet core at the formation stage. It intensified and appeared to be collocated with the 700 hPa jet core at the mature stage. At 500 hPa, the westerlies and northwesterlies prevailed. At the formation stage, the 500 hPa maximum wind (northwesterlies) occurred to the northwest of the 700 hPa jet core. At the mature stage, the maximum 500 hPa wind became westerly. Thus, the LLJ core tilted vertically southwestward from 850 to 700 hPa and became practically no tilt at the mature stage. As discussed previously, the formation and intensification of an LLJ was over and/or slightly to the southeast of the trough area for each individual case, as shown in Figs. 1–3. These relationships were well reflected in Fig. 5, as the jet tended to be located over and/or slightly to the southeast of the composite trough.

4.2 Temperature field

The composite temperature field for the formation and mature stages at 850, 700, and 500 hPa

Fig. 7. As in Fig. 5, except for the composite structure of mixing ratio (q ; g kg^{-1} ; dashed) analyzed at 0.5 g kg^{-1} intervals.

700 hPa jet core area, the mixing ratio at 850 hPa decreased from 14.7 g kg^{-1} at the formation stage to 13.3 g kg^{-1} at the mature stage. A slight decrease in mixing ratio over the same area was also observed at 700 hPa. In other words, the LLJ at the mature stage moved into the less moist area from the very moist area where the LLJ formed. At the 500 hPa level, the moisture content over the jet core area was higher at the mature stage than at the formation stage. At this level, the area of maximum mixing ratio coincided with the 700 hPa jet core.

4.4 Relative vorticity

The distribution of relative vorticity for the formation and mature stages at 850, 700, and 500 hPa is presented in Fig. 8. In general, the vorticity field was dominated by shear effect at all levels. The overall pattern of cyclonic vorticity on the left-hand side and anticyclonic vorticity on the right-hand side of the jet axis existed at each level. As the LLJ intensified, both the cyclonic vorticity ($4 \sim 5 \times 10^{-5} \text{ s}^{-1}$) and anticyclonic vorticity ($-3 \sim -4 \times 10^{-5} \text{ s}^{-1}$) at 850 and 700 hPa increased. The overall increase of relative vorticity accompanied by the wind speed

increase of LLJ was apparently associated with the trough deepening. At 700 hPa, vorticity pattern was rather symmetric with respect to the jet axis due to the nearly straight jet. Along the 700 hPa jet axis, the relative vorticity and its local rate of change were both approximately equal to zero in agreement with the wind structure associated with the nearly straight jet. Thus, all the vorticity generation processes counteracted each other and failed to generate or to dissipate the relative vorticity along the jet axis.

4.5 Horizontal divergence

Figure 9 illustrates the distribution of horizontal divergence for the formation and mature stages at 850, 700, and 500 hPa. In general, the horizontal divergence was of the same order of magnitude as that of the relative vorticity. The overall intensity at 700 hPa appeared to increase at the mature stage concurrently with the strengthening of the wind speed. The convergence was mainly observed downstream from the 700 hPa jet core and on the right-hand side of the jet axis at all levels analyzed during the formation and the

Fig. 8. As in Fig. 5, except for the composite structure of relative vorticity (ζ ; 10^{-5} s^{-1} ; dashed) analyzed at $1 \times 10^{-5} \text{ s}^{-1}$ intervals with positive values shaded.

mature stages. At 700 hPa, a couplet of divergence upstream and convergence downstream from the jet core was remarkable for both stages. This was also true at 850 hPa, indicating that the horizontal divergence field was dominated by the speed divergence/convergence rather than by the confluence/diffuence effect over the LLJ area. In the upper-level jet streak, both the speed divergence/convergence and confluence/diffuence effects are important such that the divergence is practically zero along the jet axis. A left-right antisymmetrical pattern was also evident, although to a lesser degree as compared to the upstream-downstream antisymmetry. Over the area to the left-hand side of the jet axis upstream from the jet core, convergence at 700 hPa and 850 hPa was collocated with divergence at 500 hPa at both stages. The reverse was true on the right-hand side. At 700 hPa, the antisymmetrical pattern on the left and right sides was similar to that of an upper-level jet streak (*e.g.*, Uccellini and Johnson, 1979). Divergence was observed on the right-/left-hand side of the upstream/downstream region and convergence occurred on the left-/right-hand side of the upstream/downstream region.

4.6 Vertical velocity

The distribution of vertical velocity for the formation and mature stages at 800, 600, and 400 hPa is presented in Fig. 10. The major features were consistent between Figs. 9 and 10 because the vertical velocity was computed kinematically through integration of the continuity equation. The overall pattern showed a stronger antisymmetry between the upstream region and the downstream region than that between the left-hand side and the right-hand side in the upstream and downstream regions. At the formation stage, upward motion was mainly observed downstream from the 700 hPa jet core with the maximum center located on the right-hand side of the jet axis at all levels. A maximum upward velocity was about $-5 \mu \text{ bs}^{-1}$ at 800 and 600 hPa and decreased to a value of $-2.5 \mu \text{ bs}^{-1}$ at 400 hPa. The area of secondary upward motion occurred on the left-hand side of the jet axis in the upstream region with a maximum value of $-3.75 \mu \text{ bs}^{-1}$ at 600 hPa. The area of maximum downward motion was observed over the area immediate downstream from the 700 hPa jet core at 800 hPa ($+2.5 \mu \text{ bs}^{-1}$) and tilted toward the south at 600 hPa.

Fig. 9. As in Fig. 5, except for the composite structure of divergence (D ; 10^{-5} s^{-1} ; dashed) analyzed at $0.5 \times 10^{-5} \text{ s}^{-1}$ intervals with negative values (convergence) shaded.

($+3.75 \mu \text{ bs}^{-1}$) and 400 hPa ($+3.75 \mu \text{ bs}^{-1}$). At the mature stage, the upward motion was again mainly observed in the downstream region with the maximum center located along and on the right-hand side of the 700 hPa jet axis at all levels. Downward motion prevailed in the upstream region especially on the right-hand side of the 700 hPa jet axis. The area of maximum downward motion was located along the 700 hPa jet axis over the upstream entrance region with a value of $+3.75 \mu \text{ bs}^{-1}$ at 800 hPa and 600 hPa and decreased to a value of $+2.5 \mu \text{ bs}^{-1}$ over the immediate upstream of the jet core at 400 hPa. The weaker upward motion and downward motion at 400 hPa as compared to those at 600 hPa are consistent with the reversed cross-jet ageostrophic flows at 700 hPa and 500 hPa discussed in the following section.

The distribution of vertical velocity at 600 hPa showed a gross pattern of upward motion on the left-/right-hand side of the upstream/downstream region and downward motion on the right-/left-hand side of the upstream/downstream region for both stages. Comparing the distribution of temperature (Fig. 6) and vertical velocity (Fig. 10), a thermally

indirect circulation with cold air rising on the cyclonic side and warm air sinking on the anticyclonic side seems to dominate across the jet axis over the jet core and upstream regions at both stages. And a thermally direct circulation appears to prevail over the downstream region. Note also that downward motion on the anticyclonic side of the jet axis was roughly collocated with the relatively dry air at both stages (Fig. 7).

4.7 Ageostrophic wind

Figure 11 presents the distribution of ageostrophic wind for the formation and mature stages at 850, 700, and 500 hPa. The ratio of the ageostrophic wind to the geostrophic wind is also indicated. In general, the ageostrophic flow consisted of two components. One was along the contour (primarily along the jet axis in the geostrophic wind direction), and the other was in the direction across the contour (*i.e.*, cross-jet direction). The ageostrophic flow was generally small at 500 hPa for both stages with a ratio smaller than 20 % of the geostrophic flow over most of the area. The ratio was also small at 850 hPa, except over the area along the 850 hPa jet

Fig. 10. The composite structure of vertical velocity (ω ; $10^{-2} \mu \text{ bs}^{-1}$; dashed) analyzed at $125 \times 10^{-2} \mu \text{ bs}^{-1}$ intervals with negative values (upward motion) shaded at 800 hPa (a, b), 600 hPa (c, d) and 400 hPa (e, f) with respect to the axis of the low-level jet at 700 hPa during its formation stage (left panel) and mature stage (right panel). The wind plots in each panel are for the formation (left) and mature (right) stages at 700 hPa.

axis where the ratio was greater than 40 % of the geostrophic flow at the formation stage and greater than 30 % at the mature stage. At 700 hPa near jet core, however, the ratio was quite large with an area of greater than 60 % at the formation stage and greater than 80 % at the mature stage. In other words, the 700 hPa LLJ was highly ageostrophic with the observed wind speed about 1.6 ~ 1.8 times that of the geostrophic wind. Over this area, the ageostrophic wind direction was mainly along the jet axis indicating the supergeostrophic nature of the LLJ similar to that observed over Japan area (e.g., Matsumoto *et al.*, 1971; Matsumoto, 1972).

The ratio of the ageostrophic wind to the geostrophic wind reached a maximum value at the LLJ level. This indicates that the opposite sign of the vertical shear between the observed wind and the geostrophic wind occurred below and above the jet level. In other words, the observed shear ($\frac{\partial V}{\partial z}$) was greater than the geostrophic shear ($\frac{\partial V_g}{\partial z}$) below the jet level and the opposite was true above

that level. The secondary circulation across the jet axis would be expected in response to this unbalanced situation between the motion field and the mass field. A thermally indirect circulation would be expected below the jet level with upward motion on the cyclonic side of the jet axis and downward motion on the anticyclonic side under this condition, as discussed by Matsumoto (1972). This is in good agreement with the observed vertical motion field on the left and right sides as presented in Fig. 10. Upward motion on the cyclonic side of the jet core and downward motion on the anticyclonic side was observed below the jet level at both stages. The antisymmetrical patterns of vertical motions on the left/right side and upstream/downstream presented in Fig. 10 were related to the nature of ageostrophic flows across and along the jet axis, respectively.

At the formation state, the cross-contour flow was remarkable in the upstream region from the anticyclonic side to the cyclonic side (i.e., from higher to lower heights) at 700 hPa and from the cyclonic

Fig. 11. The composite structure of ageostrophic wind ($\vec{V}_a$) and geopotential height (solid; dam) at 850 hPa (a, b), 700 hPa (c, d) and 500 hPa (e, f) with respect to the axis of the low-level jet at 700 hPa (center line in each panel) during its formation stage (left panel) and mature stage (right panel). Wind plots with full barb and half barb represent 10 kt (5 ms⁻¹) and 5 kt (2.5 ms⁻¹), respectively. Dashed lines indicate the ratio of the ageostrophic wind to the geostrophic wind with the ratio greater than 50 % shaded. Heavy solid arrows illustrate the stream lines of the cross-contour ageostrophic flows.

side to the anticyclonic side (*i.e.*, from lower to higher heights) at 500 hPa. Over the same region, the ageostrophic flows were less organized at 850 hPa. In the downstream region at 500 hPa, the cross-contour flow was reversed from that in the upstream region. Over the same area, the cross-contour flow was from the cyclonic side to the anticyclonic side at 850 hPa. The ageostrophic flow was mainly in the geostrophic wind direction at 700 hPa with a modification from the low-pressure side to the high-pressure side. Therefore, the secondary circulations across the 700 hPa jet axis in the upstream and downstream regions at the formation stage can be inferred from this ageostrophic wind pattern. Upstream from the jet core, the divergence/convergence at 500 hPa on the cyclonic/anticyclonic side of the jet axis as presented in Fig. 9 was due to this ageostrophic flow. The reversed ageostrophic flow across the jet axis, although

to a lesser degree, was observed over the downstream region. Comparing to the temperature distribution as presented in Fig. 6, a thermally indirect circulation occurred in the upstream region with cold air rising on the cyclonic side and warm air sinking on the anticyclonic side. On the other hand, a thermally direct circulation across the 700 hPa jet axis in the downstream region existed in the 850–500 hPa layer. This secondary circulation was responsible for the shift of the center of maximum upward motion toward the right-hand side of the jet axis at all levels analyzed, as presented in Fig. 10. Therefore, the nature of secondary circulations across the 700 hPa jet axis was different from that of the upper-level jet streak. A thermally direct circulation in the entrance region and a thermally indirect circulation in the exit region were usually observed for the upper-level case (*e.g.*, Uccellini and Johnson 1979).

At the mature stage, the ageostrophic flow

was from the anticyclonic/cyclonic side to the cyclonic/anticyclonic side at 700/500 hPa in the entrance region. The reverse flow was observed at 700 and 500 hPa in the exit region. At 850 hPa, the ageostrophic flow was in the same direction as that of 700 hPa. Again, a thermally indirect circulation in the upstream region and a thermally direct circulation in the downstream region occurred at the mature stage. This is consistent with the distribution of the vertical velocity as shown in Fig. 10. Similar to that at the formation stage, the shift of the maximum upward motion towards the right-hand side of the jet axis in the downstream region was due to the existence of the thermally direct circulation.

5. Discussion and concluding remarks

Three cases of southwesterly LLJs which had a life span of greater than 36 hours, originated in southern China, and passed over the TAMEX area in May 1987, were selected in this study. To suppress minor differences among different cases of LLJs, a composite technique was employed to obtain the horizontal and vertical structures of the LLJ with respect to the nearly straight jet at 700 hPa. Figures 1–3 indicate that the LLJ at 700 hPa in each case formed in the prevailing southwesterly flows over the area of developing trough. It intensified and moved eastward along with the deepening trough at the mature stage. The jet core tilted upward towards west-southwest from 850 to 700 hPa at the formation stage and became collocated at the mature stage. The decrease in geopotential heights and increase in height gradient over the LLJ area as well as the doubling of horizontal length scale associated with the deepening of trough from formation stage to mature stage are well reflected in the composite shown in Fig. 5. Thus, a non-quasigeostrophic trough intensification process appears to be the mechanism for the formation/intensification of the LLJ in this case. This is in contrast to the convective momentum transport mechanism proposed by Matsumoto and Ninomiya (1969) and the Coriolis acceleration mechanism suggested by Chen (1982) and Chou *et al.* (1990) for the formation of Mei-Yu LLJs.

The upward increase of wind speed along the jet axis from 850 to 700 hPa was not in agreement with the thermal wind relation, as the temperature gradient was mainly along the jet axis (Fig. 5). In other words, the LLJ was essentially not in a geostrophic/thermal wind balance. It was highly supergeostrophic. This ageostrophic characteristic of the LLJ was consistent with the ageostrophic flows as presented in Fig. 11. The ageostrophic flows were mainly along the jet axis near the jet core area and across the jet axis in the upstream and downstream regions. The LLJ was accompanied by warm advection over the area analyzed and by moisture flux convergence in the downstream region for both the

formation and mature stages.

The distribution of relative vorticity and horizontal divergence associated with the LLJ at 700 hPa was similar to that of the upper-level jet streak (*e.g.*, Uccellini and Johnson, 1979). In the upper-level jet streak case, the wind velocity is much greater than the phase velocity of the jet ($\vec{V} \gg \vec{C}_J$). Thus, the horizontal vorticity advection term is approximately balanced by the divergence term in the vorticity equation. A clear association between the horizontal vorticity advection and divergence is shown in Figs. 8 and 9 in this LLJ case as well. The positive vorticity advection and the divergence were observed on the right-/left-hand side of the upstream/downstream region. Negative vorticity advection and convergence occurred on the left-/right-hand side of the upstream/downstream region. Thus, the divergence in association with the vorticity advection was related to the ageostrophic circulation across the jet axis in the entrance and exit regions of the LLJ. Also, the divergence pattern caused by the ageostrophic wind occurred along the jet axis. Therefore, the antisymmetrical pattern of the divergence field accompanying the LLJ was apparently related to the ageostrophic flows along and across the jet axis (Fig. 11).

One of the most intriguing features was the distribution of vertical velocity and the associated secondary circulation across the 700 hPa jet axis. At both the formation and mature stages, the area of primary upward motion was located in the exit region with the maximum center shifted towards the right of the jet axis at 800, 600, and 400 hPa (Fig. 10). The main upward motion shift downwind was mainly due to the speed convergence downstream of the jet core caused by the along-jet ageostrophic wind (Fig. 11). The shift of the maximum upward motion towards the right was due to the existence of thermally direct circulation consistent with the ageostrophic flows illustrated in Fig. 11. Upward motion of the relatively cold air occurred on the cyclonic side of the jet axis over the jet core and entrance regions. The reverse was true on the anticyclonic side (Figs. 5 and 10). Thus, a thermally indirect circulation was observed across the jet axis in the entrance and jet core regions. As discussed earlier, the horizontal divergence pattern associated with the 700 hPa LLJ was similar to that of the upper-level jet streak. This is consistent with the across-jet ageostrophic flow pattern as air parcel accelerates in the entrance region and decelerates in the exit region (Figs. 5 and 11). From the mass continuity consideration, the upward/downward motion must occur over the low-level convergence/divergence region. This appears to be the case as observed in Figs. 9 and 10. In response to the across-jet ageostrophic wind in the entrance and exit regions, the reversed ageostrophic

flows occurred in the mid-troposphere over the same regions (Fig. 11). Therefore, the nature of the secondary circulation associated with the LLJ is quite different from that of an upper-level jet streak. In the latter case, a thermally direct circulation would occur in the entrance region below the jet level in the troposphere with a thermally indirect circulation in the exit region (*e.g.*, Uccellini and Johnson, 1979). Finally, a thermally indirect circulation would be expected below the jet level over the jet core region, as the wind was highly supergeostrophic along the jet axis such that the observed vertical shear ($\frac{\partial V}{\partial z}$) was much greater than the geostrophic shear ($\frac{\partial V_g}{\partial z}$) (*e.g.*, Matsumoto, 1972).

Acknowledgments

We would like to express our sincere appreciation to the referees and to the Editor (Professor Toshio Harimaya), whose thoughtful comments and suggestions improved our presentation. Thanks are also due to Mr. J.S. Yang and Mr. T.S. Wang for preparing the manuscript. This research was supported in part by NSC 86-2111-M-002-006-AP6.

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TAMEX 期間中に観測された南中国上の下層ジェットの合成構造

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下層ジェット (LLJ) の構造と発達段階を示すために、3 例の南西下層ジェットが 1987 年 TAMEX 観測期間中 (5 月–6 月) から選ばれた。LLJs の異なった事例間の微小な差を取り除くために合成解析法が使われ、700 hPa 面でのジェット軸に関する全気象パラメーターが得られた。

LLJ は、非地衡風トラフ強化過程と関連して形成、強化されたことが解析結果から示された。それは超地衡風の性質を持っていた。暖気移流がジェット域で卓越し、水蒸気フラックス収束がジェット軸の下流域で起こっていた。発散と上昇流の分布は、出口部のジェットに沿った収束場によって起こされた上昇運動の上流域と下流域での非対称パターンに大きな特徴があった。またそれより小さい左右での非対称パターンも見られた。ジェット軸を横切る 2 次循環の特徴は上層ジェットのものとまったく違っていた。ジェット軸を横切る熱的間接循環はジェットの入口部と軸部において、熱的直接循環は出口部において観測された。