Characteristics of Low-Level Jets over Northern Taiwan in Mei-Yu Season and Their Relationship to Heavy Rain Events

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ABSTRACT

The present study investigates the characteristics of low-level jets (LLJs) (≥12.5 m s⁻¹) below 600 hPa over northern Taiwan in the mei-yu season and their relationship to heavy rainfall events (≥50 mm in 24 h) through the use of 12-h sounding data, weather maps at 850 and 700 hPa, and hourly rainfall data at six surface stations during the period of May–June 1985–94. All LLJs are classified based on their height, appearance (single jet or double jet), and movement (migratory and nonmigratory). The frequency, vertical structure, and spatial and temporal distribution of LLJs relative to the onset of heavy precipitation are discussed.

Results on the general characteristics of LLJs suggest that they occurred about 15% of the time in northern Taiwan, with a top speed below 40 m s⁻¹. The level of maximum wind appeared mostly between 850 and 700 hPa, with highest frequency at 825–850 hPa. A single jet was observed more often (76%) than a double jet (24%), while in the latter case a barrier jet usually existed at 900–925 hPa as the lower branch.

Migratory and nonmigratory LLJs each constituted about half of all cases, and there existed no apparent relationship between their appearance and movement. Migratory LLJs tended to be larger in size, stronger over a thicker layer, more persistent, and were much more closely linked to heavy rainfall than nonmigratory jets. They often formed over southern China between 20° and 30°N and moved toward Taiwan presumably along with the mei-yu frontal system.

Before and near the onset of the more severe heavy rain events (≥100 mm in 24 h) in northern Taiwan, there was a 94% chance that an LLJ would be present over an adjacent region at 850 hPa, and 88% at 700 hPa, in agreement with earlier studies. Occurrence frequencies of LLJs for less severe events (50–100 mm in 24 h) were considerably lower, and the difference in accumulative rainfall amount was seemingly also affected by the morphology of the LLJs, including their strength, depth, elevation of maximum wind, persistence, proximity to northern Taiwan, source region of moisture, and their relative timing of arrival before rainfall. During the data period, about 40% of all migratory LLJs at 850 or 700 hPa passing over northern Taiwan were associated with heavy rainfall within the next 24 h. The figure, however, was much lower compared to earlier studies, and some possible reasons are offered to account for this deficit.

1. Introduction

a. Literature review

Over east Asia from May to July, the frequent and repeated occurrence of the quasi-stationary (or slow moving) mei-yu front (or baiu front) provides a mechanism for uplifting and brings unstable weather to Taiwan, southern China, and Japan. During this period (called the mei-yu season), heavy precipitation and flash floods are often produced by active mesoscale convective systems (MCSs) embedded inside the cloud band along the mei-yu front. One feature that has long been recognized as an important factor in the development of the MCSs is the low-level jet (LLJ), defined by Ray (1986, p. 173) as an intense, narrow, quasi-horizontal current of wind that is associated with strong vertical shear (e.g., Akiyama 1973; Ninomiya and Murakami 1987; Chen and Yu 1988; Ding 1992; Y.-L. Chen et al. 1994; Arritt et al. 1997). The presence of a southerly or southwesterly LLJ equatorward of the mei-yu front helps the convection in at least three ways. It transports...
Fig. 1. The 850-hPa synoptic weather maps over east Asia at (a) 0000 and (b) 1200 UTC 26 May 1999. Solid lines are geopotential height contours (gpm; at 30-gpm intervals with single digit omitted), and dashed lines are isotherms (°C; at 3°C intervals). Heavy dashed line indicates wind shift line (mei-yu front). The full barb and half barb represent 5 and 2.5 m s⁻¹, respectively. Dash-dot line delineates 15 m s⁻¹ isotach, and arrows indicate LLJ axis.
TABLE 1. Twenty-four-hour accumulative rainfall amount (mm) from 1400 UTC 26 May to 1400 UTC 27 May (0000–2400 LST 27 May) 1999 at six surface stations over northern Taiwan (see Fig. 2 for locations).

<table>
<thead>
<tr>
<th>Station</th>
<th>ID</th>
<th>Rainfall amount</th>
<th>Station</th>
<th>ID</th>
<th>Rainfall amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tamshui</td>
<td>46690</td>
<td>36.0</td>
<td>Chutzehu</td>
<td>46693</td>
<td>84.6</td>
</tr>
<tr>
<td>Anpu</td>
<td>46691</td>
<td>79.3</td>
<td>Keelung</td>
<td>46694</td>
<td>76.1</td>
</tr>
<tr>
<td>Taipei</td>
<td>46692</td>
<td>82.0</td>
<td>Hsinchu</td>
<td>46757</td>
<td>139.2</td>
</tr>
</tbody>
</table>

warm and moist air from lower latitudes toward the front, provides low-level convergence downstream from the jet core, and helps establish a favorable, convectively unstable environment (e.g., Ninomiya and Akiyama 1974; Chen 1983; Y.-L. Chen 1993; Y.-L. Chen and Li 1995; Chen and Hsu 1997; Chen et al. 2000).

Several mechanisms have been put forward from past studies as the responsible process for the development and intensification of LLJs under different conditions. Over the United States, LLJs often develop in response to an enhanced pressure gradient at low levels, under a thermally indirect transverse circulation associated with an upper-level jet (ULJ) streak at its exit region (Uccellini and Johnson 1979; Uccellini 1980; T.-C. Chen and Kpaeveh 1993), or to the southeast of the center of a deepening extratropical cyclone (or trough) at the lee of the Rockies through thermal wind adjustment (Arritt et al. 1997; Iguau and Nielsen-Gammon 1998). During these processes, diabatic effects from latent heat release (and surface fluxes) can also join the interaction and contribute positively toward the LLJ formation (e.g., Gall 1976; Emanuel et al. 1987; Uccellini et al. 1987).

Over the Great Plains, low-level wind speeds also exhibit pronounced diurnal variation with a nocturnal maximum due to the inertial oscillation of frictional drag inside the planetary boundary layer (PBL; e.g., Blackadar 1957; Bonner 1968; Mitchell et al. 1995; Zhong et al. 1996).

Low-level jets over east Asia have been studied somewhat less extensively, particularly in their climatology. Earlier studies hypothesized that LLJs are produced by downward transport of westerly momentum through vertical mixing from cumulus convection (e.g., Matsumoto 1973; Ninomiya and Akiyama 1974), but this mechanism cannot fully account for the appearance of a wind speed maximum of the LLJ and its directional difference from the upper-level westerly winds (e.g., Y.-L. Chen et al. 1994). By studying the LLJ cases during the 1987 Taiwan Area Mesoscale Experiment (TAMEX), X.-A. Chen and Chen (1995) and Y.-L. Chen et al. (1997) found that most southern China LLJs before the seasonal transition develop analogously to their North American counterparts and are closely linked to lee cyclogenesis (or lee troughing) east of the Tibetan Plateau, while diabatic (latent) heating may contribute more after the transition, or at later stages of the LLJ development (also Pu and Chen 1986; Chen 1993). Chou et al. (1990), through a two-dimensional modeling study, suggested that active cumulus convection along the mei-yu front can promote low-level convergence, and the lower (southerly) branch of the convectively induced secondary circulation can lead to LLJ development south of the front through Coriolis acceleration. Similar results were also obtained by Nagata and Ogura (1991), S.-J. Chen et al. (1998), and more recently by Chen et al. (2003). In a case study, Hsu and Sun (1994),

![Fig. 2. Geographical distribution of sounding (Panchiao) and rainfall stations (Tamshui, Anpu, Taipei, Chutzehu, Keelung, and Hsinchu) over northern Taiwan. Shadings represent smoothed terrain (km), with elevation ranges indicated at the lower-right corner.](image-url)
Fig. 3. Distribution of qualified LLJ cases over northern Taiwan with pressure (hPa) using different criteria of 0, 1, 3, 5, and $7 \times 10^{-3}$ s\(^{-1}\) for the vertical shear required above wind maximum (as identified using sounding data at Panchiao) in May–Jun 1985–94. The other five criteria (see section 2a for details) were also applied in the identification. The criterion eventually selected in this study was $1 \times 10^{-3}$ s\(^{-1}\) (solid line).

Fig. 4. Schematic illustration of the classifications of low-level jets based on their height (LLJ and BJ), appearance in the vertical (SJ and DJ), and movement (M and NM). The abbreviations (bold) based on a single attribute are LLJ (low-level jet, above the 900-hPa level), BJ (barrier jet, below the 900-hPa level), SJ (single jet), DJ (double jet), M (migratory), and NM (nonmigratory). Double jet can be further divided into DJU and DJL (upper and lower branch). Combined abbreviations based on multiple attributes introduced in sections 3–5 (e.g., SLLJ, MLLJ, and MSLLJ) are also given. For the classification based on movement, the use of a smaller ellipse does not imply that the migratory jets are a subset of nonmigratory jets.

on the other hand, suggested that sufficient heating could be achieved just from a large area of stratiform clouds, rather than deep cumulus clouds, to result in the intensification of LLJs.

In addition to the aforementioned mechanisms, orographic blocking on prevailing air flow at a low Froude number (Fr) flow regime can often produce local wind maxima inside the PBL at various regions around the world (e.g., Smith and Grubišić 1993; Georgelin et al. 1996; Douglas et al. 1998; Igau and Nielsen-Gammon 1998; Li and Chen 1998; Skamarock et al. 1999; Chelton et al. 2000). These wind maxima forced by terrain, however, often occur within 1 km above the surface and represent a different class of jets, and perhaps should be referred to as “barrier jets” (BJs). For the Taiwan area, BJs often form along the northwestern coast during the mei-yu season under the prevailing southwesterly because of the blocking effect of the Central Mountain Range (CMR; e.g., Chen and Hui 1992; Lin 1993; Li et al. 1997; Li and Chen 1998).

Because of the positive role of the LLJ in feeding the convection and conditioning the environment, previous studies have shown that it is strongly correlated with heavy rainfall (e.g., Akiyama 1973; Chen 1988; Chen and Yu 1988; Kuo and Chen 1990). Tsay (1991) concluded that the environment is especially conducive to heavy precipitation over northern Taiwan when the LLJ is coupled with a ULJ. Chen and Yu (1988) examined 35 heavy rainfall events ($\geq 100$ mm day\(^{-1}\)) over northern Taiwan in May–June of 1965–84, and found 84% of them to be preceded by an LLJ ($\geq 12.5$ m s\(^{-1}\)) at 700 hPa 12 h prior to the onset of the event. Conversely, when an LLJ of at least 15 m s\(^{-1}\) was present over northern Taiwan, there was a 91% chance that heavy precipitation was in progress or would begin within
TABLE 2. Heavy rainfall events (left) type A, numbered as A01 through A17, and (right) type B, numbered as B01 through B17, over northern Taiwan. Stations 1 through 6 represent Tamshui, Anpu, Taipei, Chutzehu, Keelung, and Hsinchu, respectively. For type A events, a circle indicates that the station reached the criterion of $\geq 100$ mm (24 h)$^{-1}$, and a solid circle denotes the station with the highest rainfall in the event. Triangles (open and solid) for type B events have similar meanings, except that the criterion is $50–100$ mm (24 h)$^{-1}$. In the table, "mo" indicates month.

<table>
<thead>
<tr>
<th>No.</th>
<th>Yr/mo (yymm)</th>
<th>Start–end (dd/LST)</th>
<th>Duration (h)</th>
<th>Station rainfall</th>
<th>No.</th>
<th>Yr/mo (yymm)</th>
<th>Start–end (dd/LST)</th>
<th>Duration (h)</th>
<th>Station rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>A01</td>
<td>8505</td>
<td>2818–2907</td>
<td>14</td>
<td>O ● ○ ○</td>
<td>B01</td>
<td>8506</td>
<td>0718–0811</td>
<td>18</td>
<td>△ △ △ △ △ △</td>
</tr>
<tr>
<td>A02</td>
<td>8605</td>
<td>1404–1409</td>
<td>6</td>
<td>● ○ ○</td>
<td>B02</td>
<td>8506</td>
<td>1307–1320</td>
<td>14</td>
<td>△ △</td>
</tr>
<tr>
<td>A03</td>
<td>8606</td>
<td>0417–0503</td>
<td>11</td>
<td>● ○ ○ ●</td>
<td>B03</td>
<td>8605</td>
<td>1223–1301</td>
<td>3</td>
<td>△ △</td>
</tr>
<tr>
<td>A04</td>
<td>8705</td>
<td>1622–1722</td>
<td>25</td>
<td>○ ● ○ ●</td>
<td>B04</td>
<td>8606</td>
<td>0611–0621</td>
<td>11</td>
<td>△ △</td>
</tr>
<tr>
<td>A05</td>
<td>8706</td>
<td>2505–2510</td>
<td>6</td>
<td>● ○ ○ ● ●</td>
<td>B05</td>
<td>8705</td>
<td>0409–0501</td>
<td>17</td>
<td>△ △ △ △</td>
</tr>
<tr>
<td>A06</td>
<td>8805</td>
<td>2214–2218</td>
<td>5</td>
<td>● ●</td>
<td>B06</td>
<td>8706</td>
<td>0811–0818</td>
<td>8</td>
<td>△ △ △ △</td>
</tr>
<tr>
<td>A07</td>
<td>8806</td>
<td>2614–2618</td>
<td>5</td>
<td>● ○ ● ●</td>
<td>B07</td>
<td>8805</td>
<td>2517–2607</td>
<td>15</td>
<td>△ △ △ △</td>
</tr>
<tr>
<td>A08</td>
<td>8905</td>
<td>2908–2922</td>
<td>15</td>
<td>○ ● ○ ● ○ ○</td>
<td>B08</td>
<td>8806</td>
<td>1718–1720</td>
<td>3</td>
<td>△ △</td>
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<tr>
<td>A09</td>
<td>9006</td>
<td>0903–0916</td>
<td>14</td>
<td>● ○ ○ ● ● ○</td>
<td>B09</td>
<td>8905</td>
<td>0519–0523</td>
<td>5</td>
<td>△ △</td>
</tr>
<tr>
<td>A10</td>
<td>9106</td>
<td>2216–2320</td>
<td>29</td>
<td>● ○ ○ ● ● ○</td>
<td>B10</td>
<td>9006</td>
<td>1005–1016</td>
<td>12</td>
<td>△ △ △ △ △</td>
</tr>
<tr>
<td>A11</td>
<td>9106</td>
<td>2410–2421</td>
<td>12</td>
<td>● ●</td>
<td>B11</td>
<td>9105</td>
<td>0115–0206</td>
<td>16</td>
<td>△ △ △ △ △</td>
</tr>
<tr>
<td>A12</td>
<td>9206</td>
<td>0710–0902</td>
<td>41</td>
<td>○ ● ○ ○ ○ ○</td>
<td>B12</td>
<td>9106</td>
<td>2014–2017</td>
<td>4</td>
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</tr>
<tr>
<td>A13</td>
<td>9306</td>
<td>0509–0522</td>
<td>14</td>
<td>○ ○ ○ ○ ○ ○</td>
<td>B13</td>
<td>9205</td>
<td>0914–0917</td>
<td>4</td>
<td>△ △</td>
</tr>
<tr>
<td>A14</td>
<td>9306</td>
<td>0818–0824</td>
<td>7</td>
<td>● ○ ○ ● ● ○</td>
<td>B14</td>
<td>9205</td>
<td>2205–2216</td>
<td>12</td>
<td>△ △ △ △</td>
</tr>
<tr>
<td>A15</td>
<td>9405</td>
<td>0124–0208</td>
<td>9</td>
<td>○ ○ ○ ●</td>
<td>B15</td>
<td>9305</td>
<td>2701–2706</td>
<td>6</td>
<td>△ △</td>
</tr>
<tr>
<td>A16</td>
<td>9405</td>
<td>0402–0418</td>
<td>17</td>
<td>● ●</td>
<td>B16</td>
<td>9306</td>
<td>0204–0211</td>
<td>8</td>
<td>△ △</td>
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<tr>
<td>A17</td>
<td>9406</td>
<td>1814–1824</td>
<td>11</td>
<td>○ ○ ○ ● ●</td>
<td>B17</td>
<td>9405</td>
<td>1106–1112</td>
<td>7</td>
<td>△ △ △ △</td>
</tr>
</tbody>
</table>

Mean/total 14.2 6 8 4 6 7 11 Mean/total 9.6 7 10 7 8 6 9

Fig. 5. Distribution of LLJ cases of different types over northern Taiwan with (a) pressure (hPa) and (b) maximum wind speed (m s$^{-1}$) using all six criteria (as identified using sounding data at Panchiao; see section 2a for details) in May–Jun 1985–94. The types include single jet (SJ), upper branch of double jet (DJU), and lower branch of double jet (DJL).
a southwesterly LLJ with maximum wind axis (≥15 m s$^{-1}$) along the southeastern coast of China (also at 700 hPa). At earlier times, the jet was weaker and farther west (not shown). At 1200 UTC, the LLJ moved southeastward (Fig. 1b) along with the front at 850 hPa and the surface. With the jet migrating offshore, wind speed at northern Taiwan increased rapidly from 10 to 20 m s$^{-1}$. Shortly after the LLJ’s arrival, heavy rainfall occurred. Over the 24 h from 1400 UTC 26 May to 1400 UTC 27 May, the accumulative rainfall reached 139.2 mm at Hsinchu, and at least 76 mm at four other stations in northern Taiwan (Table 1; see Fig. 2 for locations). Besides the case presented here, plenty other examples in which a heavy rainfall event took place under the influence of an LLJ can be found in the literature (e.g., Chen and Yu 1988; Chen and Li 1995; Li et al. 1997).

### 2. Data and methods of analysis

Data used in this study to identify and analyze LLJs over northern Taiwan were twice-daily sounding data (at 0000 and 1200 UTC) taken operationally at Panchiao (Taipei) station (Fig. 2), and 12-h east Asian weather maps at 700 and 850 hPa for the period of May–June 1985–94. The sounding included all standard and significant levels, which typically totaled to 30 below 5 km, with an uneven vertical spacing of 50–300 m between most levels (usually smaller toward the ground). To examine the relationship of LLJs to heavy rain, hourly rainfall data at six surface stations over northern Taiwan, including Tamshui, Anpu, Taipei, Chutzehu, Keelung, and Hsinchu, for the same period were also used (Fig. 2). First, weather maps were reviewed to mark time intervals during which wind fields over northern Taiwan were affected by typhoon or tropical depression, and afternoon showers in rainfall data were also identified. All these periods were excluded from subsequent analyses to ensure that both LLJs and heavy rain events occurred in an environment not atypical during the mei-yu season, and most likely under the influence of the mei-yu front.

#### a. Analysis and classification of low-level jets

In order to use sounding data at Panchiao to identify their occurrences, a set of criteria suitable for LLJs over northern Taiwan needed to be specified. Past studies have employed similar criteria that include 1) height of maximum wind at 900–600 hPa in the lower troposphere, 2) maximum wind speed ≥12.5 m s$^{-1}$, 3) direction of maximum wind between 180° and 270° (southerly to westerly), 4) horizontal shear near wind maximum ≥7.0 × 10$^{-3}$ s$^{-1}$, and 5) vertical shear below wind maximum ≥7.0 × 10$^{-3}$ s$^{-1}$ (Chen 1979; Chen and Yu 1988; Chen et al. 1994). The current study largely followed these criteria, except that all wind maxima from the surface to the 600-hPa level were considered in criterion 1 to include barrier jets (Li and Chen 1998).

#### b. An example of an LLJ over northern Taiwan

It is perhaps appropriate at this point to first give a brief example of an LLJ over northern Taiwan in mei-yu season that was associated with a heavy rain event (Fig. 1). At 0000 UTC 26 May 1999, an east-northeast–west-southwest-oriented mei-yu front was present near the southeastern coast of China at the surface (not shown). A clear wind shift line (i.e., mei-yu front) also existed at 850 hPa some 100 km north of the surface front, with northeasterly to northerly flow farther to the north (Fig. 1a). South of the wind shift line, there existed a southwesterly LLJ with maximum wind axis (≥15 m s$^{-1}$) along the southeastern coast of China (also at 700 hPa). At earlier times, the jet was weaker and farther west (not shown). At 1200 UTC, the LLJ moved southeastward (Fig. 1b) along with the front at 850 hPa and the surface. With the jet migrating offshore, wind speed at northern Taiwan increased rapidly from 10 to 20 m s$^{-1}$. Shortly after the LLJ’s arrival, heavy rainfall occurred. Over the 24 h from 1400 UTC 26 May to 1400 UTC 27 May, the accumulative rainfall reached 139.2 mm at Hsinchu, and at least 76 mm at four other stations in northern Taiwan (Table 1; see Fig. 2 for locations). Besides the case presented here, plenty other examples in which a heavy rainfall event took place under the influence of an LLJ can be found in the literature (e.g., Chen and Yu 1988; Chen and Li 1995; Li et al. 1997).

### Table 3. (a) Frequency of occurrence (%) and (b) averaged pressure (hPa) and speed (m s$^{-1}$) of maximum wind for different types of LLJs/BJs. Types include a single jet (SJ) and an upper branch (DJU) and a lower branch (DJL) of a double jet. The total number of cases in each type is given in parentheses.

<table>
<thead>
<tr>
<th>Type of LLJ/BJ</th>
<th>Height (pressure level)</th>
<th>All (185)</th>
<th>SJ (141)</th>
<th>DJU (44)</th>
<th>DJL (44)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700–850 hPa (LLJ)</td>
<td>61%</td>
<td>72%</td>
<td>82%</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>900–925 hPa (BJ)</td>
<td>23%</td>
<td>14%</td>
<td>0%</td>
<td>75%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>84%</td>
<td>86%</td>
<td>82%</td>
<td>82%</td>
<td></td>
</tr>
</tbody>
</table>

#### (b) Mean pressure (hPa)/speed (m s$^{-1}$) of maximum wind

<table>
<thead>
<tr>
<th>Type of LLJ/BJ</th>
<th>Height (pressure level)</th>
<th>SJ</th>
<th>DJU</th>
<th>DJL</th>
</tr>
</thead>
<tbody>
<tr>
<td>700–850 hPa (LLJ)</td>
<td>783.9/18.7</td>
<td>829.2/19.7</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>900–925 hPa (BJ)</td>
<td>907.5/16.5</td>
<td>—</td>
<td>910.2/16.9</td>
<td></td>
</tr>
</tbody>
</table>

24 h. They also found that convection would most likely result in a weakening in the LLJ through vertical mixing, and thus LLJs are apparently the cause, rather than the result, of the MCSs near Taiwan (Chen and Yu 1988).

From the above literature review, it is obvious that the LLJ is intimately linked to the severity of convection and the occurrence of heavy rainfall, and thus successful forecasts of heavy rains rely on adequate knowledge of the LLJ. Climatological studies on the characteristics of LLJs in east Asia, however, have been few compared to those in the United States (e.g., Bonner 1968; T.-C. Chen and Kpaeyeh 1993; Mitchell et al. 1995; Arritt et al. 1997), with the exceptions of Chen and Yu (1988) and X.-A. Chen and Chen (1995) using a relatively limited number of cases. The purpose of the present study, therefore, is to provide a more complete and more detailed picture regarding the characteristics of LLJs in the proximity of northern Taiwan, including their frequency, spatial distribution, and vertical structure, and investigate further their statistical relationship to heavy precipitation, through the inclusion of a larger number of cases. Here, the focus is placed upon northern Taiwan because it is the first place to be affected by LLJs usually approaching from the north or northwest in association with the mei-yu front, and also because the location is close to terrain-induced barrier jets (Li and Chen 1998).
levels with the central-difference method) both below and above, we considered an additional criterion on wind shear above the wind maximum necessary. Such a shear was inherently required in past studies (because of the wind maximum of LLJs), but its magnitude was never specified. Here, because of surface friction, vertical shear below the jet must be greater than that above, and several different threshold values of 0, 1, 3, 5, and $7 \times 10^{-3}$ s$^{-1}$, were tested as criterion 6 together with all other requirements in the identification of LLJs, except criterion 4 since it was not applicable using Panchiao sounding data alone.

Figure 3 presents the testing results. The distribution of LLJ appearances with pressure (or equivalently height, stratified every 25 hPa) has a double-peak structure, with a primary maximum at 900–925 hPa and a secondary maximum at 825–850 hPa. The counts between these two levels, from 850 to 900 hPa, are few, and suggest distinctly different mechanisms responsible for the formation of LLJs above and below 875 hPa. At 900–925 hPa, the jets correspond to barrier jets within the boundary layer due to terrain blocking. Their counts decreased relatively little (from 54 to 40) as criterion 6 was raised from 0 to $7 \times 10^{-3}$ s$^{-1}$, indicating that BJs are often accompanied by strong vertical shear both above and below the wind maximum. At the second peak of 825–850 hPa, on the other hand, the number of qualified LLJ appearances dropped rapidly once criterion 6 exceeded $1 \times 10^{-3}$ s$^{-1}$ (Fig. 3). Because these cases are similar to those closely linked to heavy rainfall events and studied by previous researchers, and are of our major interests, we have chosen to use $1 \times 10^{-3}$ s$^{-1}$ as the required magnitude for vertical shear above the jet maximum, and the counts at 825–850 hPa (49) remained close to those of BJs at 900–925 hPa (50). Thus, five criteria were applied to identify LLJs using Panchiao sounding data, including the above-mentioned criteria 2, 3, and 5, as well as 1) height of maximum wind between surface and 600 hPa, and 6) vertical wind shear above wind maximum $\geq 1.0 \times 10^{-3}$ s$^{-1}$. For cases that satisfied these criteria simultaneously, they are referred to as LLJs if the maximum wind

\footnote{Note that since these criteria (1–3, 5, and 6) make use of the sounding data, LLJs tracked on constant pressure maps would not necessarily satisfy them all.}
occurred above the 900-hPa level, or termed BJ if otherwise (no higher than the 900-hPa level) for ease of distinction. This classification is in agreement with past results that showed that with the high terrain of the CMR (≥2 km) extending into northern Taiwan (Fig. 2), the top of the splitting level and barrier jets, although varying depending on the value of Fr, were usually located near 1 km (e.g., Li and Chen 1998; Wang and Chen 2003).

All LLJ/BJ appearances in the Panchiao sounding below 600 hPa can be grouped into two types: a single jet (SJ) or double jet (DJ) based on the number of wind maxima in the vertical. According to the characteristics of their movement, they can also be classified as migratory (M) jets from upstream or nonmigratory (NM; i.e., stationary) jets developed locally. This is done through the analysis of 850- and 700-hPa weather maps (mainly isotachs), and four conditions must be met for LLJs to be classified as migratory: 1) they must satisfy criterion 4 for horizontal wind shear, 2) they must exist on at least two consecutive maps (∼12 h), 3) at least three adjacent stations are needed to support the analysis of elongated isotachs encircling the jet core, and finally 4) they exhibit a clear tendency to move downstream.

Through these requirements, cases that were short-lived (<12 h), small in areal extent, and most often, simply not resolved on weather maps, were all classified into the nonmigratory group, as they were considered local events. In later sections, comparisons of jets in different categories can be made based on their height (LLJ versus BJ), appearance (or number of wind maxima; SJ versus DJ) in the vertical, and their movement (M versus NM) as described above. Figure 4 gives a summary of this classification scheme, including the abbreviations of various types of jets to be introduced in sections 3 to 5.

b. Analysis of heavy rain events

The heavy rain events in the current study were classified into two types: A and B. Type A events were those with 24-h accumulative rainfall reaching 100 mm at least at one station [among six stations in northern Taiwan (Fig. 2); Chen and Yang 1988]. In addition, rainfall during the same 24 h at no fewer than three other stations needed to reach 20 mm, and therefore local heavy rain events were excluded. The first hour that the accumulative rainfall reached 10 mm was
Fig. 8. Same as Fig. 6, but for (a) migratory SLLJ and DLLJ, (b) nonmigratory SLLJ and DLLJ above 900 hPa, (c) migratory SBJ and double barrier jet (DBJ), and (d) nonmigratory SBJ and DBJ below 900 hPa. Solid lines depict SLLJ and DLLJ, and dashed lines depict SBJ and DBJ.
marked as the starting time of the heavy rain event, while the ending time was recorded when none of the six stations received an hourly rainfall greater than 1 mm. The criteria for type B events are the same as type A, except that the required 24-h accumulative rainfall was 50–100 mm, instead of ≥100 mm. Thus, type A events registered a higher amount of precipitation than type B ones. Using this method, the heavy rainfall event associated with the LLJ example in section 1b would have been classified as a type A event (Table 1), starting at 2100 UTC 26 May 1999.

Table 2 summarizes the identified heavy rain events of both types A and B over northern Taiwan. Each type consisted of 17 cases, and thus on average 1.7 type A and 1.7 type B events occurred during each mei-yu season of May–June. Hsinchu was particularly prone to heavy rain events as the synoptic time closest to their commencement, and these two stations also had more type B events than other sites. The averaged duration for type A events was 14.2 h, significantly longer than that of 9.6 h for type B ones. The preferred starting time was in the afternoon, as 7 type A cases and 6 type B ones started between 1300 and 1800 LST (Table 2).

c. Analysis of the relationship between LLJs and heavy rainfall

To facilitate the discussion on the relationship between LLJs/BJs and heavy rain events, $t_o$ is defined for heavy rain events as the synoptic time closest to their commencement, and $t_p$ is defined for migratory LLJs as the time when the 10 m s$^{-1}$ isotach of the jet moved over northern Taiwan on 700- or 850-hPa weather maps. Here, “northern Taiwan” is defined as the rectangular area of 24°–26°N, 120.5°–122.5°E (a $2° \times 2°$ region centered near Panchiao; cf. Fig. 2), while the area “adjacent to Taiwan” is inside 20°–30°N, 110°–130°E. Thus, occurrence frequencies of LLJs/BJs before and after heavy rain events over northern Taiwan, and characteristics of migratory LLJs, can be further examined.

3. Characteristics of low-level jets in northern Taiwan

a. General characteristics

Using the criteria described in section 2a, there were a total of 185 LLJ/BJ appearances (or counts) in northern Taiwan in May–June 1985–94 as determined locally from Panchiao sounding data (excluding cases of strong southwesterly wind due to typhoons or tropical depressions). Here, it is perhaps necessary to note that a single LLJ event in the atmosphere might register more than one count at Panchiao, depending on its intensity, duration, and vertical structure, and it might not satisfy criterion 4. The number of 185 averaged to 18.5 times per mei-yu season and accounted for about 15% of all soundings during the data period. Significantly more appearances of the SJ type (141) were observed than the DJ type (44 occurrences and 88 counts of jet branches). Their height distribution (Fig. 5a), similar to Fig. 3, suggested that both SJ and DJ types appeared most frequently at 900–925 and 825–850 hPa, and relatively fewer cases occurred near and above 700 hPa. Above 900 hPa, the SJ was the most common type, especially at 600–800 hPa. More BJs appeared as the lower branch of a double jet (DJL) rather than as SJ, while the upper branch (DJU) was largely confined within 800–900 hPa (Fig. 5a). The number of LLJ appearances decreased monotonically with wind speed for all types once the speed exceeded 20 m s$^{-1}$ (Fig. 5b). While none of the DJL cases exceeded 25 m s$^{-1}$, very few cases of other types reached the speed range of 30–40 m s$^{-1}$. The averaged height and maximum wind speed for BJs below 900 hPa were very similar regardless of whether they appeared as an SJ or DJL (Table 3b). For LLJs between 700 and 850 hPa, on the other hand, DJU cases tended to have a lower elevation and a slightly faster speed than SJ cases.

The composite vertical profiles of horizontal wind speed, centered at the level of jet maximum, from 2 km below to 3 km above, for different types of LLJs are presented in Fig. 6. The single low-level jet (SLLJ) cases at 700–850 hPa (solid; Fig. 6a) tended to accompany a much thicker layer of strong winds than single barrier jets (SBJs) at 900–925 hPa (dashed). Since composites for DJU and DJL were drawn from the same group of cases with two jets at different levels, their wind speed profiles were similar, and both associated with layers of strong wind deeper than their SJ counterparts (Fig. 6b). The two jets in DJ cases were on average separated by about 800 m. In Fig. 6a, a layer of relatively strong wind also appeared at about 800 m above the jet core in the SBJ composite, but the vertical wind shear of cases included was too weak to satisfy both criteria 5 and 6.

b. Interannual and intraseasonal variations

Figure 7 depicts interannual and intraseasonal variations in the number of SJ, DJ, and total LLJs in our data period. Note that the appearances of DJs were counted only once here. The trends for SJ and DJ were quite similar during the 10 mei-yu seasons of 1985–94 and seemingly had a 5-yr cycle, with most cases in 1998 followed by 1993 (Fig. 7a). From May to June, Fig. 7b suggests that there were more LLJ appearances starting from early June, especially the SJ type, consistent with the gradual strengthening in prevailing southwesterly wind. In addition, there appeared to exist a 15-day cycle in the data, as relatively more LLJs occurred during 6–10 and 21–25 May as well as 6–10 and 21–25 June.
4. Comparison of migratory and nonmigratory low-level jets

a. General characteristics

When the 185 LLJs identified at Panchiao were classified based on movement using weather maps at 850 and 700 hPa, 94 and 91 were determined to be migratory and nonmigratory (or stationary), respectively, and thus each group accounted for about 50% of all LLJ appearances. Hence, more local, short-lived jets identified from Panchiao sounding data but not resolved by weather maps occurred nearly as frequently as the larger LLJs seen on weather maps. Both groups, nevertheless, exhibited a similar DJ-to-SJ ratio of about 1:3, so different types of LLJs in their vertical structure in our study did not seem to have preferred characteristics of movement, and vice versa.

When the numbers of migratory and nonmigratory jets of different types were plotted against pressure, the overall distributions were quite similar to Fig. 5a and therefore are not shown here. Additional information, however, could still be revealed when the two diagrams were compared. At the peak level of 825–850 hPa for LLJs, migratory jets (MLLJs) occurred slightly more often than nonmigratory ones (NMLLJs; cf. Fig. 4). For BJJs at 900–925 hPa, about 3 times as many cases were of the MDBJ type as the MSBJ type in the migratory group, while NMDBJ and NMSBJ types in the nonmigratory group, in contrast, were nearly identical in number, and both significantly more than MSBJs (not...
shown). This suggests that single barrier jets over northern Taiwan tended to be local and stationary, consistent with their nature of being induced by terrain blocking (Li and Chen 1998), while migratory barrier jets (MBJs) were classified as such mainly because of their association with a migratory upper branch.

When the composite wind speed profiles for migratory and nonmigratory LLJs (above 900 hPa) were compared (Figs. 8a and 8b), it is obvious that migratory LLJs, regardless of their types [SLLJ or double low-level jet (DLLJ)], tended to be stronger than nonmigratory jets, both in wind speed at the jet core and the thickness of associated strong wind layer (≥12.5 m s⁻¹). The difference was particularly large between the two DLLJ types, and reached nearly 5 m s⁻¹ at 1–3 km above the jet core. For BJs (Figs. 8c and 8d), the MSBJ and MDBJ types were also stronger than their nonmigratory counterpart. The NMSBJ composite had the shallowest layer of strong wind (≥12.5 m s⁻¹), extending vertically from the jet core for only about 200 m in both directions. As a result, wind speed difference between MSBJ and NMSBJ was also significant at 0.5–3 km above the jet. Thus, from Fig. 8 one can conclude that both migratory LLJs/BJs were in general stronger than nonmigratory ones over northern Taiwan. In addition, consistent with Fig. 6, the layer of strong winds associated with the DJ type in each group, migratory or not, also tended to be thicker than the SJ type, while the difference was apparently most clear between NMDBJ and NMSBJ.

Fig. 9. (Continued)
FIG. 10. Scatterplots of wind directions (degrees) at Panchiao and nearby synoptic stations on (a) 850- and (b) 700-hPa weather maps for all LLJs above 900 hPa (173 occurrences) in May–Jun 1985–94. Crosses depict migratory, and open circles depict nonmigratory, LLJs. For each LLJ occurrence, only one map of 850 or 700 hPa was used depending on which was closer to the level of jet maximum.

b. Geographical distribution of migratory LLJs

Of the 94 appearances of migratory LLJs (and BJs), 58 (62%) were seen at 850 hPa while 69 (73%) could be analyzed at 700 hPa. Thus, many migratory LLJs were quite deep and extended at least from 850 to 700 hPa. These occurrences were attributed from a total of 46 individual LLJ cases (each lasting for ≥12 h, or two synoptic times), of which 30 and 28 were identifiable at 850 and 700 hPa, respectively. By defining $t_{12}$ as the time when the 10 m s$^{-1}$ isotach moved inside 24°–26°N, 120.5°–122.5°E (section 2c), the geographical distribution of these migratory LLJs at different stages can be plotted and further examined. Results at 850 hPa are presented in Fig. 9, since more occurrences and individual cases were identified at this level. The migratory LLJs eventually affecting northern Taiwan tended to form over southern China between 20° and 30°N (Fig. 9a), with the highest frequency (near 23°N, 109°E) just to the east of the Tibetan Plateau, in agreement with Chen and Chen (1995). The main axis of the jets was oriented from southwest to northeast, also roughly parallel to the terrain. As the LLJs migrated eastward at $t_{12}$ and $t_{24}$, their overall shape became much more elongated, with the area of high frequency extending farther downstream (Figs. 9b and 9c). In addition, the orientation of maximum axis also turned slightly, into west-southwest to east-northeast. From $t_{12}$ to $t_{24}$, the LLJs moved southward significantly, and the frequency converged toward the main axis passing through northern Taiwan (Fig. 9d). The distribution at 700 hPa (not shown) indicated that the frequency axis was orientated from west-southwest to east-northeast and was located farther north than at 850 hPa during the early stages before $t_{24}$. The veering of the jet axis with height and the northward tilt implied that these LLJs usually formed in a baroclinic environment over southern China, ahead of a trough within warm air advection, in a synoptic setting quite similar to the one shown in Fig. 1 and also consistent with the results of X.-A. Chen and Chen (1995).

c. Topographical effects

To examine the topographical effects of Taiwan, wind directions at Panchiao on synoptic weather maps were compared with those at nearby stations at the time of each LLJ occurrence above 900 hPa (totaled at 173), using whichever map of 850- or 700-hPa was closer to the level of jet maximum. As shown in Fig. 10, when migratory and nonmigratory LLJs occurred, respectively, 83% and 77% of all corresponding points at 850 hPa, as well as 67% and 68% of points at 700 hPa were located below the oblique line, indicating that the wind direction at Panchiao had a smaller angle than its environment. Among the 30 LLJ cases with the 10 m s$^{-1}$ isotach moving over northern Taiwan at 850 hPa in section 4b, 11 cases had their jet core passing directly over. Eight of them intensified in speed from $t_{12}$ to $t_{24}$, but only 2 cases exhibited a similar strengthening at 700 hPa (both not shown). Thus, results here and from Fig. 10 indicate that prevailing southwesterly flow in the lower troposphere was often deflected northward because of terrain blocking of Taiwan. The blocking produced local convergence and subsequent increase in wind speed through the same mechanism for barrier jet formation, but its effect gradually diminished at levels farther up.

When LLJs appeared in Panchiao sounding data, but
the corresponding area of strong winds was absent at both 850- and 700-hPa maps, or was present but could not meet all four requirements for horizontal shear, duration, size, and movement described in section 2a, they were classified as nonmigratory cases (91 out of 185). Then, the synoptic time when the jet first appeared in Panchiao sounding data was simply taken to be $t_0$. Scatterplots of their maximum wind speeds at endpoints of each of the 12-h intervals (from $t_{-24}$ to $t_{+24}$) are shown in Fig. 11. The vast majority of cases are located above the oblique line in Fig. 11b, and thus showed intensification in wind speed from $t_{-12}$ to $t_0$. Between $t_0$ and $t_{+12}$, in contrast, most cases experienced rapid weakening (Fig. 11c), while no preferred trend was observed from $t_{-24}$ to $t_{-12}$ and $t_{+12}$ to $t_{+24}$ (Figs. 11a and 11d). Thus, nonmigratory LLJs/BJs over northern Taiwan tended to be relatively short-lived and were apparently local phenomena, as they were mostly only resolved by sounding data but not by weather maps.

5. Relationship of low-level jets to heavy rainfall

a. Occurrence frequencies of LLJs related to heavy rainfall

Table 4 lists the occurrence frequencies (%) of migratory LLJs at 850 and 700 hPa at different times relative to the synoptic time closest to the onset of heavy rain events (defined as $t_0$). For type A events, highest frequencies (42%) of LLJ over northern Taiwan (24°–26°N, 120.5°–122.5°E) were reached at $t_{-12}$ at both 850 and 700 hPa, in agreement with Chen and Yu (1988), and the frequencies dropped rapidly to only 6% at $t_{+12}$ (Table 4, top half). When a larger area adjacent to Taiwan (20°–30°N, 110°–130°E) was considered, frequencies of LLJ increased significantly and reached as high as 94% at $t_{-12}$ and $t_0$ at 850 hPa, and 88% from $t_{-24}$ to $t_{+12}$ at 700 hPa. The majority of the LLJs (over northern Taiwan) associated with type A heavy rains were of the SJ type (Table 5, top half), particularly the
more moisture to the region, prolong the duration of heavy rain, and allow for a higher amount of rainfall to accumulate. For the relative frequencies of various types of LLJs/BJs associated with type B heavy rain events, results also suggest the MSLJJ to be the primary type observed (18%–35% from \( t_{r,24} \) to \( t_{r,12} \); Table 5, bottom half).

**b. Geographical distribution of LLJs related to heavy rainfall**

Geographical distribution of MLLJ axes (identified using areas with wind speed \( \geq 10 \text{ m s}^{-1} \)) at 850 hPa from \( t_{r,24} \) to \( t_{r,0} \) for the 17 type A heavy rain events in May–June 1985–94 is presented in Figs. 12a–c. At \( t_{r,24} \), these LLJ streaks were located along the southeast coast of China, and over the East China Sea and adjacent area of Taiwan, and oriented from west-southwest to east-northeast (Fig. 12a). Their starting points were mostly over the South China Sea or surrounding coastal regions, and a few were near the Taiwan Strait. Many LLJ streaks moved southeastward to concentrate along the coast of China at \( t_{r,12} \), bringing warm and moist air from the South China Sea near Hainan Island (centered near 19°N, 110°E; Fig. 12b). At this time, many streaks also passed directly over northern Taiwan. At (the synoptic time closest to) the onset of type A heavy rain (\( t_{r,0} \); Fig. 12c), the core of many jets at 850 hPa had just passed Taiwan, while most remaining ones still extended far back to the South China Sea. In general, the 850-hPa LLJ streaks associated with the 17 type B heavy rain events (Figs. 12d–f) were located over similar areas as those for type A heavy rains from \( t_{r,24} \) to \( t_{r,0} \). A more detailed comparison, however, reveals that the distribution of streaks for type B events was more widespread, and many of them were shorter in length, farther away from northern Taiwan, did not extend into the

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**Table 4. Occurrence frequencies (%) of migratory LLJs (\( \geq 10 \text{ m s}^{-1} \)) over northern Taiwan (inside 24°–26°N, 120.5°–122.5°E) or in an adjacent area (inside 20°–30°N, 110°–130°E) at 850 and 700 hPa at different times (from \( t_{r,24} \) to \( t_{r,12} \)) relative to the starting time (defined at \( t_{r,0} \)) of (top) type A and (bottom) type B heavy rain events in May–Jun 1985–94 (each type consists of 17 events).

<table>
<thead>
<tr>
<th>Time</th>
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<th>Adjacent area</th>
<th>Northern Taiwan</th>
<th>Adjacent area</th>
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<td>Type B heavy rain events</td>
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<td>18%</td>
<td>82%</td>
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<tr>
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<td>29%</td>
<td>88%</td>
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<td>82%</td>
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<td>18%</td>
<td>76%</td>
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**Table 5. Occurrence frequencies (%) of different types of LLI/BJ over northern Taiwan as determined from Panchiao sounding data at different times (from \( t_{r,24} \) to \( t_{r,12} \)) relative to the starting time (defined as \( t_{r,0} \)) of (top) type A and (bottom) type B heavy rain events in May–Jun 1985–94 (each type consists of 17 events). MLLJ and NMLLJ represent migratory and nonmigratory LLJs, respectively, and they may overlap with BJ.

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* Both jets are above the 900-hPa level.
South China Sea, or passed over land for longer distances, especially before the heavy rains at \( t_{j-24} \) and \( t_{j-12} \) (Figs. 12d and 12e). Thus, their ability to transport moisture to northern Taiwan before and near the onset of a heavy rainfall event was, in general, weaker. Similar differences between the distributions of MLLJ streaks associated with the two rainfall types were also quite clear at 700 hPa (not shown). Hence, when compared with type A ones, type B heavy rain events tended to accompany LLJs whose capability to transport moisture was weaker or that did not concentrate the moisture supply toward northern Taiwan, and consequently, the accumulative rainfall amounts were lower.

c. Vertical structure of LLJs related to heavy rainfall

The hodographs constructed from averaged vertical profiles of horizontal wind at Panchiao among the 17 type A heavy rain cases from \( t_{j-24} \) to \( t_{j+12} \) are presented in Figs. 13a–d. Deep layers of strong west-southwesterly to westerly winds (at least close to 12.5 m s\(^{-1}\)) in the troposphere, extending from about 1.5 km all the way to 10 km, appeared by \( t_{j-24} \) (Fig. 13a). With time, low and midlevel wind speed (about 2–6 km) increased and reached a maximum of 15.7 m s\(^{-1}\) at about 2.5 km at \( t_{j-12} \) (Fig. 13b), in agreement with the increase in LLJs’ occurrence frequency between \( t_{j-24} \) and \( t_{j-12} \) (Tables 4 and 5). At \( t_{j0} \), the jet near 2.5 km weakened while wind speeds at 5–7 km increased (Fig. 13c). Easterly winds also started to appear at the surface, indicating the passage of the mei-yu front. Finally at \( t_{j+12} \), wind speeds at jet level further decreased while the postfrontal air thickened to about 800 m (Fig. 13d). On the other hand, upper-level winds (9–10 km) strengthened, leaving relatively weak winds at 5–7 km. Chen and Yu (1988) hypothesized that the weakening of LLJ after rainfall started was partially due to vertical mixing by cumulus convection. Finally, since the appearance of BJs inside the PBL was infrequent in heavy rain events (Table 5), there was little sign for the existence of near-surface strong winds in Figs. 13a–d.

Similar hodographs for type B heavy rain events indicate that wind speeds were significantly slower than those accompanying type A events in the lower troposphere (1–4 km), and an LLJ structure was absent (<12.5 m s\(^{-1}\)) in the composite profile at \( t_{j-24} \) (Fig. 13e). The strengthening of low-level winds started at \( t_{j-12} \) (Fig. 13f), and the maximum wind speed and a jet structure (13.5 m s\(^{-1}\) at 3.2 km) appeared at \( t_{j0} \) (Fig. 13g). After heavy rain, low-level winds also weakened more rapidly than in type A cases, which still preserved a jet structure near 3.5 km (Figs. 13d and 13h). Therefore, when LLJs associated with type B heavy rain events were compared with those associated with type A ones, the former tended to exhibit weaker speeds in the lower troposphere, to have a jet core level somewhat higher, and to persist a shorter period of time.

d. Precipitation and heavy rains during LLJ passages

Up to this point, sections 5a–c have discussed characteristics of LLJs at different times relative to \( t_{j0} \), or the onset of heavy rains. In this section, the relationship is examined from the other perspective, that is, based on \( t_{j0} \), the time when the migratory LLJ (area \( \approx 10 \text{ m}^2 \)) moved over northern Taiwan (24°–26°N, 120.5°–122.5°E) on 850- or 700-hPa charts, and heavy rain probabilities and the evolution of rainfall intensity during LLJ passages are discussed.

As mentioned in section 4b, the 94 appearances of MLLJs at Panchiao came from 46 individual cases, among which 30 and 28 were identifiable at 850 and 700 hPa, respectively. For those at 850 hPa, 9 and 3 cases (30% and 10%) produced a type A and type B heavy rain event during their passage, respectively, while the corresponding numbers were 7 and 4 (25% and 14%) at 700 hPa. Thus, about 40% of all migratory LLJs (on weather maps) passing over northern Taiwan in mei-yu season were associated with heavy rainfall (between \( t_{j-13} \) and \( t_{j+36} \)). The probability distribution of \( t_{j0} \) (the synoptic time closest to the onset) of heavy rainfall when an 850-hPa LLJ appeared (Fig. 14a) indicates that none of the events took place by \( t_{j-12} \), then the probability increased through \( t_{j-24} \) and fell afterward when both rain types were considered (solid line). More events started at \( t_{j+24} \) than at any other time (33% of type A and 67% of type B), while the onset of another 33% of type A events were at \( t_{j0} \) and coincided with the LLJ’s arrival at northern Taiwan. For 700-hPa MLLJs (Fig. 14b), the probability also reached the peak at \( t_{j+24} \) (29% of type A and 50% of type B), but the overall distribution with time was more widespread. Admittedly, the sample size of heavy rain events was relatively small here (12 at 850 hPa and 11 at 700 hPa, respectively), but Fig. 14 did show increased probabilities for both types of heavy rainfall to occur immediately after the arrival of the LLJ from \( t_{j0} \) to \( t_{j+24} \) quite consistently, thus suggesting a close relationship between the jets and heavy precipitation.

When type A and type B events were combined, the averaged 6-h accumulative rainfall (millimeters) from \( t_{j-24} \) to \( t_{j+36} \) indicates that most precipitation fell after \( t_{j0} \), with the primary peak between \( t_{j+12} \) and \( t_{j+24} \) and a secondary peak between \( t_{j+6} \) and \( t_{j+12} \) (Fig. 15a). Rainfall associated with 850-hPa LLJs that did not cause a heavy rain event, on the other hand, was consistently low (<1 mm) with no apparent trend. The results for 700-hPa MLLJs (Fig. 15b) were similar to those at 850 hPa, with rainfall also occurring mostly after \( t_{j0} \) for jets associated with heavy rainfall. However, there existed only one major peak between \( t_{j+18} \) and \( t_{j+24} \).

6. Discussion

From our study on the characteristics of LLJs over northern Taiwan in section 3, it was found that the ma-
Fig. 12. Geographical distribution of axes of 850-hPa migratory LLJs (defined by wind speed $\geq 10$ m s$^{-1}$) at (a) 24 h before ($t_{r-24}$), (b) 12 h before ($t_{r-12}$), and (c) $t_{r}$ of type A heavy rain events in May–Jun 1985–94, with $t_{r}$ defined as the synoptic time closest to the onset of the heavy rain (see text for further details).
Fig. 12. (Continued) (d)–(f) Same as (a)–(c), except for type B heavy rain events. The number of each LLJ case is shown at the endpoints of the axes.
Majority of LLJs took the form of a single jet (SJ; 141 occurrences or 76%) during the data period. The remaining 24% had a double jet (DJ) structure, with its lower branch most commonly being a barrier jet (BJ) below 900 hPa (Fig. 5a). Above the 900-hPa level, LLJs (including both SJs and DJS) were stronger in maximum wind speed and were associated with a thicker layer of winds $\geq 12.5$ m s$^{-1}$ than the BJs (Fig. 6), in accordance with the fact that the latter were induced locally because of terrain blocking of the CMR (Lin 1993; Li and Chen.
Fig. 14. Probability (or frequency) distribution (%) of heavy rain onset from 24 h before ($t_{j-24}$) to 36 h after ($t_{j+36}$) the synoptic time when migratory LLJs moved over northern Taiwan inside 24°–26°N, 120.5°–122.5°E (defined as $t_{j}$) at (a) 850 and (b) 700 hPa at 12-h intervals. Dashed, dash–dot, and solid lines represent averaged probability of type A (9 cases), type B (3 cases), and all heavy rain events.

From Fig. 5, it is clear that BJs near Taiwan occurred in an elevation distinctly different from the ordinary LLJs and could be readily identified using the criteria developed in section 2a.

The analysis in section 4 revealed that about 50% of all LLJs that appeared in Panchiao sounding data were migratory cases that formed over southern China to the lee of the Tibetan Plateau and subsequently moved southeastward presumably along with the mei-yu front, similar to the scenario described by Chen and Chen (1995). The other 50%, most of them not resolved by weather maps, were classified as nonmigratory LLJs, but their strength was on average weaker than MLLJs in terms of maximum wind speed and depth of strong winds (Fig. 8), as well as duration (Fig. 11). For the very few cases of NMLLJs that appeared on weather maps (and Panchiao sounding data) but showed no movement, previous studies suggested that they were more likely to associate with a slow-moving or stationary mei-yu front at a later stage of the frontal development, when cumulus convection along the front might play a more important role toward their intensification (Chou et al. 1990; S.-J. Chen et al. 1998; Chen et al. 2003). The mechanism for the development of local NMLLJs above 900 hPa over northern Taiwan, since it was not the focus of present study, remains largely unaddressed here.

In agreement with Chen and Yu (1988), in section 5 it was found that a very high percentage of type A heavy rain events ($\geq 100$ mm in 24 h) over northern Taiwan during the data period were accompanied by an LLJ in close proximity or in an adjacent area at 850 or 700 hPa (88%–94% from $t_{r-24}$ to $t_{r+12}$; Table 4). The majority of these jets were MLLJs (53% at $t_{r-12}$; Table 5) originating over southern China, rather than the usually weaker NMLLJs developed locally (6% at $t_{r-12}$). The LLJs associated with heavy rains presumably played the role of transporting warm and moist air northward, producing convective instability and enhancing low-level convergence along the mei-yu front, thereby facilitating the
development and maintenance of MCSs (e.g., Ninomiya and Akiyama 1974; Chen 1983, 1988; Kuo and Chen 1990). For type B events (50–100 mm in 24 h), the frequencies of 850-hPa LLJ appearances over northern Taiwan were considerably lower than in type A events (18% versus 42% at $t_{\text{r},12}$), as were the percentages in the adjacent area just before and at $t_{\text{r},0}$ (76% versus 94%). The difference in LLJ frequencies between the two types of heavy rain events at 700 hPa, in contrast, was much less, except notably in the timing of the highest frequency relative to rainfall ($t_{\text{r},12}$ for type A and $t_{\text{r},0}$ for type B; Table 4). Therefore, whether a more severe type A event, or a less severe type B event, would occur over northern Taiwan, appeared to be closely linked to the morphology of the LLJ: its proximity to northern Taiwan, whether it penetrated down to a lower level (closer to 900 hPa) where the moisture was more abundant, and the relative timing of heavy rain after the LLJ’s arrival. Other discernable factors for LLJs associated with a type A event include that they tended to be stronger, more persistent (Fig. 13), larger in areal extent, and passed over the warmer water of the South China Sea for longer distances prior to the heavy rain events (Fig. 12).

It was found that about 40% of all migratory LLJs passing over northern Taiwan were associated with heavy rainfall within 24 h, and the remaining 60% were not (section 5d). This figure of 40% is much lower than the 91% obtained by Chen and Yu (1988), and at least two factors that could contribute to this marked difference are offered here. First, a more stringent criterion in maximum wind speed ($\geq 15$ m s$^{-1}$) was used by Chen and Yu (1988) for their identification of LLJs, as opposed to $12.5$ m s$^{-1}$ used here. Second, their analysis was performed using only 850- and 700-hPa weather maps, while LLJs here were identified mainly using sounding data, which have a much higher vertical resolution. Thus, an LLJ with wind speed of $\geq 15$ m s$^{-1}$ is very likely to exhibit an even higher speed at its core somewhere between 850 and 700 hPa (which is often the case based on the present study). The scatterplot in Fig. 16 shows a positive correlation (coefficient =
0.474) between the maximum wind speed of an LLJ and the highest 24-h accumulated rainfall among the six stations over northern Taiwan and supports the notion that the stronger LLJs studied by Chen and Yu (1988) could result in a significantly higher likelihood of heavy rainfall. Nevertheless, since about 60% of LLJ passages did not cause heavy rainfall in the present study, other favorable conditions obviously must also exist for heavy rain events to occur (also Fig. 15), unless the LLJ is significantly stronger than average. Thus, from an operational standpoint, the passage of an LLJ in the lower troposphere can be considered a nearly necessary condition (but not a sufficient condition by itself) in producing heavy rainfall events.

Since the maximum wind of most LLJs over northern Taiwan occurred between 850 and 700 hPa, especially for SJs, as indicated by sounding data (Fig. 5a), it follows that using 12-h weather maps to analyze LLJs is often less than ideal to capture their true characteristics. Arritt et al. (1997) discussed the advantages of wind profiler data over conventional sounding, particularly in the analysis of the diurnal variation of LLJs (over the U.S. Great Plains) with a higher temporal resolution. Since a wind profiler network is unavailable over upstream and adjacent regions to Taiwan, a few errors were likely to be inevitable in our classification of LLJ movement (migratory or nonmigratory) based only on weather maps 12 h apart. For instance, a total of seven MSBJ occurrences were identified below 900 hPa (when an SBJ existed in Panchiao sounding data and an LLJ was also present on the 850-hPa map farther upstream 12 h earlier; details not shown), but true barrier jets should be local and stationary in nature (e.g., Li and Chen 1998). Given data availability in the future, it can be further investigated whether LLJs over southern and southeastern China also experience diurnal oscillation in their strength near the top of the PBL, similar to those over the United States (Blackadar 1957; Bonner 1968; Mitchell et al. 1995). If they do (and perhaps to a lesser degree), migratory LLJs can possibly at times lead to wind maximum inside the PBL, or merge with a barrier jet below 900 hPa. These questions, however, remain to be answered in the future.

7. Conclusions

The present study utilized twice-daily sounding data at Panchiao, hourly rainfall data at six surface stations
over northern Taiwan, and operational east Asian weather maps at 850 and 700 hPa in May–June 1985–94 to investigate the mesoscale climatological characteristics of LLJs below 600 hPa (including barrier jets below 900 hPa due to terrain blocking) in mei-yu season, as well as their relationship to the total of 34 heavy rainfall events that occurred during the data period. The frequency of occurrence, vertical structure, spatial and temporal distributions of LLJs were obtained and discussed according to their form of appearance (single or double jet), type of movement (migratory or nonmigratory), and the severity of associated heavy rainfall (type A of $\geq 100$ mm in 24 h or type B of 50–100 mm in 24 h).

Major findings can be summarized as follows:

1) During mei-yu season, LLJs occurred about 15% of the time in northern Taiwan, with a peak speed ranging from 12.5 to almost 40 m s$^{-1}$. The majority of LLJs took the form of a single jet (76%) with jet core located between 850 and 700 hPa. The remaining 24% were double jets, with the upper branch maximized near 825–850 hPa and the lower branch at 900–925 hPa (being a barrier jet), and the two branches were on average 800 m apart. Compared to barrier jets, LLJs (600–900 hPa) were stronger over deeper layers regardless of their form of appearance.

2) Migratory and nonmigratory LLJs each constituted about half of all cases, and little relationship seemed to exist between movement and appearance of LLJs. Migratory LLJs tended to be stronger than nonmigratory ones, especially for the double jets, while nonmigratory single barrier jets were the weakest among all types. Migratory LLJs mostly formed over southern China between 20° and 30°N then moved toward Taiwan, and many of them were thick enough to appear on both 850 and 700 hPa upon arrival. Nonmigratory LLJs, on the other hand, were apparently short-lived local phenomena, as most of them could not be resolved by weather maps.

3) Heavy rainfall events over northern Taiwan were closely linked to LLJs. Type A events (at least 100 mm in 24 h) had a 94% chance of being accompanied by an LLJ at 850 hPa, and an 88% chance of LLJ appearance at 700 hPa, over regions adjacent to Taiwan from 12 h prior to the onset of heavy rainfall. At both 850 and 700 hPa, 42% of type A heavy rains had LLJ presence exactly over northern Taiwan at 12 h before the event started. The majority of LLJs linked to heavy rainfall were migratory ones, as they were also stronger and persisted longer than nonmigratory LLJs.

4) When type B events (50–100 mm in 24 h) occurred, frequencies of LLJ passages directly over northern Taiwan (18%) were considerably lower than those associated with type A events, but percentages of LLJs over adjacent areas at 700 hPa were nearly the same. The difference between type A and type B events was closely linked to LLJ’s morphology, such as its strength, depth, elevation of maximum wind, persistence, proximity to northern Taiwan, and relative timing of arrival before heavy rainfall, as well as source region of moisture, preferably over the South China Sea.

5) About 40% of all migratory LLJs passing over northern Taiwan were associated with heavy rainfall within the next 24 h, but the remaining 60% were not. The 40% value was significantly lower than that obtained by previous studies. Possible reasons were offered to account for this difference, which was likely a result of a less stringent requirement in the LLJ peak wind speed used in the present study.

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