Low-Level Jets in Heavy Rainfall in Taiwan

Subjects: Meteorology & Atmospheric Sciences
Contributor: Yi-Leng Chen

During the early summer rainy season over Taiwan, three types of low-level jets are observed, including a synoptic low-level jet (SLLJ) situated in the 850–700 hPa layer in the frontal zone, a marine boundary layer jet (MBLJ) embedded within the southwesterly monsoon flow over the northern South China Sea at approximately the 925 hPa level, and an orographically induced jet at approximately the 1 km level off the northwestern Taiwan coast (e.g., barrier jet (BJ)).

Keywords: synoptic-system-related low-level jets ; low-level jets ; Mei-Yu

1. Introduction

Over East Asia, the Asian summer monsoon is one of the most dominant climate systems on earth and it can bring frequent heavy rainfall periods to the affected region. The summer monsoon rainy season from early June through July is known as the Baiu season in Japan [1], Changma season in Korea [2], and Mei-Yu season in China [3]. Taiwan has an early summer rainy season under the southwesterly monsoon flow (Mei-Yu) from mid-May to mid-June and the typhoon season from late June to September [4][5][6][7][8]. Heavy rainfall events are one of the extreme weather phenomena that pose a significant challenge for both scientific research and operational forecasts. These events share two essential characteristics globally: copious moisture and destabilization effects due to lifting, e.g., [3][9][10][11][12][13][14][15][16][17][18][19][20][21][22].

There are different types of “low-level jets” (LLJs) around the globe [23], such as in Europe [24][25][26], the Alps [11][17], East Asia [15][27][28][29][30][31][32][33][34][35][36][37][38], the Caribbean [39][40], the U.S East coast [41], the Carolina coast [42], the California Coast [43], the Pacific Northwest [14][44], the Great Plains states [45][46][47][48][49], and subtropical South America [50][51][52]. In some cases, LLJs may play important roles in moisture transport and/or lifting, leading to heavy precipitation events.

G. Chen and Yu [28] used horizontal wind speed greater than 12.5 m s^{-1} at the 850 hPa level and greater than 15 m s^{-1} at the 700 hPa level to identify the LLJs from weather maps. Tao and Chen [3] also classified LLJs using wind speed at the 925 hPa, 850 hPa, and 700 hPa levels. In addition to horizontal wind speed, both Chen et al. [32] and Du et al. [53][54] included vertical wind shear in their LLJ criteria, using high resolution data from numerical models. Du et al. [53] used two criteria to identify LLJs: a wind speed maximum greater than 10 m s^{-1} in the lowest 4 km and a decrease in winds with height, by at least 3 m s^{-1}, above the level of maximum winds. Du et al. [53] classified LLJs during the Mei-Yu season over China into two types: synoptic-system-related low-level jets (SLLJs) in the 900–600 hPa layer and boundary layer jets (BLJs) below the 900 hPa level. Over the southern China coast, SLLJs occur most frequently in April–June, whereas BLJs are more frequent in May–July [55]. During BLJ events, rainfall has a local maximum on the southern windward side of the coastal mountain ranges caused by orographic lifting. However, rainfall has a local maximum on the coast and in inland areas during SLLJ events due to horizontal moisture transport by SLLJs.

During the early summer rainy season over Taiwan, there are three distinct types of low-level jets: the SLLJ located southeast of an 850–700 hPa Mei-Yu frontal cyclone along the large-scale Mei-Yu trough [28][31][32][33][56][57]; the marine boundary layer jet (MBLJ) associated with intensification of the southwesterly monsoon flow in the marine boundary layer (MBL) over the northern South China Sea [58][59][60]; and the barrier jet (BJ) of approximately 14 m s^{-1} at the 1-km level, blowing parallel to the coastal terrain along the northwestern Taiwan coast [61][62][63][64][65].

2. The SLLJs Associated with Mei-Yu Fronts

The Taiwan Area Mesoscale Experiment (TAMEX) during May–June 1987 [66] and the Terrain-influenced Monsoon Rainfall Experiment (TiMREX) during May–June 2008 [67][68][69][70] were conducted to study the processes leading to heavy rainfall during the early summer rainy season in Taiwan. During TAMEX, all the Mei-Yu fronts over southern China resemble mid-latitude cold fronts with horizontal temperature differences of approximately 5–7 K in the lowest levels, and a marked northward vertical tilt [5][71][72][73][74]. An synoptic-system-related upper-level jet (SULJ) and tropopause folding associated with the upper-level front are also evident. During the passage of a midlatitude trough, the cold air behind the trough from northern China moves into the south China plain [5][71][72][74]. As a result, the surface front over southern China advances southeastward and moves across the Taiwan area. During the last TAMEX frontal event affecting Taiwan during 24–25 June 1987, the low-level horizontal temperature differences and baroclinic characteristics were less significant, as compared to other cases earlier in the season. This is the result of increased warming over the North China Plain with increased solar heating during the seasonal change in mid-June [74].

A TiMREX case during the Intensive Observing Period (IOP) #3 from 1200 UTC 29 May to 0600 UTC 30 May 2008 [69] and a case on 3 June 1984 [75], as well as in other recent studies [60][76] all confirm these Mei-Yu frontal systems possess baroclinic characteristics.

As the Mei-Yu jet/front system moves toward the subtropics, the depth of the postfrontal cold air decreases to a rather shallow depth of ~1 km over the Taiwan area [5][71][72][73] in response to a smaller Coriolis parameter. At the leading edge, the fine-scale structure of the shallow front in the lowest levels resembles a density current, as observed by an instrumented aircraft.

During the 1980–1984 Mei-Yu season, G. Chen and Yu [28] observed that 12 h before the commencement of a heavy rainfall event over northern Taiwan, there is an 84% chance that a SLLJ of at least 12.5 m s^{-1} is present at the 700 hPa level. Similarly, when a SLLJ greater than 12.5 m s^{-1} is present at the 700 hPa level, there is a 91% probability that a heavy precipitation event, greater than 100 mm day^{-1}, will occur over northern Taiwan. They suggested that the SLLJ is driven by convective heating [28][31][77][78] and that the SLLJ is responsible for the transport of warm, moist air to the prefrontal atmosphere of the Mei-Yu frontal zone [4].

TAMEX and recent studies have showed that SLLJs in the warm sector of Mei-Yu fronts are caused by a mass-momentum adjustment process in response to moist baroclinic forcing during the deepening of a Mei-Yu jet/front system [32][33][79]. Each Mei-Yu front affecting Taiwan during TAMEX was accompanied by a SLLJ of varying intensity [56][63][74]. The frontal cyclone during 1–3 June 1987 was the deepest cyclone observed during TAMEX [33].

During TAMEX, each SLLJ event began when an upstream mid-latitude trough approached the Tibetan Plateau from the west/northwest with an initial vortex forming on the leeside of the Tibetan Plateau or the Yun-Gui Plateau [56]. As the trough advanced southeastward into the China Plain, the lee vortex developed into a Mei-Yu frontal cyclone with a SLLJ in its southeastern flank. A SULJ/front with tropopause folding was evident in the upper levels. The intensification of the SLLJ (SULJ) is caused by the cross-isobaric wind component towards the low-pressure center of the frontal cyclone (upper-level tough) as the frontal cyclone deepens. Additionally, a weak thermally indirect circulation to the south is diagnosed.

From calculations of energy conversion of the SLLJ case during 1–3 June 1987, X. Chen and Chen [79] determined that the divergent kinetic energy (k_D) is generated from potential energy (PE) through the cross-contour divergent winds. The generated k_D is then converted into nondivergent kinetic energy (k_{ND}) via a conversion process through the secondary circulation across the jet/front system. In the upper levels, the conversion from potential energy to k_{ND} via cross-contour nondivergent winds is the major source for the k_{ND} associated with intensification of the SULJ. In this case, the upper-level divergence ahead of the trough provides the upper-level support needed for the SLLJ development.

Model sensitivity tests with (CTRL) and without latent heat release (NOLH) of the 1–2 June 1987 case reveals that tropopause folding is present even without latent heat release [33]. The deepening of the Mei-Yu frontal cyclone is caused by vertical motion associated with the propagating upper-level short-wave trough and is enhanced by latent heat release. The baroclinic conversion is enhanced by latent heat release, especially in the upper troposphere. In the upper levels, the thickness ahead of the trough increases, resulting in further deepening of the cyclone. The SLLJ develops through the Coriolis force acting on the cross-contour ageostrophic winds in response to the increased pressure gradients as the frontal cyclone deepens. This mechanism is at variance with the conditional instability of the second kind (CISK) process suggested by G. Chen and Chang [80] and Chou et al. [77].

In the 29–30 May 2008 case, Tu et al. simulated a low-level frontal cyclone along the southeastern China coast as the 700 hPa short-wave trough moves over the low-level moist tongue. In the regional domain with a 27 km grid, quasi-geostrophic (QG) frontogenesis is diagnosed ahead of the 700 hPa trough axis without latent heat release in the model. In the nested 9 km grid, the latent heat release associated with the convective activity generates significant potential vorticity (PV) at low levels, leading to a more intense frontal cyclone and a stronger SLLJ.

Numerical simulations with a 9 km grid for the 1–2 June 2017 case reproduces a Mei-Yu frontal structure that is similar to the results analyzed by TAMEX studies. The potential vorticity associated with the Mei-Yu frontal zone slopes vertically northward. A potential vorticity maximum generated by upright cumulus convection extends vertically upward above the surface front. The spin up of the frontal cyclone is caused by a moist baroclinic process. These results are consistent with previous studies [32][33] and the study presented by Park et al. [38] for heavy rainfall events during the Changma season over the Korean Peninsula. Park et al. [38] determined that the baroclinic trough from the west plays an important role in triggering vertical motion and the development of a surface cyclone with a SLLJ on the southeastern flank of the cyclone. Using the QG omega equation, they demonstrated that in the developing stage of heavy rainfall events, both the dynamic forcing and diabatic forcing are equally important. However, the effects of latent heating are more important in the mature stage.

From the calculations of heat and moisture budgets for a heavy rainfall case over the south China coast during 20–23 May 1987, it is apparent that the tendency and horizontal advection terms are considerably smaller than the vertical advection terms, suggesting that vertical motion is the dominant mechanism in the production of heavy rainfall. There are two heavy rainfall periods centered around 0000–1200 UTC 20 May and 0000–1200 UTC 22 May with rainfall accumulation greater than 50 mm and 150 mm, respectively. During 20–22 May, positive vorticity advection by thermal winds is diagnosed ahead of the deepening 850 hPa trough [61]. Prior to the first peak rainfall period on 20 May, upper-level divergence is computed in the diffluent airflow at the 300 hPa level between the upper-level westerlies and the northeastern flank of the upper-level Asian cyclone. A similar large-scale environment is also found with the heavy rainfall case during 24–25 June 1987 [62]. In the second period on 22 May, strong upper-level frontogenesis due to horizontal deformation is diagnosed along the trough axis. The heaviest rainfall occurs when the low-level baroclinic forcing is coupled with the upper level forcing as the upper-level trough approaches. Park et al. [38] found that the heavy rainfall events in South Korea during the summer monsoon are organized by the vertical motions associated with a baroclinic trough with positive feedback from latent heating. The thermally direct secondary circulation at the entrance region of the SULJ provides additional upper level forcing aloft.

Hsiao and Chen [81] revisited the 10–15 June 1975 case studied by G. Chen and Chang [80] using the European Centre for Medium-Range Weather Forecast (ECMWF) Reanalysis (ERA-40) data with 23 vertical levels. In this case, a mid-latitude omega blocking pattern in place on 10 June had developed into a Rex blocking pattern by 12 June. A trough axis extends from a low associated with the block. The surface front over south China moved slowly southward and affected the Taiwan area for more than four days. In the low levels, prefrontal warm, moist southwesterly flow converged with postfrontal cold, dry northwesterly flow. At the 500 hPa level, a high equivalent potential temperature axis was present, which coincided with the area of rising motion in the baroclinic zone. The high equivalent potential temperature air in the mid-levels was brought vertically upward from low levels by the rising motions in the baroclinic zone. In the upper levels, an upper-level front with tropopause folding was also present (not shown). The SULJ and the upper-level front advanced southward. The frontal structure and characteristics are remarkably similar to those found during TAMEX and in recent studies. Note that in the composite analysis presented by G. Chen and Chang [80] for the same case, the appreciable temperature gradients across the surface front in the low levels and the baroclinic signatures in the upper levels are completely absent when using the filtered and subjectively analyzed 240 km grid data and composite procedures that used data based on only four vertical levels (e.g., 850 hPa, 700 hPa, 500 hPa, and 400 hPa levels).

3. The Interactions of the Three Types of LLJs on Heavy Rainfall over Taiwan

One of the important findings of TAMEX was the role of localized convergence between the BJ and frontal wind shift line [60][62][75][76][82] or the southwesterly flow [64] off the northwestern/western Taiwan coast on the development of deep convection under favorable large-scale settings. The orientation and depth of the Mei-Yu front also impacts the rainfall pattern as the front interacts with the island terrain.

Li et al. [62] studied an unexpected heavy rainfall event (>231 mm) that occurred along the northwestern coast during TAMEX IOP #13 during 24–25 June 1987 using upper-air, surface mesonet, and dual-Doppler radar data. As a NE–SW oriented Mei-Yu front moved southeastward from southern China to the Taiwan area, the shallow (~1 km) postfrontal cold air in the lowest levels was decelerated by the hilly terrain along the southeastern China coast. As a result, a low-level wind shift line associated with a pressure trough at the 850 hPa level moved over the terrain along the southeastern China coast into the Taiwan Strait before the arrival of the Mei-Yu frontal boundary at the surface. The large scale settings of this event were characterized by: (1) a SLLJ with a wind speed about 13 m s^{-1} ahead of the 850 hPa trough; (2) low-level winds veering with respect to height, suggesting warm advection in the prefrontal atmosphere; (3) an axis of high equivalent potential temperature in the prefrontal atmosphere with large equivalent potential temperature gradients between the warm, moist SLLJ and the relatively dry and cold northeasterly flow behind the Mei-Yu trough; (4) coupling between the low-level forcing (warm advection and frontal lifting) and upper-level divergence in the diffluent airflow region on the northeastern flank of the South Asian anticyclone.

A long-lived rainband developed over the northern Taiwan Strait between the barrier jet and the northwesterly flow behind the wind shift line. The rainband consisted of several long-lived (>2 h) reflectivity maxima at different stages of its life cycle. The reflectivity maxima formed on the southwestern tip of the rainband and intensified during their movement from the southwest to the northeast. During the mature stage, the reflectivity maxima were rooted within the low-level convergence zone approximately 3 km deep and tilted southeastward with height with sinking motion in the lower troposphere. The continued generation of the reflectivity maxima along the localized convergence zone maintained the long lifecycle of the rainband, resulting in persistent heavy rainfall along the northwestern coast as the reflectivity maxima moved onshore. During the early stage of the rainband's development, the reflectivity maxima on the northeastern part of the rainband merged with the convective line associated with the land breeze front.

During TAMEX IOP #3 from 21–22 May 1987, a rainfall maximum of more than 40 mm h^{-1} occurred along the western/northwestern coast of Taiwan under favorable large-scale settings. This event occurred under large-scale rising motion ahead of the 850 hPa jet/front system. Concurrently, an upper-level trough deepened and moved toward South China [61]. A SLLJ greater than 15 m s^{-1} ahead of the 850 hPa trough impinged on the Central Mountain Range. A barrier jet developed off the northwestern Taiwan coast due to orographic blocking. During 1000–1600 local standard time (LST), three rainbands formed in succession within the orographically induced convergence zone over the Taiwan Strait. The deflected southerly flow converged with the prevailing southwesterly flow, which was modified by the storm-induced westerlies immediately behind the convective line. Modeling results confirmed that the localized convergence off the northwestern coast was caused by orographic effects and the convective feedbacks.

During TAMEX, daily rainfall incidences along the northwestern/western coast were less than 40%. Nevertheless, more than 80% of rainfall there occurred during the passage of Mei-Yu systems. It is apparent that during frontal passages, the barrier jet plays an important role in enhancing the amount of rainfall over the northwestern and western coasts [62][64]. In contrast, over the island interior, daily rainfall incidences are greater than 60–70%, but less than 50% of total rainfall amount there occurs during frontal periods [83] . Model simulations by Tu et al. [60] indicated that the barrier jet also transports moisture to the frontal zone, which is consistent with previous studies [8][62][75][76].

For a NNE–SSW oriented Mei-Yu front that occurred on 3 June 1984 [75], the pre-existing rainfall was enhanced as the front moved over the northeastern Taiwan Strait, where the prevailing southwesterly winds converged with the orographically deflected flow, with a southerly wind component off the western/northwestern Taiwan coast. As the pre-existing convective rainfall continued to move toward northern Taiwan, it was enhanced in a localized low-level convergence zone over the northwestern coast, where a barrier jet converged with the northwesterly winds behind the surface front. Furthermore, on the morning of 3 June 1984, rainfall was simulated where the barrier jet encountered the leading edge of the cold pool caused by rain evaporative cooling, as suggested by Chiou and Liu [84].

Chen et al. [76] studied the interaction between an E–W oriented Mei-Yu jet/front system and topography for a heavy rainfall event over northern Taiwan during 11–12 June 2012. All three jets (SLLJ, MBLJ and BJ) co-existed in this event. In this case, in addition to excessive rainfall on the windward sides of the Snow Mountains and the Ali-Shan Mountains, there was a maximum rainfall accumulation (~435 mm) over the northwestern Taiwan coast and another rainfall maximum of approximately 477 mm within the Taipei Basin. The MBLJ brought in excessive moisture from the northern South China Sea, while the secondary circulation associated with the SLLJ provided the large-scale lifting mechanism, and local effects by the BJ and front-terrain interaction determined the timing and distribution of localized heavy rainfall during the frontal passage over northern Taiwan. From 2200 LST 11 June to 0200 LST 12 June, the rainfall maximum along the northwestern coast was related to the arrival of scattered prefrontal radar echoes, followed by the convective line associated with the Mei-Yu front. The convective activities over the northwestern coast were enhanced by the localized convergence between the southerly BJ and the postfrontal west-northwesterly flow. From 0200–0800 LST 12 June, the relatively deep postfrontal cold air, approximately 1.5 km deep, moved over the Yang-Ming Mountains, with peaks approximately 1120 m in height, into the Taipei Basin as the Mei-Yu front arrived with cold northeasterlies near the surface and northwesterlies behind the 850 hPa trough. In this case, the Mei-Yu front stalled, resulting in heavy precipitation over the Taipei Basin for 6 h. Additionally, the 850 hPa postfrontal northwesterlies impinged on the northwestern slopes of the Snow Mountains, which resulted in heavy orographic precipitation there as the Mei-Yu system continued to advance southward.

Tu et al. [60] studied another unusually heavy rainfall event along the northern coast of Taiwan during 1–2 June 2017. In this case, all three types of low-level jets (SLLJ, MBLJ, and BJ) co-existed and, again, the timing and distribution of localized heavy rainfall over northern Taiwan were determined by front-terrain interaction. In contrast to the case studied by Chen et al. [76], the E–W oriented shallow Mei-Yu front (less than 850 m) was anchored over the northern side of the Yang-Ming Mountains, with peaks approximately 1120 m high, for 8 h during the early morning (0200–1000 LST). Persistent orographic rainfall along the northern coast resulted in a rainfall accumulation of more than 600 mm. As the postfrontal cold air continued to push southward, eventually the cold air was able to pass over the Yang-Ming Mountains and moved into the Taipei Basin, which had a Mei-Yu frontal rainband. Furthermore, the southwesterly BJ converged with the postfrontal northwesterly flow, resulting in a local rainfall maximum over the northwestern coast. As the Mei-Yu front continued to advance southward, orographic precipitation occurred over the northwestern slopes of the Snow Mountains as the northwesterly flow behind the 850 hPa trough impinged on the Snow Mountains.

From the composite for 21 MBLJ days during 2008–2012, the NE–SW cross section through the Taiwan Strait reveals the existence of a horizontally oriented MBLJ (>12 m s^{-1}) over the northern South China Sea at the 925 hPa level. A SLLJ extends upward between 900–650 hPa around 25.3° N ahead of the frontal zone. Because this cross-section passing through the BJ, the SLLJ has merged with the BJ at low levels with a jet core greater than 14 m s^{-1} at approximately the 925 hPa level. On the eastern side, in the cross section along 124° E, the orographically enhanced wind maximum greater than 11 m s^{-1} in the boundary layer is evident around 23.5° N. A SLLJ extends upward around 27.5° N, above the sloping frontal surface. An upper-level jet core greater than 35 m s^{-1} is also present. For heavy rainfall events over Taiwan, the MBLJ brings in moisture, whereas the secondary circulation associated with the jet/front system provides the large-scale lifting mechanism and possible upper-level dynamic forcing aloft. Over northern Taiwan, interactions of the jet/front system with terrain and rain evaporative cooling are important in determining the timing and distribution of localized rainfall.

References

1. Ninomiya, J.; Murakami, T. The Early Summer Rainy Season (Baiu) over Japan; Monsoon Meteorology; Chang, C.-P., Krisnamurti, T.N., Eds.; Oxford University Press: Oxford, UK, 1987; pp. 93–121.
2. Lee, J.-Y.; Kwon, M.; Yun, K.-S.; Min, S.-K.; Park, I.-H.; Ham, Y.-G.; Lin, E.K.; Kim, J.-H.; Seo, K.-H.; Kim, W.; et al. The long-term variability of Changma in the East Asian summer monsoon system: A review and revisit. Asia Pac. J. Atmos. Sci. 2017, 53, 257–272.
3. Tao, S.; Chen, L. A Review of Recent Research on the East Asia Summer Monsoon in China; Monsoon Meteorology; Chang, C.-P., Krisnamurti, T.N., Eds.; Oxford University Press: Oxford, UK, 1987; pp. 60–92.
4. Chen, G.T.-J. Observational aspects of the Mei-Yu phenomenon in subtropical China. J. Meteorol. Soc. Jpn. 1983, 61, 306–312.
5. Chen, Y.L.; Zhang, Y.-X.; Hui, N.B.-F. Analysis of a surface front during the early summer rainy season Over Tai-wan. Mon. Weather Rev. 1989, 117, 909–931.
6. Chen, C.-S.; Chen, Y.-L. The rainfall characteristics of Taiwan. Mon. Weather Rev. 2003, 131, 1323–1341.
7. Chen, C.-S.; Chen, Y.-L.; Liu, C.-L.; Lin, P.-L.; Chen, W.-C. Statistics of heavy rainfall occurrences in Taiwan. Weather Forecast. 2007, 22, 981–1002.
8. Kerns, B.W.J.; Chen, Y.-L.; Chang, M.-Y. The diurnal cycle of winds, rain, and clouds over Taiwan during the Mei-Yu, Summer, and Autumn rainfall regimes. Mon. Weather Rev. 2010, 138, 497–516.
9. Ogura, Y.; Asai, T.; Dohi, K. A case study of a heavy precipitation event along the Baiu front in Northern Kyushu, 23 July 1982: Nagasaki heavy rainfall. J. Meteorol. Soc. Jpn. 1985, 63, 883–900.
10. Akaeda, K.; Reisner, J.; Parsons, D. The Role of mesoscale and topographically induced circulations in initiating a flash Flood Observed during the TAMEX Project. Mon. Weather Rev. 1995, 123, 1720–1739.
11. Buzzi, A.; Tartaglione, N.; Malguzzi, P. Numerical simulations of the 1994 Piedmont Flood: Role of orography and moist processes. Mon. Weather Rev. 1998, 126, 2369–2383.
12. Zhu, Y.; Newell, R.E. A proposed algorithm for moisture fluxes from atmospheric rivers. Mon. Weather Rev. 1998, 126, 725–735.
13. Teng, J.-H.; Chen, C.-S.; Wang, T.-C.C.; Chen, Y.-L. Orographic effects on a squall line system over Taiwan. Mon. Weather Rev. 2000, 128, 1123–1138.
14. Garvert, M.F.; Colle, B.A.; Mass, C.F. The 13–14 December 2001 IMPROVE-2 Event. Part I: Synoptic and mesoscale evolution and comparison with a mesoscale model simulation. J. Atmos. Sci. 2005, 62, 3474–3492.

15. Lin, Y.-L.; Chiao, S.; Wang, T.-A.; Kaplan, M.L.; Weglarz, R.P. Some Common Ingredients for Heavy Orographic Rainfall. Weather Forecast. 2001, 16, 633–660.
16. Medina, S.; Smull, B.F.; Houze, R.A.; Steiner, M. Cross-Barrier Flow during Orographic Precipitation Events: Results from MAP and IMPROVE. J. Atmos. Sci. 2005, 62, 3580–3598.
17. Bougeault, P.; Binder, P.; Buzzi, A.; Dirks, R.; Kuettner, J.; Houze, R.; Smith, R.B.; Steinacker, R.; Volkert, H. The MAP Special Observing Period. Bull. Am. Meteorol. Soc. 2001, 82, 433–462.
18. Witcraft, N.C.; Lin, Y.-L.; Kuo, Y.-H. Dynamics of orographic rain associated with the passage of a tropical cyclone over a mesoscale mountain. Terr. Atmos. Ocean. Sci. 2005, 16, 1133–1161.
19. Schroeder, T.A. Meteorological analysis of an Oahu flood. Mon. Weather Rev. 1977, 105, 458–468.
20. Kodama, K.; Barnes, G.M. Heavy rain events over the south-facing slopes of Hawaii: Attendant conditions. Weather Forecast. 1997, 12, 347–367.
21. Tu, C.-C.; Chen, Y.-L. Favorable conditions for the development of a heavy rainfall event over Oahu during the 2006 wet period. Weather Forecast. 2011, 26, 280–300.
22. Jayawardena, I.M.S.; Chen, Y.-L.; Nash, A.J.; Kodama, K. A comparison of three prolonged periods of heavy rainfall over the Hawaiian Islands. J. Appl. Meteorol. Clim. 2012, 51, 722–744.
23. Parish, T.R. On the forcing of the summertime Great Plains Low-Level jet. J. Atmos. Sci. 2017, 74, 3937–3953.
24. Browning, K.A.; Pardoe, C.W. Structure of low-level jet streams ahead of mid-latitude cold fronts. Q. J. R. Meteorol. Soc. 1973, 99, 619–638.
25. Kotroni, V.; Lagouvardos, K. Low-level jet streams associated with atmospheric cold fronts: Seven case studies from the Fronts 87 Experiment. Geophys. Res. Lett. 1993, 20, 1371–1374.
26. Lavers, D.A.; Villarini, G.; Allan, R.; Wood, E.; Wade, A. The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large-scale climatic circulation. J. Geophys. Res. Earth Surf. 2012, 117, D20106.
27. Akiyama, T. Ageostrophic low-level jet stream in the Baiu season associated with heavy rainfalls over the sea area. J. Meteorol. Soc. Jpn. 1973, 51, 205–208.
28. Chen, G.T.-J.; Yu, C.-C. Study of low-level jet and extremely heavy rainfall over Northern Taiwan in the Mei-Yu season. Mon. Weather Rev. 1988, 116, 884–891.
29. Tsay, C.-Y. The coupling of upper-level and low-level jet streaks during TAMEX period. Atmos. Sci. 1991, 19, 67–87, (In Chinese with English Abstract).
30. Nagata, M.; Ogura, Y. A modeling case study of interaction between heavy precipitation and a low-level jet over Japan in the Baiu season. Mon. Weather Rev. 1991, 119, 1309–1336.
31. Chen, G.T.-J.; Wang, C.-C.; Lin, D.T.-W. Characteristics of low-level jets over Northern Taiwan in Mei-Yu season and their relationship to heavy rain events. Mon. Weather Rev. 2005, 133, 20–43.
32. Chen, Y.-L.; Chen, X.-A.; Zhang, Y.-X. A diagnostic study of the low-level jet (LLJ) during TAMEX IOP 5. Mon. Weather Rev. 1994, 122, 2257–2284.
33. Chen, Y.-L.; Chen, X.A.; Chen, S.; Kuo, Y.-H. A numerical study of the low-level jet during TAMEX IOP 5. Mon. Weather Rev. 1997, 125, 2583–2604.
34. Shin, C.-S.; Lee, T.-Y. Development mechanisms for the heavy rainfalls of 6–7 August 2002 over the middle of the Korean Peninsula. J. Meteorol. Soc. Jpn. 2005, 83, 683–709.
35. Pham, N.T.; Nakamura, K.; Furuzawa, F.A.; Satoh, S. Characteristics of low-level jets over Okinawa in the Baiu and post-Baiu seasons revealed by wind profiler observations. J. Meteorol. Soc. Jpn. 2008, 86, 699–717.
36. Chen, R.; Tomassini, L. The role of moisture in summertime low-level jet formation and associated rainfall over the East Asian monsoon region. J. Atmos. Sci. 2015, 72, 3871–3890.
37. Liu, X.; Luo, Y.; Huang, L.; Zhang, D.; Guan, Z. Roles of double low-level jets in the generation of coexisting inland and coastal heavy rainfall over South China during the presummer rainy season. J. Geophys. Res. Atmos. 2020, 125, e2020JD032890.
38. Park, C.; Son, S.-W.; Kim, J.-H. Role of baroclinic trough in triggering vertical motion during summertime heavy rainfall events in Korea. J. Atmos. Sci. 2021, 78, 1687–1702.
39. Cook, K.H.; Vizy, E.K. Hydrodynamics of the Caribbean low-level jet and its relationship to precipitation. J. Clim. 2010, 23, 1477–1494.

40. Muñoz, E.; Busalacchi, A.J.; Nigam, S.; Ruiz-Barradas, A. winter and summer structure of the Caribbean low-level jet. J. Clim. 2008, 21, 1260–1276.
41. Uccellini, L.W.; Petersen, R.A.; Kocin, P.J.; Brill, K.F.; Tuccillo, J.J. Synergistic interactions between an upper-level jet streak and diabatic processes that influence the development of a low-level jet and a secondary coastal cyclone. Mon. Weather Rev. 1987, 115, 2227–2261.
42. Doyle, J.D.; Warner, T.T. A three-dimensional investigation of a Carolina low-level jet during GALE IOP 2. Mon. Weather Rev. 1993, 121, 1030–1047.
43. Ralph, F.M.; Neiman, P.J.; Wick, G.A. Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North Pacific Ocean during the winter of 1997/98. Mon. Weather Rev. 2004, 132, 1721–1745.
44. Neiman, P.J.; Ralph, F.M.; Wick, G.A.; Kuo, Y.-H.; Wee, T.-K.; Ma, Z.; Taylor, G.H.; Dettinger, M.D. Diagnosis of an intense atmospheric river impacting the Pacific Northwest: Storm summary and offshore vertical structure observed with COSMIC satellite retrievals. Mon. Weather Rev. 2008, 136, 4398–4420.
45. Holton, J.R. The diurnal boundary layer wind oscillation above sloping terrain. Tellus 1967, 19, 199–205.
46. Bonner, W.D. Climatology of the low-level jet. Mon. Weather Rev. 1968, 96, 833–850.
47. Uccellini, L.W. On the role of upper tropospheric jet streaks and leeside cyclogenesis in the development of low-level jets in the Great Plains. Mon. Weather Rev. 1980, 108, 1689–1696.
48. Pu, B.; Dickinson, R.E. Diurnal spatial variability of Great Plains summer precipitation related to the dynamics of the low-level jet. J. Atmos. Sci. 2014, 71, 1807–1817.
49. Du, Y.; Rotunno, R. A Simple analytical model of the nocturnal low-level jet over the Great Plains of the United States. J. Atmos. Sci. 2014, 71, 3674–3683.
50. Garreaud, R.; Muñoz, R. The low-level jet off the west coast of subtropical South America: Structure and variability. Mon. Weather Rev. 2005, 133, 2246–2261.
51. Salio, P.; Nicolini, M.; Zipser, E.J. Mesoscale convective systems over southeastern South America and their relationship with the South American low-level jet. Mon. Weather Rev. 2007, 135, 1290–1309.
52. Rasmussen, K.L.; Houze, R.A. Convective initiation near the Andes in subtropical South America. Mon. Weather Rev. 2016, 144, 2351–2374.
53. Du, Y.; Zhang, Q.; Chen, Y.-L.; Zhao, Y.; Wang, X. Numerical simulations of spatial distributions and diurnal variations of low-level jets in China during early summer. J. Clim. 2014, 27, 5747–5767.
54. Du, Y.; Chen, Y.-L.; Zhang, Q. Numerical Simulations of the Boundary Layer Jet off the Southeastern Coast of China. Mon. Weather Rev. 2015, 143, 1212–1231.
55. Du, Y.; Chen, G. Climatology of low-level jets and their impact on rainfall over southern China during the early-summer rainy season. J. Clim. 2019, 32, 8813–8833.
56. Chen, X.A.; Chen, Y.-L. Development of Low-Level Jets during TAMEX. Mon. Weather Rev. 1995, 123, 1695–1719.
57. Chen, Y.-L.; Tseng, S.-F. Comments on “The intensification of the low-level jet during the development of mesoscale convective systems on a Mei-Yu Front”. Mon. Weather Rev. 2000, 128, 495.
58. Tu, C.-C.; Chen, Y.-L.; Lin, P.-L.; Du, Y. Characteristics of the marine boundary layer jet over the South China Sea during the early summer rainy season of Taiwan. Mon. Weather Rev. 2019, 147, 457–475.
59. Tu, C.-C.; Chen, Y.-L.; Lin, P.-L.; Lin, P.-H. The relationship between the boundary layer moisture transport from the South China Sea and heavy rainfall over Taiwan. Terr. Atmos. Ocean. Sci. 2020, 31, 159–176.
60. Tu, C.-C.; Chen, Y.-L.; Lin, P.-L.; Huang, M.-Q. Analysis and Simulations of a heavy rainfall event associated with the passage of a shallow front over Northern Taiwan on 2 June 2017. Mon. Weather Rev. 2022, 150, 505–528.
61. Chen, Y.-L.; Li, J. Large-Scale conditions favorable for the development of heavy rainfall during TAMEX IOP 3. Mon. Weather Rev. 1995, 123, 2978–3002.
62. Li, J.; Chen, Y.-L.; Lee, W.-C. Analysis of a heavy rainfall event during TAMEX. Mon. Weather Rev. 1997, 125, 1060–1082.
63. Li, J.; Chen, Y.-L. Barrier jets during TAMEX. Mon. Weather Rev. 1998, 126, 959–971.
64. Yeh, H.-C.; Chen, Y.-L. The role of offshore convergence on coastal rainfall during TAMEX IOP 3. Mon. Weather Rev. 2002, 130, 2709–2730.
65. Yeh, H.-C.; Chen, Y.-L. Numerical simulation of the barrier jet over northwestern Taiwan during the Mei-Yu season. Mon. Weather Rev. 2003, 131, 1396–1407.

66. Kuo, Y.-H.; Chen, G.T.-J. The Taiwan area mesoscale experiments: An overview. Bull. Amer. Meteor. Soc. 1990, 71, 488–503.

67. Ciesielski, P.E.; Chang, W.-M.; Huang, S.-C.; Johnson, R.H.; Jou, B.J.-D.; Lee, W.-C.; Lin, P.-H.; Liu, C.-H.; Wang, J. Quality-controlled upper-air sounding dataset for TiMREX/SoWMEX: Development and corrections. J. Atmos. Ocean. Technol. 2010, 27, 1802–1821.

68. Xu, W.; Zipser, E.J.; Chen, Y.-L.; Liu, C.; Liou, Y.-C.; Lee, W.-C.; Jou, B.J.D. An orography-associated extreme rainfall event during TiMREX: Initiation, storm evolution, and maintenance. Mon. Weather Rev. 2012, 140, 2555–2574.

69. Tu, C.-C.; Chen, Y.-L.; Chen, C.-S.; Lin, P.-L.; Lin, P.-H. A comparison of two heavy rainfall events during the Terrain-Influenced Monsoon Rainfall Experiment (TiMREX) 2008. Mon. Weather Rev. 2014, 142, 2436–2463.

70. Wang, C.-C.; Hsu, J.C.-S.; Chen, G.T.-J.; Lee, D.-I. A study of two propagating heavy-rainfall episodes near Taiwan during SoWMEX/TiMREX IOP-8 in June 2008. Part I: Synoptic evolution, episode propagation, and model control simulation. Mon. Weather. Rev. 2014, 142, 2619–2643.

71. Chen, Y.-L.; Hui, N.B.-F. Analysis of a shallow front during TAMEX. Mon. Weather Rev. 1990, 118, 2607–2623.

72. Chen, Y.-L.; Hui, N.B.-F. Analysis of a relatively dry front during the Taiwan Area Mesoscale Experiment. Mon. Weather Rev. 1992, 120, 2442–2468.

73. Trier, S.B.; Parsons, D.B.; Matejka, T.J. Observations of a subtropical cold front in a region of complex terrain. Mon. Weather Rev. 1990, 118, 2449–2470.

74. Chen, Y.-L. Some synoptic-scale aspects of the surface fronts over southern China during TAMEX. Mon. Weather Rev. 1993, 121, 50–64.

75. Chen, C.-Y.; Chen, Y.-L.; Chen, C.-S.; Lin, P.-L.; Liu, C.-L. Revisiting the heavy rainfall event over Northern Taiwan on 3 June 1984. Terr. Atmos. Ocean. Sci. 2013, 24, 999.

76. Chen, Y.-L.; Chu, Y.-J.; Chen, C.-S.; Tu, C.-C.; Teng, J.-H.; Lin, P.-L. Analysis and simulations of a heavy rainfall event over Northern Taiwan during 11–12 June 2012. Mon. Weather Rev. 2018, 146, 2697–2715.

77. Chou, L.C.; Chang, C.-P.; Williams, R.T. A numerical simulation of the Mei-Yu Front and the associated low-level jet. Mon. Weather Rev. 1990, 118, 1408–1428.

78. Hsu, W.-R.; Sun, W.-Y. A numerical study of a low-level jet and its accompanying secondary circulation in a Mei-Yu system. Mon. Weather Rev. 1994, 122, 324–340.

79. Chen, X.A.; Chen, Y.-L. Kinetic energy budgets of the low-level jet during TAMEX IOP 5. J. Meteorol. Soc. Jpn. 2002, 80, 1–19.

80. Chen, G.T.-J.; Chang, C.-P. The structure and vorticity budget of an early summer monsoon trough (Mei-Yu) over southeastern China and Japan. Mon. Weather Rev. 1980, 108, 942–953.

81. Hsiao, F.; Chen, Y.-L. Revisiting the structure and characteristics of an early summer monsoon trough over South China in 1975. SOLA 2014, 10, 194–198.

82. Ke, C.-Y.; Chung, K.-S.; Wang, T.-C.C.; Liou, Y.-C. Analysis of heavy rainfall and barrier-jet evolution during Mei-Yu season using multiple Doppler radar retrievals: A case study on 11 June 2012. Tellus A Dyn. Meteorol. Oceanogr. 2019, 71, 1571369.

83. Yeh, H.-C.; Chen, Y.-L. Characteristics of rainfall distributions over Taiwan during Taiwan Area Mesoscale Experiment (TAMEX). J. Appl. Meteor. Climatol. 1998, 37, 1457–1469.

84. Chiou, T.K.; Liu, F.C. A mesoscale analysis of heavy rainfall on 3 June 1984 and the discussion of flash floods in northern Taiwan. Meteorol. Bull. 1985, 31, 1–14, (In Chinese with English Abstract).