Recent Development of Heavy Rain Research Associated with Summer Monsoon in East Asia Excited by Advances in Weather Radar

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1. Introduction
Recent concerns on heavy rainfalls associated with summer monsoon in East Asia are extreme rainfall in localized areas. People are taking a lifestyle that is susceptible to localized heavy rainfalls with the development of transportation networks and urbanization. Popularization of mobile phone made immediate transmission of heavy rain disaster-related information possible, however the time and spatial resolution of the prediction information in provided is low. Recent advancement of radar monitoring of heavy rainfall assures accurate estimation of rainfall intensity in high spatial resolution and provides further innovation of technology in short-term forecasting of heavy rainfalls. In order to meet this imperative, we need to improve our understanding on structure of precipitation systems producing heavy rainfalls in localized area; detailed analyses should be based on radar observation data. Studies with radar on heavy rainfall events associated with summer monsoon in East Asia in recent 10 years are reviewed in this article. Heavy rainfalls associated with typhoon and in close relation with monsoon are also briefly discussed. Most of articles reviewed are based on the papers published in referred journals however some interesting results from conference papers are also included for completeness.

Heavy rainfalls in East Asia are associated with summer monsoon: Meiyu (in China), Baiu (in Japan) and Changma (in Korea) fronts. The Meiyu/Baiu/Changma front has been studied by many researchers (Chen 2004; Tao and Chen 1987; Ninomiya and Muraki 1986; Kato 1989). Development of Doppler radar networks in recent 10 years in China, Hong Kong, Taiwan, Korea and Japan, and major mesoscale field campaigns with new research radars, promoted the understanding on heavy rainfalls. Studies on these heavy rainfalls in East Asia related to summer monsoon studies and their major contributions will be included in this article.

2. Monsoon rain in East Asia
Based on the understanding of the Meiyu/Baiu/Changma frontal rainfalls by recent 10 years field campaigns and radar observations, the authors discussed a way to understand the relation between water vapor fields and heavy rainfall. Heavy rainfalls in association with summer monsoon occur in the western edge of the subtropical high (Pacific high); where moist air flow in the low altitude is clockwise around the subtropical high and converges with that around stagnant typhoon, tropical depression or low pressure system. The convergence area of the moist airflow around the subtropical high and a stationary front correspond to heavy rainfall area. Heavy rainfalls in the southwesterly moist airflow around the Pacific high are also our research targets. A schematic illustration of candidate locations of heavy rainfall and low-altitude moist airflow in East Asia in summer monsoon is shown in Fig.1.

Area (1): moist airflows in low altitude, east-northeasterly around the Pacific high and southeasterly around a tropical depression, merge at the east coast of island (ex. Taiwan Island).

Area (2): moist airflows in low altitude, southeasterly around the Pacific high and
southwesterly around a tropical depression, merge at the east coast of island (ex. Southern coast of Honshu Island, Japan).

Area (3): moist airflows in low altitude, northwesterly around a tropical depression and southwesterly around the Pacific high, merge at the east coast of island (ex. Taiwan Island).

Area (4): moist airflows in low altitude, southwesterly around northwestern part of the Pacific high, supply large amount of water vapor to island and stationary front (ex. West of Taiwan Island and west of Kyushu Island, Japan).

Area (5): moist airflows in low altitude, southwesterly around northwestern part of the Pacific high, supply large amount of water vapor to the warm front side of a stationary front crossing the west coast of island (ex. West coast of Korean Peninsula and west coast of Honshu Island, Japan).

Area (6): moist airflows in low altitude, southwesterly around northwestern part of the Pacific high, supply large amount of water vapor to the cold front side of a stationary front crossing the west coast of island (ex. West coast of Taiwan Island and west coast of Kyushu Island).

2.1 TAMEX initiation

First analysis on rainfall systems with Doppler radar and aircraft data in this area was carried out in Taiwan Area Mesoscale Experiment (TAMEX: Kuo and Chen 1990). Trier et al. (1989) have shown the not-too-tall convection with large reflectivity over ocean around Taiwan (Fig.2). Ray et al. (1991) described the Meiyu frontal systems observed by Doppler radar over northwest of Taiwan. The front was shallow and the precipitation widespread, both ahead of and behind the front. The front was only 1.6-km deep over a distance of 100 km. Using velocity-azimuth display (VAD) data, a portion of the frontogenetic function was computed during the times the front was in the vicinity of the radar. The increase in both convergence and deformation contributed to large values of the frontogenetic function. Wang et al. (1990) and Lin et al. (1990) studied the

Fig.1. Schematic illustration of the location and situation of typical heavy rainfalls associated with summer monsoon in East Asia. Typical areas of heavy rainfall around the Pacific high are shown by red shade (Area (1) - Area (6)). Red arrows indicate moist flow in low altitude. Tropical depression (TD) and small low pressure system (L) are shown by blue circles. Stationary fronts of the Meiyu, Baiu and Changma are shown by blue lines with “L (low pressure system)”. Each box explains the situation of heavy rainfall in typical Areas (1) - (6). Gray shade indicates island or land. Valleys in the land are not shown explicitly.
fast propagating subtropical squall line (IOP 2 of TAMEX) and found the similarity with the tropical squall lines.

Jorgensen et al. (1991), Jou and Yu (1993), and Yu et al. (1999) applied NOAA P3 aircraft data to study the MCS over the SE ocean of Taiwan. The MCS was associated with an oceanic MCV with a diameter about 70km and the development of vorticity was related to stretching mechanism. Jou and Deng (1992, 1998) using dual-Doppler wind synthesized technique to study the prevailing low-level jet over northwest of Taiwan and found the jet was lifted from 925 hPa to 850 hPa or higher when encountered the deep convective precipitation systems along the Meiuyu front. Shallow frontal rainband was triggered by the speed convergence of the low-level jet and the deep convective systems were related to the pre-frontal convergence line formed by the LLJ and westerly flow. Li et al. (1997) attributed the low-level jet as the consequence of Taiwan topography and named it as barrier jet (BJ). The convergence of this BJ with the prevailing westerly flow (WF) along the wind-shift line at low levels is the major triggering mechanism for the development and maintenance of the heavy rain system in this area (Fig.3). The area of rainfall corresponds to the Area (5) and (6) in Fig.1 as well as the west coast of Kyushu island explained in the next subsection, though orography of Taiwan makes unique feature of the barrier jet.

Fig.2 Range-height indicator scans of (a) reflectivity and (b) radial velocity at 1108 LST 8 June 1987 at the NCAR CP-4 radar site. The azimuth angle is 10°. The hatched region in (a) indicates reflectivity greater than 35 dBZ, and the darkened regions are greater than 45 dBZ. The shaded regions in (b) are for radial velocity (northeasterly flow) moving toward the radar. (Figure taken from Trier et al. (1989))

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Fig.3 Schematic diagram for the structure of the rainband. The barrier jet (BJ) converges with the westerly flow (WF) along the wind-shift line (heavy, dashed line) in low levels. The northwesterly flow (NWF) dominates in the upper troposphere. The vertical cross sections show the long-lived reflectivity maxima embedded in the rainband at the early, well developed, and late stage, respectively. The solid lines represent radar echo boundary with reflectivity core areas shaded. The thin arrows on the cross sections indicate the relative airflow to the rainband system. (Figure taken from Li et al. (1997))
2.2 Kyushu island, Japan

In northern Kyushu, Japan, a historical heavy rainfall (313 mm/3hrs and 572 mm/day) event that occurred at Nagasaki in 1982 is well known. Ogura et al. (1985) analyzed the heavy rainfall event using Japan Meteorological Agency radar data to reconstruct the detailed mechanism. They discovered that convective echoes remained stationary over Nagasaki as a mesoscale cloud cluster during the heavy rainfall event. The location of the precipitation system was Area (5) in Fig. 1. In addition, a new echo cell which formed to the west of Nagasaki moved into the cloud cluster. Formation mechanism of linear rain band was explained by Seko (2001) introducing a back and side building type. Along the west coast of Kyushu, orographic heavy rainfalls are associated with continuous rainfalls in the downstreams of linear peninsula or islands parallel to the moist southwestely in the Area (4) in Fig. 1. For this area, Kanada et al. (2000) analyzed a rainfall enhancement of band-shaped convective cloud systems in the downwind side of an isolated island. Umemoto et al. (2004) and Adachi and Kato (2004) revealed a structure of convergence along the orographic rainband by using wind profiler-weather radar. Yoshizaki et al. (2000) revealed a feature of orographic rainband observed in western Kyushu by analytical and numerical studies.

Based on fundamental and local studies, the first Doppler radar observation in northwest Kyushu was performed in 1988. In this experiment, mesoscale precipitation systems with heavy rainfall have demonstrated the important role of dry air intrusion from the north in enhancing convergence along the Baiu front and convective systems (Ishihara et al. 1995; Takahashi et al. 1996). After this experiment, Doppler radar observations on the Baiu frontal heavy rainfalls were made in several places in Kyushu, e.g., in southern Kyushu in 1996 (Torrential Rainfall Experiment: TREX), in northwest Kyushu in 1997, and in southwest Kyushu in 1999 (X-BAIU: Yoshizaki et al. 2002). In these experiments, transportable X-band Doppler radar sets for research purposes were utilized.

Intensive field experiments in the eastern part of East China Sea and western Kyushu were conducted from 1998 to 2002 (Yoshizaki et al. 2002) with Doppler radars, wind profilers, an airplane, and a research vessel with on-board radar. One interesting result was the finding of a water vapor front (Moteki et al. 2004a, b), i.e., a convergence line with a large water vapor gradient distinct from the Baiu front about 100 km south of the Baiu front as shown in Fig. 4. This indicates easy generation of convection along a weak convergence line in the Area (4) in Fig. 1 in the western fringe of Pacific high.

Fig. 4 Schematic diagram of synoptic-scale structure of the Baiu frontal region based on the surface weather map at 09 JST 27 June 1999. The dark and light shaded areas indicate distribution of the oceanic moist air at the surface and the moist tongue at 700 hPa, respectively. Areas of weak and convective rainfall are surrounded by dotted and solid lines, respectively. The symbol of a stationary front in the south of the Baiu front over the East China Sea denotes the “water vapor front”, a convergence line with a large water vapor gradient distinct from the Baiu front about 100 km south of the Baiu front. The open symbol of a stationary front to the north of the Baiu front indicates the cyclonic wind-shear line at 700 hPa. (Figure taken from Moteki et al. (2004b))

In order to confirm the structure of the water vapor front proposed by Moteki et al. (2004b), dropsonde observations were conducted in 2004 and 2005 over the East China Sea (Moteki et al. 2006). Two flights each year were made during the Baiu targeting the area to the south of the Baiu front on 24 June 2004, 27
June 2004, 23 June 2005, and 24 June 2005. An aircraft observation in the west of Okinawa Island on 23 June 2005 and a numerical simulation examined the structure of the Baiu frontal zone and identified four airstreams around the zone: northeasterly, west-southwesterly, and southwesterly along the Baiu frontal cloud zone, as well as southwesterly along the oceanic zone (Maeda et al. 2008).

2.3 Yangtze River Basin
Field experiments have been conducted to better understand precipitation systems in the moist east Asian environment. The first intensive field experiments on Meiyu frontal precipitation systems with Doppler radar in the upper air sounding network were conducted in 1998 and 1999 during Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment/Huaihe River Basin Experiment (GAME/HUBEX) (Zhao and Takeda 1998, Fujiyoshi and Ding 2006). Maesaka (2003) showed two types of precipitation systems identified with IOP radar data in 1998: one without a temperature gradient in the subtropical air mass and the other with a temperature gradient resulting from the merger with a cold front.

In cases without strong temperature gradients on 29 June 1998, two dominant precipitation systems were recognized. One was a pair consisting of a convective precipitation system on the convergence line of the Meiyu front near the ground and a stratiform precipitation system. The other was a linear convective precipitation system south of the convergence line near the ground. The area of the linear convective precipitation system south of the convergence line corresponds to Area (4) in Fig.1.

2.4 Korean Peninsula
In the Korean Peninsula, the heavy rainfall of the summer monsoon brings sudden and excessive amounts of precipitation locally causing losses of lives and extensive property damages. The weather radar has proven to be the key tool in modern detection and forecasting, as well as in identifying and understanding the physics of heavy precipitation systems. Most of heavy rainfall over Korea is accompanied by synoptic-scale disturbances, typhoons, or convective systems between continental lows over northern China and the subtropical high over the western North Pacific (Lee et al., 2008). Lee et al (1998) reported that heavy rainfall occurs a surface frontal system accompanying a upper-level trough during the Changma period (in Area (4) in Fig.1) or strong instability in the vicinity of the North Pacific high in the post-Changma period (in Area (6) in Fig.1).

3. Development of radar in East Asia
Initiation of Doppler radar observation in TAMEX in 1987 propelled the observation of heavy rainfalls with Doppler radar in East Asia. Field experiments on heavy rainfalls with Doppler radar have been carried out in 1990’s and 2000’s over Japan, China and Korea. Doppler radar network completed in China, Taiwan, Korea and Japan recently are used for understanding heavy rainfall systems even in the area without research radar. Field experiments with polarimetric radar as were done in SoWMEX/TIMREX are proving the performance of the equipment for quantitative precipitation estimation (QPE). Polarimetric radar networks are under construction and preparation in East Asia.

![Figure 5](Figure taken from Uyeda (2008))
has been developed rapidly, from conventional weather and Doppler radar to polarimetric (multi-parameter) radar (Fig.5). Conventional weather radar detects precipitation and estimates precipitation intensity by measuring radar reflectivity. Doppler weather radar is widely used in research worldwide since the 1980s, and the Next-Generation Weather Radar (NEXRAD) had full-coverage Doppler radar networks over the United States since the early 1990s. Doppler radar sets have been installed for operational use in Korea, China, Taiwan, and Japan, although the Japanese network has been completed in 2013. Doppler radar observation would help in short-term forecasting of precipitation systems, though it is not so effective for QPE. Doppler radar networks were originally designed for single Doppler radar observation, but dual Doppler radar analysis is available to obtain three-dimensional wind fields in precipitation systems. As shown by Shimizu et al. (2008) dual Doppler radar analysis was conducted on a supercell-like storm near Tokyo using Haneda and Narita airport Doppler radar. Detailed analysis and numerical simulation showed that supercell-like storms form based on the balance between a weak downdraft in the storm and weak inflow into the storm in a moist environment. This study emphasizes the importance of dual Doppler radar observation of precipitation systems in research and operational use.

So far polarimetric radar has been used only for research purposes in East Asia. Polarimetric radar would be very useful in QPE using parameters of specific differential phase (KDP), correlation coefficient $\rho_{hv}(0)$ and differential reflectivity factor (ZDR). Recent textbooks on radar meteorology explain the merits of polarimetric radar for the measurement of rainfall intensity by using polarimetric factors (Doviak and Zrnic, 1993; Bringi and Chandrasekar, 2001; Fukao and Hamazu, 2013). Maki et al. (2005) showed the efficiency of KDP in estimating rainfall intensity in precipitation systems behind strong precipitation despite rain attenuation. Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan, has been installing X-band polarimetric radar (multi-parameter radar) network for large cities since July 2010. It will be utilized for daily operation in 2003 and may provide data also for heavy rainfall studies and climate studies. Extension of polarimetric radar network in East Asia would make an effective quantitative precipitation forecasting (QPF) in near future.

4. Recent studies on heavy rainfalls in East Asia

Recent field experiments with new radar, detailed analyses with operational radar data and numerical simulations with cloud resolving model are revealing characteristics of heavy rainfalls in each areas of East Asia.

4.1 Korea

Prominent researches on heavy rainfalls have been made recently in Korea.

a) Heavy rainfall in central Korean Peninsula

Understanding on heavy rainfall of the summer monsoon in Korean Peninsula and surrounding area has been improved by radar observation in recent 10 years. Jeong et al. (2012) also pointed out that heavy rainfall is related to a low-level jet (LLJ) transporting warm, moist air from southern China. Sun and Lee (2002) suggested that MCSs were observed between the upper-level jet (ULJ) to the north and LLJ to the south. In addition, the northeastward moving typhoon enhances moisture advection toward the central Korean Peninsula along the LLJ (Choi et al., 2011) for the Area (4) and (6) in Fig. 1. Hence, heavy rainfall of summer monsoon season is characterized by strong baroclinicity even though the atmosphere over Korea is generally thermodynamically neutral. This contrasts with the large convective available potential energy in the central US (Hong, 2004).

In order to elucidate the characteristics of the inner structure and flow in convective systems, high-resolution observational dataset are required. For instance, Kim and Lee (2006) investigated the characteristics of the convective systems occurring over the central Korean Peninsula using single Doppler radar
data and showed that the evolution process of the precipitation systems (in Area (6) in Fig.1). Park and Lee (2009) investigated the precipitation systems using a composited radar data which combined 19 Doppler radars in Korean Peninsula. Based on the analyses of Doppler radar data for heavy rainfall events over Korea, microphysical studies using polarimetric radar are required as an ensuing development on heavy rainfall studies.

b) Heavy rainfall in southern Korea

Observational research of the Changma frontal region has been actively conducted at the intensive observation period (IOP) of the Global Research Laboratory Pukyong-HyARC Nagoya University Observation Network in the East China Sea (GRL PHONE) which is the study designed to examine multi-scale aspects frontal precipitation system near the East China Sea (Lee et al., 2011). Many types and structures of precipitation systems were observed during GRL PHONE, which was conducted from 2006 to present in southwestern Korean Peninsula. During the GRL PHONE period, Jeong et al. (2012 and 2013) revealed that a strong equivalent potential temperature associated with warm and moist air producing into convectively unstable atmosphere was detected over the core of the LLJ (in Area (4) in Fig.1). You et al. (2010) also proved that deep warm-air advection (WAA) supports the maintenance of a convective system for a longer time and results in greater rain intensity, producing drops of larger sizes. Based on dual-Doppler radar analysis, a rear-to-front jet corresponding to a low-level jet was concurrent with a high equivalent potential temperature environment inflow over the warm front, which suggests that the rear-to-front jet with moist air induced destabilization (Fig. 6).

c) Orographic effect of rainfall enhancement

Jeju Island, southern part of Korea has frequently suffered from flooding and landslides due to orographically-intensified rainfall systems during the rainy season (June to mid–July). The island is an isolated terrain with an elliptical–shaped mountain extending east–to–west (width 35 km, length 78 km, height 1.95 km: Fig. 7a). During the rainy season when a stationary front is located off the northern shore of the island, a moist environment and ambient southwesterly winds are well predominant around the island. Lee et al. (2010, 2012 and 2013) revealed the effects of the isolated elliptic terrain on the flow modification and the related rainfall enhancement, in a moist environment by analyses of dual Doppler radar dataset and a non–hydrostatic numerical model. According to their result, when an eastward pre–existing rainfall system travels off northwestern shore, the system develops by accelerated southwesterly wind blowing parallel to the coastline, in the narrowed space between the system and terrain (Fig. 7b), as similar result showed in the northwestern offshore of Taiwan (Wang et al., 2005). On the terrain, the moist southwesterly wind, which is orographically-redirected to blow surrounding the terrain, generates an arc–shaped localized moist updraft zone (grey hatched area, Fig. 7a) on the northern side of the terrain; thus lateral side of the island becomes favorable for rainfall enhancement of pre–existing rainfall system (Fig. 7c). Besides, weaker southwesterly wind in low altitudes is revealed to have a higher potential to induce intense rainfall, also on the lee side by suppressed dry–descending air (Fig. 7d). These results suggest the low–level
southwesterly wind in a moist environment is a noticeable meteorological parameter to improve rainfall forecast over Jeju Island.

### 4.2 Japan

Recent studies are confirming the structures of linear rainband explained by Seko (2001). Band-shaped convective cloud systems (in Area (4) and (5) in Fig. 1) in the moist southwesterly to the south of the Baiu front are not so deep. Their characteristics were shown by Doppler radar observation (Shinoda et al. 2009) and polarimetric radar observation (Shusse et al. 2009, Oue et al. 2010, Oue et al. 2011) in Okinawa region. Structure and formation of rainband in the southwesterly to the south of the Baiu front over East China Sea were shown by Moteki et al. (2004a,b) for the Area (4) in Fig. 1.

Kato and Goda (2001) analyzed formation factors of heavy rainfalls (in Area (5) in Fig. 1) in Niigata-Fukushima, Japan. Kato (2005) discussed the problems in prediction using a cloud-resolving model for Area (5) in Fig. 1. A heavy rainfall from a band-shaped precipitation system, associated with a cold front, in the Area (6) in Fig. 1 over northern Kyushu, Japan have been analyzed by Kato (2006). Low-level humid air from the southwest and mid-level dry air from the west continuously flowed into the precipitation system. Low-level humid air initiated the MCSs and the middle-level dry air enhanced the convective intensity.
Morotomi et al. (2012) revealed the enhancement of rainfall by orographic effect of valley facing to the southerly moist air flow (in Area (2) in Fig. 1). A valley facing to south played a role to enhance a convection by making large convergence of moist airflow in low altitude from south.

### 4.3 China

(a) Around the Meiyu front

To study precipitation in the main Meiyu regions, intensive field experiments in the downstream of the Yangtze River were conducted with the Doppler radar and wind profiler in 2001 and 2002 in the upper-air sounding network (Geng et al. 2004; Yamada et al. 2003). This experiment was conducted by the Frontier Observational Research for Global Change (current Research Institute for Global Change, Jamstec) in cooperation with the Chinese Key Projects (Ni 2002) and the Hydrospheric Atmospheric Research Center of Nagoya University.

Yamada et al. (2003) revealed a mechanism of mesoscale convective system development along the east coast of China, i.e., convergence of a moist, strong, southwesterly inflow to the Meiyu frontal system and a low-altitude easterly flow from the ocean (Fig. 9). The convective systems west of the coast were with precipitation cores around 2 km in height. The mesoscale convective system developed higher near the coast and moved to the Japan Sea the next day, causing heavy rainfall in southern Kyushu and Shikoku, Japan.

Geng et al. (2004) and others are clarifying a variety of precipitation systems around the Meiyu front using the observational data from 2001 to 2003 in the downstream of the Yangtze River. This experiment yielded continuous data acquisition by the Hefei Doppler radar, making the statistical studies of precipitation systems possible.

(b) Convection of medium depth

Zhang et al. (2006a) clarified the predominance of the convection with medium-depth (CMD) in the south of the Meiyu front over the Huaihe River Basin and downstream of the Yangtze River by using the Hefei Doppler radar data of 2001-2003. The CMD is a concept for MCSs consisting of cumulonimbi whose echo top height with the radar reflectivity of 15 dBZ is equal to less than 8 km. The characteristics of the convective systems in a moist environment were confirmed in numerical simulation by Zhang et al. (2006b) using the cloud resolving model. The CMD formed raindrops rapidly in the low altitude below 3 km in height and precipitation particles formed mostly below the 0°C level. Kato et al. (2007) gave a theoretical explanation on the CMD by statistical analyses on the level of neutral buoyancy (LNB) around Japan during the Baiu season. The CMD Zhang et al. (2006a)

![Fig. 9 Schematic illustration of the three-dimensional structure of the mesoscale convective systems developed in the downstream of the Yangtze River near the coast. (Figure taken from Yamada et al. 2003)](image-url)
introduced corresponds to cumulonimbi that form under the surrounding atmospheric condition with middle-level LNB. The cumulonimbi which the CMD consists develop considerably higher than the level of about 700 hPa could be because they can maintain their upward motions even above the LNB against the negative buoyancy that is considerably smaller than around the tropopause.

In the south of the Meiyu/Baiu front, moist environment in low altitudes, convections that reach only to 0°C have characteristics similar in the CMD. Rainfalls from these convections observed around the Meiyu/Baiu front is important in rainfall amounts when they spread over a wide area for a long time and heavy rainfalls when they line up downstream from islands or peninsulas. For comparison of mesoscale precipitation systems in the moist environments, continuous radar observations in the tropical ocean and East Asia are expected.

To clarify the statistical features of precipitation cells during the Meiyu/Baiu period, Doppler radar data obtained at Shouxian, Anhui Province, China (continental area) from 17 June to 17 July 1998, at Zhouzhuang, Jiangsu Province, China (coastal area) from 10 June to 13 July 2001, and at Okinawa (oceanic area) from 27 May to 11 June 2004 are analyzed (Shinoda et al. 2007). From the radiosonde observations, moist layers were found to exist in the lower (less than 2 km) and middle (from 2 to 5 km) troposphere.

(c) Statistical study of squall line system

After the completion of Doppler radar network over China, statistical analyses on squall lines based on mosaics of radar reflectivity were made by Meng et al. (2013) as shown in Fig.10. The study revealed the squall lines in midlatitude east China tend to form in a moister environment with comparable background instability, and weaker vertical shear relative to their U.S. counterparts. Meng et al. (2012) simulated bowing structure of a case associated with a squall line in May. The area of the squall line propagation is not found in Fig.1 as it is related to trough and polar front. These studies are suggesting a new direction of the field experiment in the southeast coast of China.

![Fig. 10](image-url)

The composite radar reflectivity (shading in dBZ) 814 of four examples of the squall lines with different formation and organizational modes. Panels (a)-(d), (e)-(h), (i)-(l), and (m)-(p) signify leading stratiform and broken line, parallel stratiform and back building, trailing stratiform and broken areal, trailing stratiform and embedded areal, respectively. The open arrow in the last panel of each case denotes the direction of movement of the squall line during the shown period. The geography is fixed in row 2, but repositioned on the squall line in rows 1, 3, and 4. (Figure taken from Meng et al. 2013)
4.4 Taiwan

The most recent and systematic field campaign has been performed in southwest Taiwan: the Southwest Monsoon Experiment (SoWMEX)/Terrain-influenced Monsoon Rainfall Experiment (TiMREX). Interaction of southwesterly wind surge over South China Sea and the steep terrain of Taiwan during the Meiyu period (May and June) of the East Asian summer monsoon often produce severe heavy rainfall and flash flood. The experiment SoWMEX/TiMREX is a cooperative field observational program conducted jointly by the scientists of USA and Taiwan to study the mesoscale environment and the microphysical characteristics of the heavy rain weather systems. During SoWMEX/TiMREX (May and June 2008), there were two major heavy rain events observed by the intensive field campaign. One is at late May and early June and was studied by Davis and Lee (2012), Lai et al. (2011), and Ruppert et al. (2013), and the other case is on middle of June and was studied extensively by Xu et al. (2012) and Jung et al. (2012), respectively (Fig.11).

Davis and Lee (2012) showed that when the Meiyu front approached to the island, shallow secondary fronts formed along the coast area and these shallow coastal fronts formed closely associated with the earlier precipitation (Fig.12). Using enhanced dropsonde data over the Taiwan Strait, the shallow frontogenetic processes can be delineated well. These shallow coastal fronts played significant role in triggering and enhancing heavy rainfall. Lai et al. (2012) studied the mesoscale convective vortex embedded within the Meiyu frontal system using dropsonde and Doppler radar.

Their results indicating that the MCV was associated with strong equivalent potential temperature gradient (majorly the moisture gradient) and the heavy rain was associated with the strong southwesterly flows over the south and east quadrants. The enhanced low level convergence associated with the low-level
jet at the east and southeast of the system was the mechanism to maintain the convection and concentrated the vorticity associated with the MCV. It was noted that the northwest quadrant was associated drier air and the intrusion of this mid-level drier air is the possible reason the MCV did not keep deepening to become a tropical cyclone.

Ruppert et al. (2013) has discussed the disturbed and undisturbed situation for heavy rain events occurred in Taiwan during the prevailing southwesterly flow. Froude number (U/Nh, U the speed of prevailing flow, N the stability, and h is the terrain height) is an important indicator on determining the location and the mechanisms the convections triggered and maintained. Under undisturbed situation, the Froude number is usually low and the flows are deflected around the island. The late afternoon thunderstorms over the slope or peak of the mountains are expected. Under the disturbed situation, under the influence of mid-latitude frontal system, the Froude number is usually larger and there is high possibility the flow can be lifted to a higher altitude. During the disturbed period, the precipitation is more widespread, upslope, and more intense rainfall and can be elevated to a higher altitudes.

Xu et al. (2012) studied the case of June 14-16, 2008 heavy rain case over Kaohsiung during SoWMEX/TimREX. His results suggested that the orography of Taiwan was extended to the upstream ocean and played an indirect effect on the long-duration of the heavy rain event in SE of Taiwan. It was shown that the warm, moist, unstable low level jet (LLJ) was only found over the upstream ocean while the island of Taiwan was under the control of a weak cold pool. The LLJ was lifted upward at the boundary between the cold pool and the LLJ. Most convective clusters supporting the long-lived rainy mesoscale system were initiated and developed along the boundary. It is suggested by Xu et al. (2012) that the initiation and maintenance of the system is a back-building quasi-stationary process. The pre-existing cold pool produced by the previous persistent rainfall with a temperature depression of 2-4C in the lowest 500m. This study seems to suggest the mesoscale model needs to have fine boundary layer treatment in order to provide useful simulation results.

Microphysical study of heavy rainfall systems during monsoon period is one of the major scientific objectives of SoWMEX/TimREX. Jung et al. (2012) studied the precipitation characteristics of the MCS on June 2, 2008. S-Pol, Verti-X, and disdrometer data were used to identify the microphysical features. The MCS was a leading convection and trailing stratiform type squall line system. For convenience, Jung et al. has separated the system into several different sectors, convective line with center, leading edge, and trailing edge, stratiform, and reflectivity trough, respectively. It was shown that the convective center has smaller number concentration and mass-weighted mean drop diameter than observations from other maritime storms, for example, Darwin Australia and TOGA-COARE. The drop size distribution also showed the Taiwan squall line has a smaller value and narrower range of shape, slope, and intercept compared with the maritime storms, but with a larger value and broader spread of median volume drop diameter. The reason for the difference is not clear, the abundance of moisture and the intensity of the storm could be the reasons and more studies are needed to clarify the problem. Lightning data is also important to heavy rain study. Tong (2009) studied the environmental conditions and the precipitation characteristics of 40 significant continuous rain periods (SCRPs) identified by rain gauge and radar data during SoWMEX/TimREX. The 40 SCRP's were divided into three different categories according to their origin location and further development, i.e., the land-type SCR, the ocean-type SCR, and the mixed type SCR, respectively. It is shown that these SCRP's have strong diurnal variations and associated with lightning. The land-type storms were usually associated with weaker SW flows and stronger instability. The total number of the lightning is less when compared with the ocean-type, however, in terms of unit of area (density), the land-type SCRP's possessed much higher lightning density.
indicating the concentration of the deep intense convections over land.

Around Taiwan, the heavy rainfall area and situation shown in Fig.1 are not so clear, though heavy rainfall in the Area (1) in Fig.1 is seen in Typhoon Megi (2010) and in the Area (2) in Typhoon Morakot (August 2008) where a valley in the land and orography play important roles. In the very moist environment under less balaclonic situation, microphysical studies on formation of precipitation systems will be essential: observation of raindrop size distribution and identification of solid precipitation particles in precipitating cloud systems.

5. Future perspective

Structure and characteristics of heavy rainfalls associated with the Meiyu/Baiu front have been revealed by field experiments using Doppler radars and an intensive sounding network. In recent 10 years, the development processes of heavy rainfalls occurring in East Asia, in a moist environment at the western edge of the subtropical high (Pacific high) have been clarified for the island and peninsula surrounded by warm ocean. These research developments are based on the completion of operational Doppler radar network in each area and investigation using new research radar as polarimetric radar.

Collaborative field experiments and studies broadened the perspective on precipitation systems around the Meiyu, Baiu and Changma front. Further collaboration and cooperation among researchers on heavy rainfalls associated with summer monsoon in East Asia is expected. Further advancement of operational weather radar network and utilization of high resolution numerical model for assimilation would assure a better understanding of the precipitation systems and the forecasting of heavy rainfalls.

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