18. AN OVERVIEW OF SOWMEX/TIMREX

BEN JONG-DAO JOU
Department of Atmospheric Sciences
National Taiwan University, Taipei, Taiwan
E-mail: jouben@ntu.edu.tw

WEN-CHAU LEE
Earth Observing Laboratory
National Center for Atmospheric Research
Boulder, Colorado, USA
E-mail: wenchau@ucar.edu

RICHARD H. JOHNSON
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado, USA
E-mail: johnson@atmos.colostate.edu

Interactions of southwesterly wind surges over the South China Sea and the steep terrain of Taiwan during the Meiyu period of the East Asian summer monsoon often produce severe weather and heavy rainfall. The Southwest Monsoon Experiment (SoWMEX) and the Terrain-Induced Monsoon Rainfall Experiment (TiMREX) are cooperative field programs conducted by scientists from Taiwan and the United States to study the mesoscale environment and microphysical characteristics of these weather systems. The goals of these field campaigns are to improve the understanding of orographically induced heavy rain processes and to establish the ability of quantitative precipitation forecasting in order to meet the urgent need for disaster reduction due to the heavy monsoon rainfall. Aircraft dropwindsonde observations have been conducted for the first time within monsoonal flows over the South China Sea to study the kinematic and dynamic characteristics of the flow upstream of Taiwan. NCAR SPOL radar, vertical rain profilers, and disdrometers were deployed to study the cloud microphysics and evolution of heavy rainfall systems over the coastal and mountain regions of southwestern Taiwan. In this paper, an overview of the SoWMEX/TiMREX program and its operations is presented and some preliminary results from the field observations are illustrated.

1. Introduction

SoWMEX (Southwest Monsoon Experiment) and TiMREX (Terrain-influenced Monsoon Rainfall Experiment) are companion research projects organized by scientists from Taiwan and the United States, respectively, to conduct a field experiment to study monsoon rainfall around Taiwan and the northern South China Sea. The experiment is aimed at studying the monsoon rainfall during the May-June Meiyu season. This season is a climate regime characterized by frequent mesoscale convective systems (MCSs) that occur along a quasi-stationary frontal zone (Meiyu front) extending from Japan to south China, and coincides with a relative maximum in the seasonal precipitation distribution (Chen and Tsay 1978; Chen and Chang 1980). The long, narrow cloud band associated with the front first appears in southeastern

The Global Monsoon System: Research and Forecast (2nd Edition)
edited by Chih-Pei Chang et al.

China and Taiwan during May, then migrates northward to the Yangtze River region and Japan in June and July (known as Baiu in Japan), and then further northward to northern China and Korea (known as Changma in Korea) during July and August. In May and June MCSs move from west to east ahead of the front and interact with the steep topography in Taiwan, capable of producing extremely heavy precipitation (Kuo and Chen 1990).

It is known that large discrepancies between observed and model simulated precipitation characteristics are common in regions involving topography (e.g., Garvert *et al.* 2005a). Inadequate model initial conditions (upstream of the terrain), poorly understood microphysics and complicated topography have been suggested as the main sources for the lack of skills in predicting heavy orographic precipitation, and motivated many field experiments: TAMEX (Kuo and Chen 1990), COAST, CALJET, PACJET, MAP, IMPROVE I and II, and NAME (e.g., Garvert *et al.* 2005b; Rotunno and Houze 2005; Richard *et al.* 1987). Recent work in Taiwan indicated that some mesoscale numerical models, such as the Weather Research and Forecasting (WRF, Skamarock *et al.* 2005) model, showed similar discrepancies and were sensitive to the uncertainties in the model initial conditions, upstream of orographic precipitation (Chien and Jou 2004). SoWMEX/TiMREX is an outgrowth of TAMEX aimed at improving our basic understanding of prediction of terrain-influenced precipitation in a warm, moist, unstable, subtropical monsoon environment.

The multi-scale design of SoWMEX/TiMREX allows modeling and observational studies of the heavy precipitation systems and their embedded environments. The southwesterly low level jet (LLJ) associated with the Meiyu front is a component of the summer Asia monsoon circulation that transports moisture and unstable air from the tropics into the frontal zone. SoWMEX/TiMREX was conducted during the period of 15 May to 30 June 2008 in the northern South China Sea, western coastal plain and mountain slope regions of southern Taiwan. The goals of SoWMEX/TiMREX are (1) to improve the understanding of the physical processes associated with the terrain-influenced heavy precipitation systems and the monsoonal environment in which they are embedded through intensive observations, data assimilation, and numerical modeling studies, and (2) to improve the capability and accuracy of 0-36 h quantitative precipitation estimation and forecasting (QPE/QPF) on county, city and watershed scales during southwest monsoon season to meet the urgent need of disaster reduction in the Taiwan area.

2. Scientific Objectives

The five major scientific objectives of SoWMEX/TiMREX are:

(1) The effects of orography and the characteristics of upstream monsoonal flow on rainfall distributions in southern Taiwan.

Recent WRF simulations have shown sensitivity of the precipitation patterns in the southern Taiwan area to perturbed sub-synoptic moisture and temperature fields in the upstream conditions, consistent with idealized simulations (e.g., Colle *et al.* 2005). Based on TAMEX data, Chen *et al.* (1991) and Akaeda *et al.* (1995) hypothesized that the movement of pre-existing squall lines over the orography of Taiwan is controlled by the Froude number of the basic flow. For a non-rotating, conditionally unstable flow over a mesoscale mountain ridge, convective systems may propagate upstream, stay quasi-stationary or propagate downstream of the mountain (Chu and Lin 2000; Chen and Lin 2005). These propagation characteristics can then determine the precipitation distributions and amounts. In addition, the development of embedded convection and associated precipitation may strongly depend on small-amplitude upstream perturbations (Fuhrer and Schär 2005). These theories need to be further evaluated. SoWMEX/TiMREX will provide upstream conditions for determining the non-dimensional control parameters for different flow regimes, which, in turn, will help predict the rainfall distribution. Aircraft dropsonde observations upstream of Taiwan and rawinsonde observations from a Navy vessel southwest of the island are key observations in this work. Also, the GPS radio occultation (RO) soundings from FOMOSAT-III (Braun *et al.* 2003) will assist in the description of the thermodynamic characteristics of the upstream monsoon flow.

(2) The roles of Meiyu front and its mesoscale circulations in the development, maintenance and regeneration of heavy rain producing convection systems in southern Taiwan.

In the 1987 TAMEX (Kuo and Chen 1990), dual-Doppler radar analysis in northern Taiwan examined the structures of MCSs associated with Meiyu front (Trier *et al.* 1990; Ray *et al.* 1991; Jou and Deng 1992, 1998). Less known are the mesoscale kinematic and thermodynamic characteristics of the Meiyu front and the associated low-level jet (LLJ) in southern Taiwan and the adjacent oceans, and the effects of the Central Mountain Range (CMR) on Meiyu front/LLJ and heavy precipitation (Chen *et al.* 2006; Wang *et al.* 2005). SoWMEX/TiMREX collects a comprehensive dataset to examine the mesoscale characteristics of the barrier jet, island-induced flow, LLJ and Meiyu front, and their role on the formation and maintenance of MCSs in southern Taiwan. The dataset will be used to determine triggering mechanisms and key control parameters for producing heavy rainfall in southern Taiwan during the passage of Meiyu fronts. Doppler radars, surface stations, rawinsondes, ground-GPS and FOMOSAT-III/COSMIC soundings (Anthes *et al.* 2008), wind profiler, and dropsonde observations will be the key observations in this work.

(3) The effect of boundary layer processes, such as, surface moisture distributions, land-sea contrasts and mountain-valley circulations on modulation of the precipitation pattern.

The atmospheric boundary layer plays a crucial role in the initiation and evolution of convection. Circulations in the boundary layer such as sea/land breezes and thunderstorm outflows often form convergence zones (Johnson and Bresch 1991; Jou 1994; Yu and Jou 2005).

With the dense surface and advanced radar capability in SoWMEX/TiMREX, we are able to investigate the role of these convergence lines in triggering MCSs in the vicinity of the Meiyu front. These results can then be compared to regions without topographical forcing, such as Florida. The boundary-layer convergence lines over land will be characterized by the NCAR SPOL (Weckwerth and Parsons 2006). High-resolution water vapor fields will be obtained from GPS integrated water vapor sensors and radar refractivity measurements from SPOL (Fabry *et al.* 1997; Weckwerth *et al.* 2005).

(4) The microphysical processes of heavy rain producing convective systems influenced by complex terrain.

In TAMEX, there were only limited in-situ observations and no polarimetric radars, which precluded any studies designed to diagnose the microphysical processes involved in heavy rainfall formation. We seek to advance our understanding of the microphysical processes in heavy rain events during SoWMEX/TiMREX by retrieving ensemble microphysical properties using the polarimetric capabilities of the SPOL and TEAM-R (Taiwan's mobile X-band, polarimetric Doppler radar) radars (e.g., Bringi *et al.* 1986; Seliga *et al.* 1986; Vivekanandan *et al.* 1999). Our approach to microphysical studies will consider a water budget perspective. We are particularly interested in determining the relative contributions of ice and warm rain processes to heavy convective rainfall. Low-level warm rain coalescence is considered to be particularly important in enhancing rainfall, and we seek to quantify this in SoWMEX/TiMREX. Our microphysical studies will be developed within a dynamical framework (afforded by dual-Doppler observations), as couplings between dynamics and microphysics in orographic precipitation. A framework for this analysis can be found in papers recently published by Medina *et al.* (2005) and Houze and Medina (2005). Using polarimetric radars combined with dual-Doppler observations, water and ice mass fluxes can be estimated, allowing mass flux changes as a function of cloud depth to be estimated (e.g., Yuter and Houze 1995). The X-band rain profiler and Ka-band rain radar will provide highly resolved reflectivity profiles at the super-site on the windward slopes of the CMR, yielding important information on vertical structures and evolution of these precipitation systems.

(5) Improving QPE/QPF skill by better understanding of multi-scale precipitation processes and the assimilation of high-resolution observations into numerical models and nowcasting systems.

Warm season QPF remains a challenging problem and one of the three high priority goals in USWRP (Fritsch and Carbone 2004; Lang *et al.* 2004). The low skill score and lack of progress for warm season QPF can, to a large degree, be attributed to the inadequate representation of microphysical processes and the lack of knowledge of the cloud and mesoscale structures of the environment in numerical models (Yang *et al.* 2004; Chien and Jou 2004). Fritsch and Carbone (2004) suggested that better understanding of physical and microphysical processes in the precipitation systems, improved observations from remote sensing and in-situ instruments, and data assimilation as the key R&D areas to advance the skill of warm season QPF. SoWMEX/TiMREX provides a unique opportunity to evaluate the aforementioned R&D strategy and validates the performance of 0-36 hour QPF by nowcasting systems and numerical models.

3. Experiment Design

The Taiwan Central Weather Bureau (CWB) operates one of the highest density meteorological observing networks in the world. The network includes surface stations, automatic rain gauges, upper air soundings, ground-GPS stations, and around-the-island

Doppler radars. These operational observations are available through Internet and other communication systems to support high-quality data for daily operations and also for the field program. Starting in 2006, CWB launched a new observational platform, using a small jet (Astra) to release dropsondes from the upper troposphere to observe the deep-layer atmospheric properties. For SoWMEX/TiMREX field observation, in addition to these operational platforms, there are several new instrumentations provided by the United States and other countries to join the effort. The primary U.S. observational facility deployed are the NCAR S-band polarimetric radar (SPOL) which is used to diagnose precipitation processes, provide polarimetric-based rain estimates, and is operated as part of the dual-Doppler radar network. Other facilities include an X-band mobile polarimetric radar newly built by Taiwan, an X-band portable Doppler radar from Nagoya University, Japan, an X-band rain profiler from Kyongpook National University, South Korea, and five C-band radar-based disdrometers (precipitation occurrence sensing systems, POSS) from Environment Canada. These radar systems comprise an area within which the microphysical structure of rain systems and their adjacent mesoscale environment can be well sampled for diagnosis and prediction verification purposes. Figures 1 and 2 show respectively the sounding network and the deployment of radar systems of SoWMEX/TiMREX.

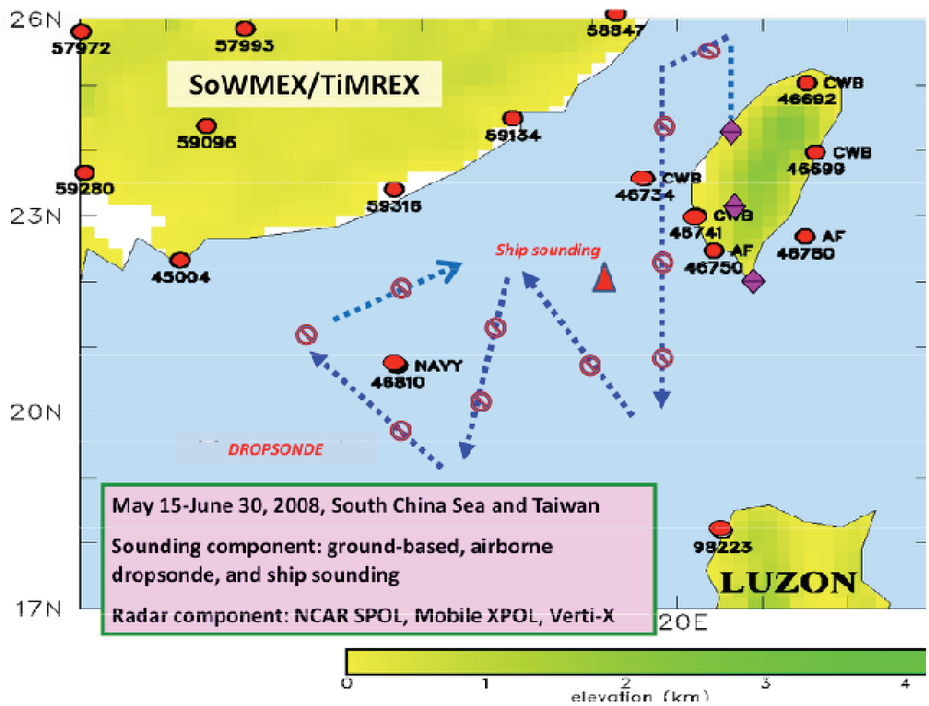


Figure 1. Upper air sounding network of SoWMEX/TiMREX, includes regular operational ground-based stations (red circles), three additional upper air sounding stations (purple diamonds), the airborne dropsonde (schematic aircraft route indicated by dashed blue line with open circles), and the shipboard sounding (red triangle) off the SW coast of Taiwan.

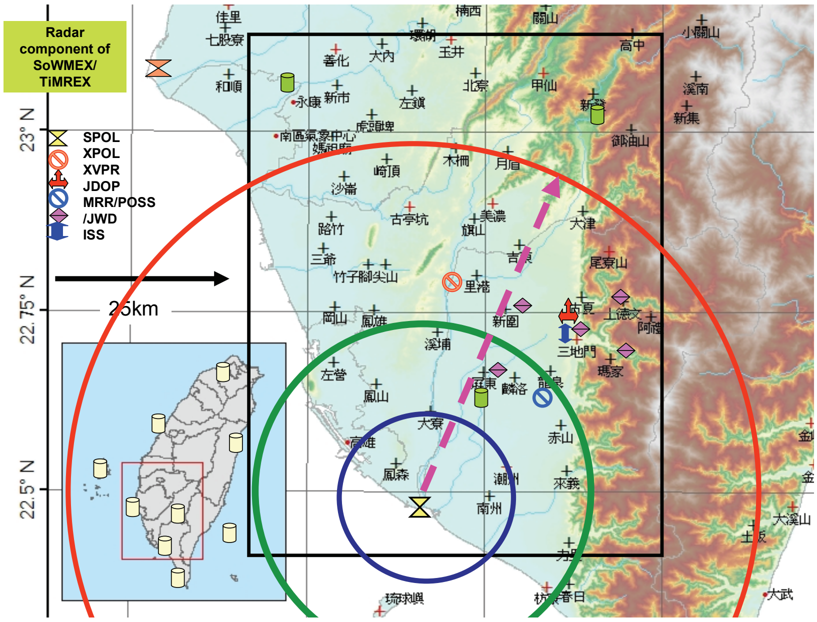


Figure 2. Rain measurement supersite (at the mountain slope of Pingtong County, includes vertically pointing rain profiler and precipitation sensing instrumentations) and radar network of SoWMEX/TiMREX.

The upstream and downstream synoptic conditions during SoWMEX/TiMREX will be sampled by concurrent field experiments proposed in East Asia, including Asian Monsoon Year (2008), TIBET experiment over the Tibetan Plateau, the South China Heavy Rain Experiment (SCHeREX), and Korea-Japan Joint intensive observation program (PHONE-08). The combined observations from these field experiments will provide a comprehensive mapping of the synoptic and mesoscale characteristics of the Asian summer monsoon.

4. Field Operations

4.1. Sounding Operation

There are three different types of upper-air sounding operations in SoWMEX/TiMREX: dropsonde, ship-borne sounding, and ground-based sounding. During the field operation period, there are 10 ground-based sounding stations and two ship-borne soundings, one southwest and the other north of the Taiwan Strait. In order to increase the spatial and temporal resolution of the mesoscale environment sampling, 14 dropsonde missions have been conducted over the northern portion of the South China Sea.

The operation of sounding network has been conducted according to several pre-designed strategies. During the special observing period (SOP), there are 4 sondes per day for all the sounding stations. Whenever, there is a frontal system approaching, the intensive observing period (IOP) is called. During IOPs, there are 8 sondes per day for ground-based sounding stations near Pingtong and in general this mode of operation is no more than 2 days. At the same time, the Astra aircraft carries out flight mission for dropsondes. Each mission usually takes about 3 hours with 12-15 dropsondes. A special arrangement is designed to have 7 continuous IOP days during the enhanced observing period (EOP). The purpose of this strategy is to avoid the possible misforecasting of the heavy rain events during the observing period.

Since four different types of sounding systems (Japan-Meisei, German-Graw, Väisälä GPS, and Vaisala tracking) are used in the field operation, an inter-comparison campaign was executed at Banciao station before the start of the operation. Several similar comparison studies are conducted for data quality purpose at both Pingtong and Dongsha stations during the field operation period.

4.2. Radar Operation

There are two types of radar operation in SoWMEX/TiMREX, the kinematic wind field retrieval mode and the microphysical retrieval mode. The wind retrieval mode is basically a dual-Doppler radar scanning strategy and the cloud physics mode is polarimetric radar scanning strategy. In the dual-Doppler mode of operation, plan-position-indicator (PPI) type scan is the major operation mode. This operation includes SPOL, Chigu, TEAM-R, and Japan radar. In the storm microphysics mode of operation, range-height-indicator (RHI) type scan is the major operation mode. This operation includes SPOL and TEAM-R. An inter-comparison test has been conducted between SPOL and TEAM-R for attenuation purpose. In addition to above radar operation, a super-site for rain measurement has been setup. Super-site instrumentations include an X-band vertical-pointing Doppler radar, a 940-MHz wind profiler, 5 Ka-band vertical pointing rain radars, 5 POSSs and 5 JW collision-type disdrometers. For the purpose of instrumentation comparison, an inter-comparison campaign among the rain measurement instrumentations has been held at National Taiwan University campus in Taipei before the field operation.

4.3. Operation Control Center and Daily Operation

The TiMREX Science Team is responsible to make critical project decisions. Scientific planning and coordination is carried out by the Scientific Planning Group (SPG). The SPG is responsible for the design, operation, and management of SoWMEX/TiMREX. The Data Management Group (DMG) is organized to oversee the collection, archival and access to all project data. The DMG reports to the SPG on a regular basis. The SoWMEX/TiMREX project has also requested NCAR EOL to provide advice and assistance in operations and data management activities during the project.

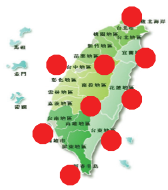
The SPG consists of principal investigators and is responsible for the overall planning, scientific objectives, and coordination of the SoWMEX/TiMREX program prior to the field experiment, including preparation of a SoWMEX/TiMREX Field Program Operations Plan. During the field phase, a Mission Selection Team (MST) is also responsible for the daily operation of SoWMEX/TiMREX and assessing how well the experimental objectives are being met. The primary field operation center is located at CWB headquarters in Taipei. A daily planning meeting was held to prepare a daily operations summary. The radar coordinator was responsible for (1) coordinating the scanning strategy among S-POL, X-DOP, RCCG, RCKT, and the TEAM radar, (2) deploying and adjusting the position of the TEAM radar, and

(3) operating the X-band and Ku-band vertical pointing radars. A sounding coordinator was to provide guidance on the set-up of dropsonde flight patterns and the deployment of transportable, regular and shipboard soundings. The Operation Center has access to all synoptic, satellite, and rain gage data as well as numerical weather prediction output and operational radar data via existing CWB facilities. Arrangements were made to transmit SPOL radar images, refractivity, and particle ID, and rainfall products to the Operation Center via high-speed data communications link. A real-time scientific display system was developed by CWB to allow the display and compositing of SPOL data along with selected regional CWB Doppler radars. Overlays of satellite imagery and potential model output are included as an aid to operations coordination of ground based mobile facilities and soundings. A SoWMEX/TiMREX Field Catalog (http://sowmex.cwb.gov.tw) was implemented to assure the full documentation of project operations and to provide a central Internet access point for all local and foreign participants to view data products, imagery and project operation plans.

5. Preliminary Scientific Results

The rainfall statistics for 2008 Taiwan Meiyu season show that in June south Taiwan had more rainfall than the climate mean (mean of 1970-2000) and the plain stations had more rainfall than stations over the high mountains (Fig. 3). In the following, some preliminary analyses from the field observations are presented.

Rainfall statistics for Meiyu season of 2008



Station and Rainfall (mm)	**Tai-pei (N)**	**Tai-chung (C)**	**Kao-hsiung (S)**	**Heng-chuun (P)**	**A-li-shan**	**Sun-Moon Lake**	**I-Lan (E-N)**	**Hwa-lien (E-C)**	**Tai-tung (E-S)**
May (mean)	258	225	177	164	531	354	264	195	157
May (08)	**319**	**332**	107	32	378	**409**	132	72	55
June (mean)	319	343	398	371	711	483	252	220	248
June (08)	361	183	**1200**	**653**	496	440	173	170	**327**

(2008) In May, north Taiwan has more rainfall than climate (1971-2000). In June, south Taiwan has much more rainfall than climate. The mountain rainfall is much less than the climate mean (A-Li-Shan)

Figure 3. Rainfall statistics in the Taiwan area for 2008 Meiyu season. The stations are selected according to their geographic locations, from north to south and from west coast, mountain, to east coast, respectively (see the red spots on the top right maps). Kaohsiung (southwest coast station) has a record breaking rainfall (triple the amount of the climate mean).

(a) The mesoscale convective vortex (MCV) embedded within the Meiyu front is an important mesoscale feature related to heavy rain. During IOP6 (June 5, 2008), a mesoscale convective vortex system was observed by dropsonde and radar network south of the Taiwan Strait (Fig.4). The precipitation area propagated with the MCV leading edge toward the southwest coast of Taiwan and brought heavy rainfall to Kaohsiung area. The center of the MCV seemed to tilt toward northwest with height and has a warm-core structure. The circulation of the vortex interacted with topography and produced interesting mesoscale phenomena. For example, observations showed a splitting of the low level cyclone into two, one moving northward and dissipating over the west coast of Taiwan and the other making a circle around the southern tip of the island and leading to lee cyclone formation. A tropical depression later developed over ocean areas northeast of Taiwan and its relationship with the lee cyclone formed earlier was not clear. According to Lee *et al.* (2005), concentrated low level vorticity centers embedded within the Meiyu front have been observed. These centers are closely related to the formation of mesolows and sometimes even develop into tropical cyclones. Lee *et al.* (2005) studied the environmental differences between the formation and non-formation cases and found that in the nonformation cases, both the northeasterlies north of the front and the monsoonal southwesterlies are intermittent and weaker so that the systems do not spin up to tropical depression intensity.

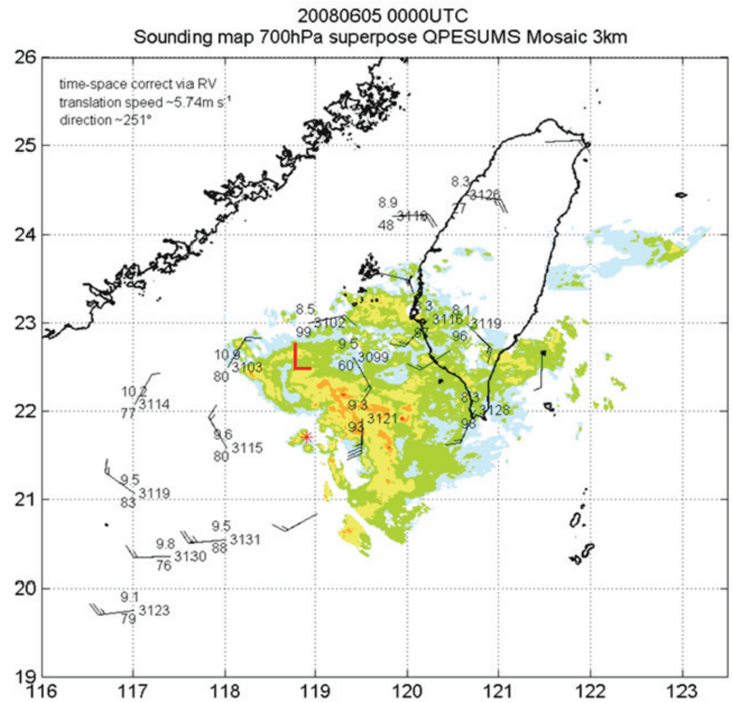
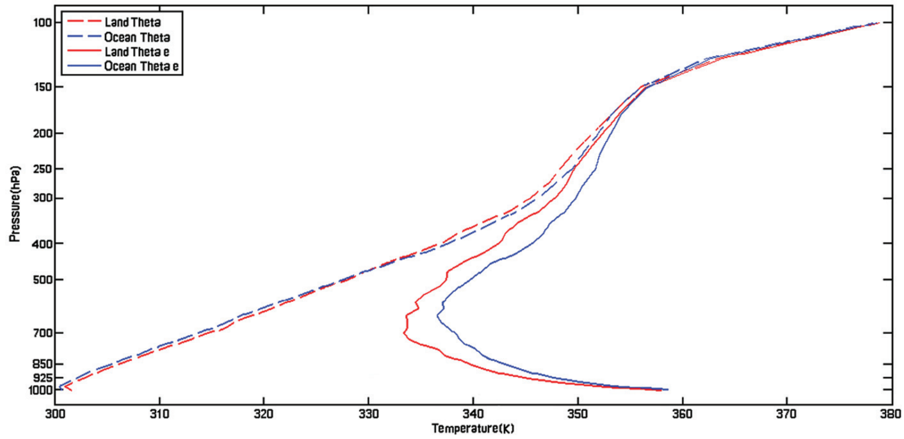


Figure 4. 700-hPa winds, temperature, and geopotential height of an approaching mesoscale convective vortex (MCV) embedded within a Meiyu front derived from dropsonde data collected during IOP6 of SoWMEX/TiMREX. The color shading is 3 km reflectivity field observed by Chigu radar on 0000 UTC June 5, 2008 (blue 10 dBz, green 20 dBZ, yellow 30 dBZ, orange 40 dBZ, and red is 50 dBZ, respectively).

(a)



(b)

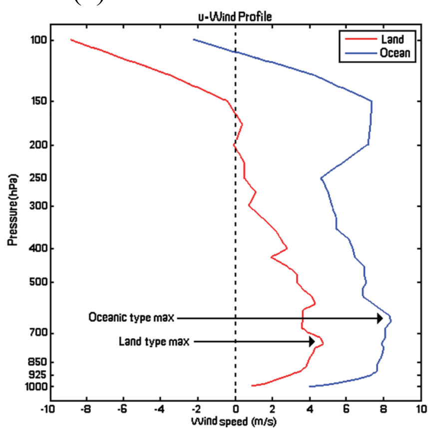


Figure 5. Environment characteristics of the significant continuous rainfall periods (SCRPs) during SoWMEX/TiMREX. (a) Potential temperature and equivalent potential temperature of land- (in red) and ocean- (in blue) type; (b) the zonal component of horizontal wind of land- and ocean-type SCRPs derived from south ship sounding.

(b) Precipitation distribution in the Taiwan area is strongly modulated by topography. During IOPs, significant continuous rainfall periods (SCRPs) are identified using Chigu Doppler radar reflectivity data and three major types of SCRPs are distinguished, i.e., land-type (originated over land), ocean-type (originated over the ocean and propagated over land), and the mixed-type (originated over ocean and new convection developed over land at the same time). During the SOP, there are 40 SCRPs with 18 land type and 17 ocean type and the other 5 mixed type. The mixed type SCRPs usually lasted longer. The thermodynamic and kinematic environment differences of land and ocean type SCRPS can be examined by compositing the ship (250 km away from the island) sounding data according to the occurrence of SCRPs (Fig. 5). The results show that the land-type SCRPs are more unstable than the ocean type with the 700 hPa minimum θe 2-3 K colder. However, the east-west component of the horizontal wind profiles shows that the ocean type has a strong low-level wind maximum signature with wind speeds much larger than the land type. This kinematic structure difference suggests that the low-level wind maximum, possibly associated with low-level jet is an important circulation feature related to the heavy rain associated with precipitation systems moving from the ocean to land.

(c) One of the major functions of the NCAR SPOL is to identify hydrometeors within the storm systems. This is done operationally by applying a particle identification algorithm to study the microphysical characteristics of heavy rain events and afternoon air mass thunderstorm cases during the intensive period. Figure 6 shows an example of hydrometeors identified in a thunderstorm case by SPOL. In the plot, different hydrometeors (for example, ice, wet and dry snow, graupel, hail, light rain, heavy rain, and drizzle particles) are identified by using environmental sounding data and SPOL observed parameters, i.e., differential reflectivity and differential phase function. The storm was developing over Pingtong area and brought showers over the local region. This system was the only convective system that developed into a thunderstorm on that day. Large raindrops and strong gusty winds were reported. The RHI plot indicated that there were large graupel particles falling through the storm and melting. At 2-3 km altitude, the data indicate a possibility of hail particles before melting out completely. These polarimetric radar parameters are important quantities to identify with regard to the likely hydrometeor particles within a storm and are valuable for quantitative precipitation estimation and forecasting which have not been possible before.

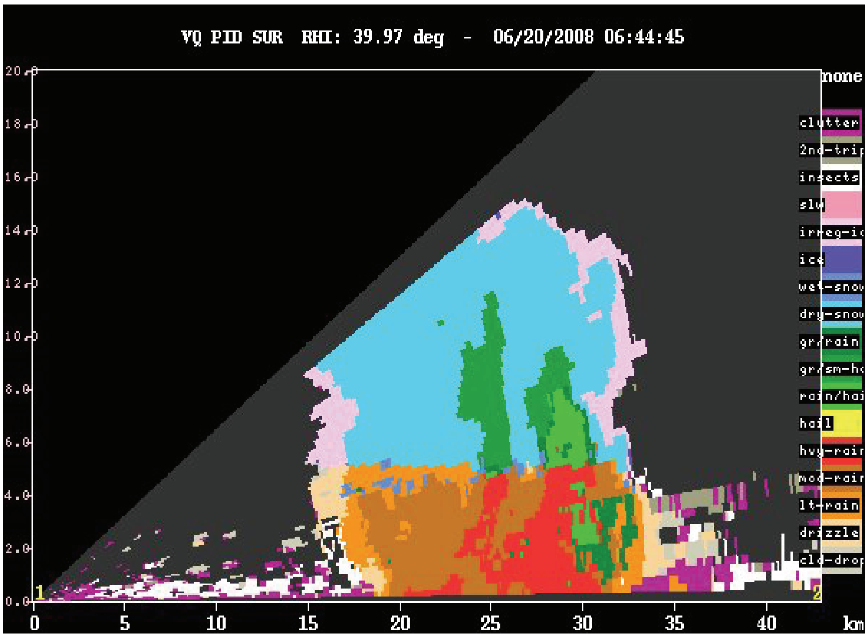


Figure 6. Hydrometeor identified in a thunderstorm system by SPOL during SoWMEX/TiMREX. The different color shading areas represent different hydrometeors within the storm. On the right, the color table indicates the hydrometeor types, from top to bottom, clutter, second-trip echo, insects, supercooled liquid water droplet, irregular ice crystal, ice crystal, wet snow, dry snow, graupel/rain, graupel/small hail, rain/hail, hail, heavy rain, moderate rain, light rain, drizzle, and cloud drops.

Table 1. SoWMEX/TiMREX SOP/IOP/EOP operation summary

IOP#	Date	Science Objectives	Dropsonde Mission	Comments
1	06Z May 19 to 00Z May 22	Frontal circulation Upstream environment for orographic convection Model verification and data assimilation	#1 at 21Z May 20, C, 3:20/12-4	SOP started on 00Z May 19
	22-26 May	Non-IOP afternoon thunderstorm and microphysics study		Radar operation continued
2	06Z May 27 to 21Z May 29	Southwesterly flow interacting with the terrain Upstream condition for mountain convection Lee side vortex/shear zone	#2 at 21Z May 28, D, 2:35/13-6	Heavy rain occurred over northern Taiwan
3	21Z May 29 to 12Z May 31	Island effects on SW (LLJ) and the Meiyu front Upstream condition for heavy precipitation	#3 at 21Z May 29, Cn, 2:43/ 15-10 #4 at 21Z May 30, Cn, 2:55/ 13-0	EOP starts on 21Z May 29 Local thunderstorm brought heavy rain to super-site.
4	21Z June 1 to 15Z June 3	Mesoscale convective systems Shallow surface front Mesoscale convective vortex	#5 at 09Z June 3, Cn, 2:29/13-0	Astra nose radar malfunction, flight was delayed.
5	18Z June 3 to 12Z June 4	Mesoscale convective systems Quasi-stationary front Mesoscale convective vortex	#6, 21Z June 3, C, 3:47/14-2 #7, 05Z June 4, E, 2:08/12-0	Torrential heavy rain occurred over central Taiwan
6	18Z June 4 to 12Z June 6	Mesoscale convective systems Quasi-stationary front Mesoscale convective vortex	#8, 21Z June 4, C, 3:25/15-1 #9, 05Z June 5, E, 2:23/10-0 #10, 21Z June 5, D, 2:35/12-1	MCV landed and brought torrential heavy rainfall to Kaohsiung. EOP ended at 18Z June 6 and SOP resumed.
	June 7-11	Non-IOP afternoon thunderstorm and microphysics study		Radar operation continued
7	00Z June 12 to 12Z June 13	Convection initiation over weak surface front, orographic convection, heavy rain over Hwalien	UAV #1, 04Z and 06Z June 12	Astra engine oil leakage and grounded for a few days
8	00Z June 14 to 12Z June 17	Southwesterly flow interacting with the terrain, upstream condition for mountain convection, low level jet, squall line from China coast, and MCV	#11, 09Z June 16, E, 2:15/10-1 #12, 21Z June 16, E, 2:25/12-0 #13, 04Z June 17, E, 2:29/14-1	Astra resumed Torrential heavy rain occurred over Kaohsiung on June 16
	June 18-22	Non-IOP afternoon thunderstorm and microphysics study		Radar operation continued
9	06Z June 23 to 12Z 26 June	Fengseng track uncertainty, Fengshen-induced southwesterly flow and related heavy rain systems	DOTSTAR flight on June 23, 2:30 #14 at 09Z June 25, E, 2:30/ 15	SOP ends on 12Z June 26 DOTSTAR on 08-10Z June 23 for typhoon track observations

6. Concluding Remarks

The actual SOP operation phase of SoWMEX/TiMREX was from May 19 to June 26, 2008, including 9 IOPs with a total of 24 IOP days within which a continuous 9-day EOP lasted from May 29 to June 6. The observations include 14 aircraft missions with 38 hours flight time and 167 dropsondes released and more than 2,000 upper air soundings launched over ground and shipboard. Major scientific objectives accomplished include: observations of the Meiyu front circulation over southern Taiwan, the MCSs related to heavy rains and mesoscale convective vortices (MCVs), the multi-line cloud bands associated with southwesterly flows over the coastal region first time observed by SPOL and their relation with diurnal variation of precipitation, and the microstructure of mountain convection observed by the rain measurement supersite and polarimetric radar network.

Table 1 lists the dates, the science objectives, and the dropsonde mission conducted of each IOP. The first and second science workshops of SoWMEX/TiMREX data quality and preliminary scientific results were held in Taipei on November 2008 and October 2009, respectively. More complete analyses and modeling works will be discussed in the third meeting scheduled for November 2010 at Taipei.

SoWMEX/TiMREX is a multi-year field-observing program, so that in addition to the mechanism of heavy monsoon rainfall weather systems, it can also contribute to the study of interannual variability. The 2009 field observing period has been carried out from May 20 to June 16, 2009, during which a two-week (June 3-16) enhanced observing period with 4 soundings per day for selected sites was conducted. Dual-Doppler analysis was performed in real time using newly-established C-band polarimetric radar at Makung and the NEXRAD system at Chigu. We are hoping that with this design, heavy rain weather systems moving from ocean to land can be captured more thoroughly. The 2010 field observing period has also been carried out from May 27-June 15, 2010. More detailed information concerning the observational platform and data archive can be found on the website: http://sowmex.cwb.gov.tw/.

Acknowledgements

SoWMEX/TiMREX is a joint research project organized by scientists from Taiwan and the United States. The primary funding for the program in Taiwan was provided by the National Science Council and the Central Weather Bureau. In the United States, funding was provided by the National Science foundation and the National Center for Atmospheric Research.

The agencies/universities which participated in SoWMEX/TiMREX include the Central Weather Bureau, the Air Force Weather Wing, the Navy, the National Taiwan University, the National Central University, the Chinese Culture University, the National Defense University, the National Taiwan Normal University, the Civil Aeronautics Administration, the Water Resource Agency, the Water, Soil Conservation Bureau, and the National Science and Technology Center for Disaster Reduction, Colorado State University, Utah University, University of California at Los Angeles, University of Hawaii, and the National Center for

Atmospheric Research.

In addition to the agencies/universities from Taiwan and the United States, there are scientists from other countries also participated the field observing program with their own instrumentations, e.g. the POSS (Precipitation Occurrence Sensing System) from Canada Environment, the vertical pointing X-band rain profiler (Verti-X) from Korea Pukyong National University, and X-band Doppler radar (X-Dop) from Japan Nagoya University.

It will be difficult to credit all the scientists and the administrative and support staff within the various agencies and universities who supported this effort. We express our sincere appreciation to every SoWMEX/TiMREX participants for making this program a success.

References

Akaeda, K., J. Reisner, and D. Parsons, 1995: The role of mesoscale and topographically induced circulations in initiating a flash flood observed during the TAMEX project. *Mon. Wea. Rev.*, **123**, 1720-1739.

Anthes, R. A. and coauthors, 2008: The COSMIC/FORMOSAT-3 mission: Early results. *Bull. Amer. Meteor. Soc.*, **89**, 313-333.

Braun, J., C. Rocken, and J. Liljegren, 2003: Comparisons of line-of-sight water vapor observations using the Global Positioning System and a pointing microwave radiometer. *J. Atmos. Oceanic Tech.*, **20**, 606-612.

Bringi, V. N., R. M. Rasmussen, and J. Vivekanandan, 1986: Multiparameter radar measurements in Colorado convective storms. Part I: Graupel melting studies. *J. Atmos. Sci.*, **43**, 2545-2563.

Chen, C. S., W. S. Chen, and Z. Deng, 1991: A study of a mountain-generated precipitation system in northern Taiwan during TAMEX IOP 8. *Mon. Wea. Rev.*, **119**, 2574-2606.

Chen, G. T.-J. and C.-Y. Tsay, 1978: A synoptic case study of Mei-Yu near Taiwan. *Pap. Meteor. Res.*, **1**, 25-36.

Chen, G. T.-J. and C.-P. Chang, 1980: The structure and vorticity budget of an early summer monsoon trough (Mei-Yu) over southwestern China and Japan. *Mon. Wea. Rev.*, **108**, 942-953.

Chen, G. T.-J., C.-C. Wang, and L.-F. Lin, 2006: A diagnostic study of a retreating Mei-Yu front and the accompanying low-level jet formation and intensification. *Mon. Wea. Rev.*, **134**, 874-896.

Chen, S. H. and Y. L. Lin, 2005: Effects of moist Froude number and CAPE on a conditionally unstable flow over a mesoscale mountain ridge. *J. Atmos. Sci*., **62**, 331-350.

Chien, F. C. and B. J.-D. Jou, 2004：MM5 ensemble precipitation forecasts in the Taiwan area for three Mei-yu seasons. *Wea. Forecast.*, **19**, 735-750.

Chu, C. M. and Y. L. Lin, 2000: Effects of orography on the generation and propagation of MCSs in two-dimensional conditionally unstable flow. *J. Atmos. Sci.*, **23**, 3817-3837.

Colle, B. A., M. F. Garvert, J. B. Wolfe, C. F. Mass, and C. P. Woods, 2005: The 13-14 December 2001 IMPROVE-2 event. Part III: Simulated microphysical budgets and sensitivity studies. *J. Atmos. Sci.*, **62**, 3535-3558.

Fabry, F., C. Frush, I. Zawadzki, and A. Kilambi, 1997: On the extraction of near-surface index of refraction using radar phase measurements from ground targets. *J. Atmos. Ocean. Tech.*, **14**, 978-987.

Fristch, J. M. and R. E. Carbone, 2004: Improving quantitative precipitation forecasts in the warm season: A USWRP research and development strategy. *Bull. Amer. Meteor. Soc.*, **85**, 955-965.

Fuhrer, O. and C. Schär, 2005: Embedded cellular convection in moist flow past topography. *J. Atmos. Sci.*, **62**, 2810-2828.

Garvert, M. F., B. A. Colle, and C. F. Mass, 2005a: The 13-14 December 2001 IMPROVE-2 event. Part I: Synoptic and mesoscale evolution and comparison with a mesoscale model simulation. *J. Atmos. Sci.*, **62**, 3474-3492.

Garvert, M. F., C. P. Woods, B. A. Colle, C. F. Mass, P. V. Hobbs, M. T. Stoelinga, and J. B. Wolfe, 2005b: The 13-14 December 2001 IMPROVE-2 event. Part II: Comparisons of MM5 model simulations of clouds and precipitation with observations. *J. Atmos. Sci.*, **62**, 3520-3534.

Houze, R. A. Jr. and S. Medina, 2005: Turbulence as a mechanism for orographic precipitation enhancement. *J. Atmos. Sci.*, **62**, 3599-3623.

Johnson, R. H. and J. F. Bresch, 1991: Diagnosed characteristics of precipitation systems over Taiwan during the May-June 1987 TAMEX. *Mon. Wea. Rev.*, **119**, 2540-2557.

Jou, B. J.-D. and S. M. Deng, 1992: Structure of a low-level jet and its role in triggering and organizing the moist convection over Taiwan. *TAO*, **3**, 39-58.

Jou, B. J.-D., 1994: Mountain-originated mesoscale precipitation systems in northern Taiwan: A case study 21 June 1991. *TAO*, **5**, 169-197.

Jou, B. J.-D. and S. M. Deng, 1998: The organization of convection in a Meiyu frontal rainband, *TAO*, **9**, 553-572.

Kuo, Y.-H. and G. T.-J. Chen, 1990: The Taiwan Area Mesoscale Experiment (TAMEX): An overview. *Bull. Amer. Meteor. Soc.*, **71**, 488-503.

Lang, T. J., L. J. Miller, M. Weisman, S. A. Rutledge, L. J. Barker III, V. N. Bringi, V. Chandrasekar, A. Detwiler, N. Doesken, J. Helsdon, C. Knight, P. Krehbiel, W. A. Lyons, D. Macgorman, E. Rasmussen, W. Rison, W. D. Rust, R. J. Thomas, 2004: The severe thunderstorm electrification and precipitation study. *Bull. Amer. Meteor. Soc.*, **85**, 1107-1125.

Lee, C. S., Y.-L. Lin, and K. K. W. Cheung, 2005: Tropical cyclone formations in the South China Sea associated with the Mei-Yu front. *Mon. Wea. Rev.*, **134**, 2670-2687.

Medina, S., B. F. Smull, R. A. Houze Jr., and M. Steiner, 2005: Cross-barrier flow during orographic precipitation events: Results from MAP and IMPROVE. *J. Atmos. Sci.*, **62**, 3580-3598.

Ray, P., A. Robinson, and Y. Lin, 1991: Radar analysis of a TAMEX frontal system. *Mon. Wea. Rev.*, **119**, 2519-2539.

Richard, E., N. Chaumerliac, J. F. Mahfouf, and E. C. Nickerson, 1987: Numerical simulation of orographic enhancement of rain with a mesoscale model. *J. Appl. Meteorol.*, **26**, 661-669.

Rotunno, R. and R. A. Houze Jr., 2005: Lessons on orographic precipitation from the Mesoscale Alpine Programme. *Quart. J. Roy. Meteor. Soc.*, **133**, 811-84539.

Seliga, T. A., K. Aydin, and H. Direskeneli, 1986: Disdrometer measurements during an intense rainfall event in central Illinois: Implications for differential reflectivity radar observations. *J. Appl. Meteorol.*, **25**, 835-846.

Skamarock, W. C. and Coauthors, 2005: *A Description of the Advanced Research WRF. Version 2.* (http://www.wrfmodel.org/wrfadmin/publications.php)

Trier, S., D. Parsons, and T. Matejka, 1990: Observations of a subtropical cold front in a region of complex terrain. *Mon. Wea. Rev.*, **118**, 2449-2470.

Vivekanandan, J., S. M. Ellis, R. Oye, D. S. Zrnic, A. V. Ryzhkov, and J. Straka, 1999: Cloud microphysics retrieval using S-band dual-polarization radar measurements. *Bull. Amer. Meteor. Soc.*, **80**, 381-388.

Wang, C.-C., G. T.-J. Chen, T.-C. Chen, and K. Tsuboki, 2005: A Numerical study on the effects of

Taiwan topography on a convective line during the Mei-Yu season. *Mon. Wea. Rev.*, **133**, 3217-3242.

Weckwerth, T. M. and D. B. Parsons, 2006: A review of convection initiation and motivation for IHOP_2002. *Mon. Wea. Rev.*, **134**, 5-22.

Weckwerth, T. M., C. R. Pettet, F. Fabry, S. J. Park, M. A. LeMone, and J. W. Wilson, 2005: Radar refractivity retrieval: Validation and application to short-term forecasting. *J. Appl. Meteorol.*, **44**, 285-300.

Yang, M.-J., B. J.-D. Jou, S.-C. Wang, J.-S. Hong, P.-L. Lin, J.-H. Teng, and H.-C. Lin, 2004: Ensemble prediction of rainfall during the 2000-2002 Mei-Yu seasons: Evaluation over the Taiwan area. *J. Geophys. Res*., **109**, D18203.

Yu, C.-K. and B. J.-D. Jou, 2005: Radar observations of diurnally forced offshore convective lines along the southeastern coast of Taiwan. *Mon. Wea. Rev.*, **133**, 1613-1636.

Yuter, S. E. and R. A. Houze Jr., 1995: Three-dimensional kinematic and microphysical evolution of Florida cumulonimbus. Part I: Spatial distribution of updrafts, downdrafts, and precipitation. *Mon. Wea. Rev.*, **123**, 1921-1940.