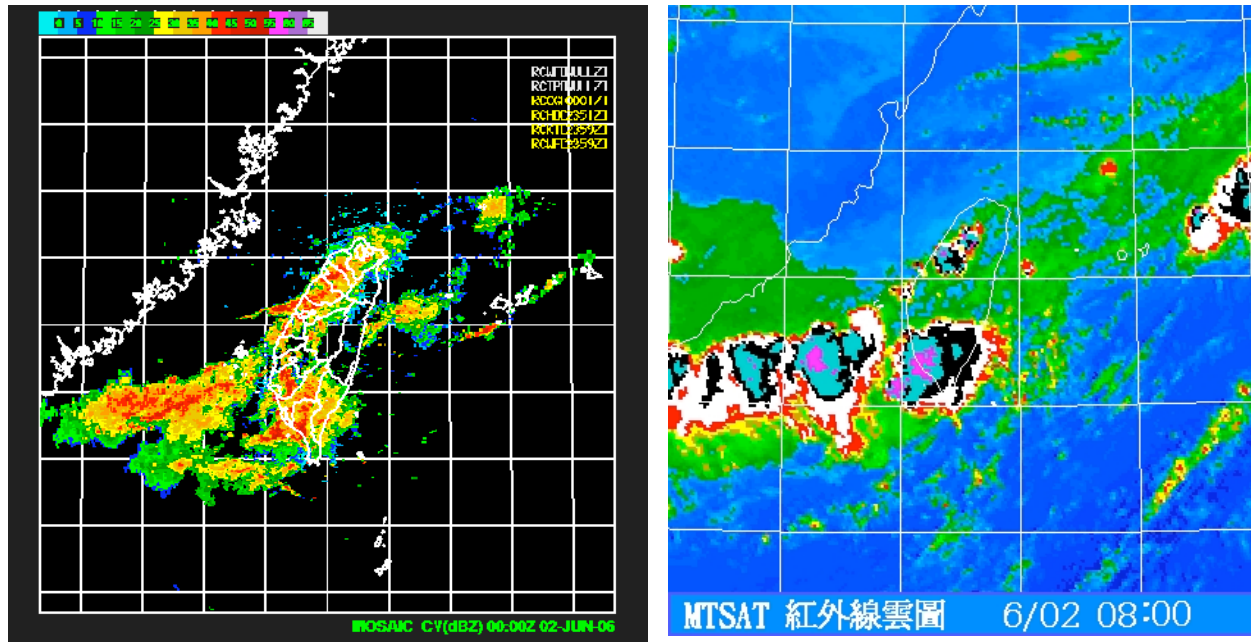


SCIENTIFIC OVERVIEW DOCUMENT

TiMREX

The Terrain-influenced Monsoon Rainfall Experiment



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1. Project Summary

The Terrain-influenced Monsoon Rainfall Experiment (TiMREX) is a joint U.S.-Taiwan multi-agency field program to be 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 goal of TiMREX is to improve understanding of the physical process 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.** TiMREX provides a unique opportunity to advance our basic understanding on the physical processes of heavy orographic precipitation in a warm, moist, and conditionally unstable atmosphere involving interactions among southwesterly monsoon [low-level jet (LLJ)], approaching front, land-sea and mountain-valley breezes and steep terrain (~3000 m). The multi-scale experiment design in TiMREX will sample not only the kinematic, thermodynamic and microphysical structures of these mesoscale convective systems (MCSs) but also their mesoscale environment and variability. The knowledge gained in TiMREX will form the basis to advance our ability to predict warm season, heavy precipitation events influenced by complex terrain.

Taiwan operates one of the highest density meteorological observing networks in the world. The NCAR S-Polka weather radar will be deployed in conjunction with a multitude of research facilities from U.S., Taiwan, and Japan to create a multi-scale, research quality network, permitting coordinated observations of the oncoming southwesterly monsoon and MCSs either propagating into or developing near Taiwan. TiMREX will focus its observational resources over southwestern Taiwan and the adjacent oceans to study orographic precipitation where heavy rainfall occurs most frequently during the Mei-Yu season. The routine observing facilities in Taiwan include dense networks of surface weather stations, rawinsondes, GPS ground receivers, wind profilers, and Doppler radars. These will be supplemented by shipboard and mobile soundings, dropsonde observations from a research aircraft, aerosondes, integrated sounding system (ISS), Ka-band rain profilers and a mobile radar. The primary proposed U.S. observational facilities to be deployed are the S-Polka polarimetric radar and two NOAA S-band rain profilers that will be used to diagnose precipitation processes, provide polarimetric-based rain estimates, and be operated as part of the dual-Doppler radar network. Assimilation of these high-resolution observations into analysis will certainly improve understanding of the physical process associate with the heavy precipitation systems, and ability of QPF for the high-impact events during the Mei-Yu season.

TiMREX is a cost-effective field program for the U.S. since Taiwan is already committed to support a mesoscale experiment during May-June 2008 in the vicinity of Taiwan. A considerable fraction of the costs of the experiment and other essential meteorological infrastructure will be provided by Taiwan. It is projected that roughly 85% of the field costs will be provided by non-U.S. funding, with the remaining 15% provided by the U.S., in the form of the S-Polka deployment. The upstream and downstream synoptic conditions during TiMREX will be sampled by concurrent field experiments proposed in East Asia, including TIBET experiment over the Tibetan Plateau, the China Heavy Rain Experiment (CheREX), and two Japanese programs (the Okinawa expedition and Palau-08). The combined observations from these field experiments will provide a comprehensive mapping of the onset of the Asian summer monsoon.

1.1 Intellectual merit

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 the following field experiments¹, TAMEX, COAST, CALJET, PACJET, MAP, IMPROVE I and II, and NAME (e.g., Garvert et al. 2005b; Rotunno and Houze 2005; Richard et al. 2005). Recent work in Taiwan indicated that some mesoscale numerical models, such as the Weather Research and Forecasting (WRF) model, showed similar discrepancies and were sensitive to the uncertainties in the model initial conditions, upstream of orographic precipitation (F.-C. Chien 2006, personal communication). TiMREX is an outgrowth and extension of the science carried out in previous field programs in the international meteorological community aiming at improving our basic understanding of and prediction of terrain-influenced precipitation in a warm, moist, unstable, subtropical monsoon environment. TiMREX is unique to these earlier experiments in the following three aspects:

- (1) Warm season flash floods are extreme hazards in the U. S. but the repeatability of these events at the same location is rare. It is difficult to plan a field project to study them in the U.S. During the Mei-Yu season in Taiwan, such events occur with a degree of regularity. These convective systems are frequently embedded within the Mei-Yu front and are influenced by southwesterly monsoon flow, land-sea thermal contrast, and orography. Taiwan is a natural laboratory for the study of physical process leading to heavy orographic precipitation.
- (2) Orographic precipitation experiments (COAST, CALJET, PACJET, MAP, IMPROVE I and II) were conducted during either fall or winter seasons in mid-latitudes with a relatively stable environment except that NAME and SPACE were conducted in summer and COPS will be conducted in continental Europe during the summer of 2007. TiMREX will be conducted in a subtropical, warm, and potentially unstable flow regime with an isolated, steep mountain range and large diurnal variations in airflow and weather. For NAME, convection typically formed over the high terrain of the Sierra Madre Occidental, then progresses westward towards the coastal plain and the Gulf of California. In Taiwan, precipitation moves onshore and then into the high terrain, in sharp contrast to the situation in Mexico.
- (3) A series of field programs, IHOP_2002, CSIP, and COPS, are aimed at improving convective precipitation forecasts. These three convection initiation and QPF field programs together cover broad flow regimes, varying topography and extreme land-use variations. TiMREX nicely complements and extends these studies into a different environment and complex terrain regime.

¹ The South Park Area Cumulus Experiment (SPACE, 1977, Cotton and Knupp 1982), Taiwan Area Mesoscale Experiment (TAMEX, 1987; Kuo and Chen 1990), The Coastal Observation and Simulation with Topography Experiment (COAST, Bond et al. 1997), California Land-Falling Jets Experiment (CALJET, 1998, Ralph et al. 2003), Mesoscale Alpine Program (MAP, 1999; Bougeault et al. 2001), Pacific Land-Falling Jets experiment (PACJET, 2000-2002, Neiman et al. 2005), Improvement of Microphysical Parameterization through Observational Verification Experiments I and II (IMPROVE, 2001, Stoelinga et al. 2003), International H₂O Project (IHOP_2002), and the North American Monsoon Experiment (NAME, 2004, Higgins et al. 2006), Convective Storm Initiation Project (CSIP), and Convective Orographic Precipitation Studies (COPS, <http://www.uni-hohenheim.de/spp-iop/>).

1.2 Broader impacts

The multi-scale design of TiMREX allows modeling and observational studies of the heavy precipitation systems and their embedded environments. The southwesterly LLJ associated with the Mei-Yu front is a component of the summer Asia monsoon circulation that transports moisture and unstable air from the tropics into the frontal zone. TiMREX will advance our understanding of the effect of this important component of the global circulation system on producing orographic heavy precipitation influenced by steep terrain. Better understanding of the physical processes of these common factors leading to orographic precipitation in TiMREX has potential applications in the U.S. (e.g., California coastal range and Sierra Nevada mountains, Rocky Mountains, Appalachian Mountains, and the Hawaiian Islands) and other regions of the world (e.g., European Alps, Pyrenees, Apennines, Scandinavian mountains, Western Ghats in India, New Zealand Alps, and Andes in South America, to name a few). The focus on convective scale precipitating system structure and microphysical processes will improve QPE/QPF in mesoscale numerical models and nowcasting systems. The localized heavy rainfall events during the Mei-Yu season over Taiwan frequently lead to floods and landslides which result in human casualties, heavy property damage and impede agricultural production in a populous, developed country. Knowledge gained from TiMREX to improve forecasting of heavy rains will have significant benefits for local governments, emergency managers and general public, far beyond the field of meteorology. TiMREX will provide opportunity for many graduate and undergraduate students from the U.S. and Taiwan to participate in the field experiment, data analyses and modeling efforts in mesoscale meteorology.

2. Background

The Mei-Yu (plum rain) season is a climate regime characterized by frequent MCSs that occur along an ENE-WSW oriented, quasi-stationary convergence zone (or the Mei-Yu front) (Fig. 1, Wang et al. 1990). It first appears in southern China during May, affects Taiwan and southeastern China from mid-May to mid-June. Although each individual front moves southwards, the mean positions of the fronts experience sequential northward jumps from May to August. It first migrates northward to the Yangtze River region and southern Japan during 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. Climatologically, the Mei-Yu rainy season in the vicinity of Taiwan lasts from mid-May to mid-June (C.-S. Chen and Chen 2003). MCSs originated from southern China often move from west to east across the Taiwan Strait, interact with the steep topography in Taiwan and produce extremely heavy precipitation (Kuo and Chen 1990; G. Chen 1995). TAMEX and post TAMEX studies (e.g., Jou and Deng 1989, 1992, 1998; Deng 1992; Wang et al. 1990; Lin et al. 1990, 1992; 1993; Li et al 1997) showed that these systems have the same general characteristics as MCSs over the rest of the world (e.g., Houze and Betts 1981; Chong et al. 1987; Houze 1993; 1997; Houze et al. 1989; Kingsmill and Houze 1999a, b). These heavy rainfall events occurred in some degrees of regularity during

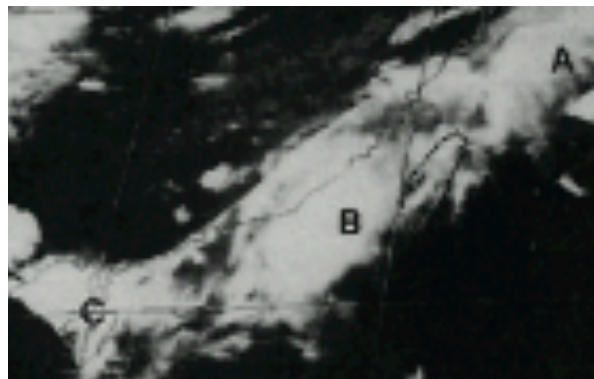


Figure 1. An IR satellite images at 20 LST (12 UTC) 16 May 1987. The separate organized MCSs are labeled A, B and C. (Wang et al. 1990)

the Mei-Yu season over Taiwan (see Section 3). Therefore, Taiwan is an ideal natural laboratory to study the physical processes leading to the development of heavy orographic precipitation in a warm, moist, and conditionally unstable subtropical environment.

The climatological and synoptic characteristics of the Mei-Yu front have been extensively studied by meteorologists in Taiwan, China, Japan and Korea (e.g., G. Chen and Chi 1980; G. Chen 1983; Matsumoto et al. 1971; Ninomiya 1984). On average, 4-5 frontal systems affect Taiwan during the Mei-Yu season each year (G. Chen 1983). TAMEX (1987) used three ground-based C-band Doppler radars, an airborne Doppler radar, and enhanced surface and sounding networks as the primary instruments to study Mei-Yu front and MCSs affecting northern Taiwan. Lesser known are the characteristics of Mei-Yu front and its role associated with MCS development and heavy rainfall events in southern Taiwan where TiMREX is focused.

A LLJ is frequently observed on the warm side of the Mei-Yu front (G. Chen 1983) and often precedes heavy rainfall events over northern Taiwan by as much as 12 hours (G. Chen and Yu 1988; G. Chen et al. 2005). The LLJ is found to be a common ingredient for producing heavy orographic precipitation in other parts of the world, such as China, Japan, and Korea, European Alps, U.S. Sierra Nevada, Rockies and Appalachians, and New Zealand Alps (e.g., Lin et al. 2001; Lin 2005; Neiman et al. 2004; Neiman et al. 2005; Ralph et al. 2003; Witcraft et al. 2005). The LLJ not only transports moisture into the frontal zone but also destabilizes the atmosphere, which provides a favorable environment for the development of heavy precipitation. Y.-L. Chen et al. (1994) and X.-A. Chen and Chen (1995) found that the development of LLJ before the seasonal transition in mid-June is closely related to the developing lee cyclone east of the Tibetan Plateau and is a result of a mass-momentum adjustment process in a moist baroclinic environment (Y.-L. Chen 1993). The feedback effects by convective heating on the jet/front circulation are also important (Hsu and Sun 1994; Y.-L. Chen et al. 1997; X. A. Chen and Chen 2002). In some instances, the strengthening of the LLJ over the Taiwan area is related to the transient western expansion of the semi-permanent subtropical high over the western Pacific (Y. L. Chen and Tseng 2000; G. Chen et al. 2006). TAMEX studies found that heavy rainfall events are frequently related to a coupling between the LLJ and upper-level synoptic forcing (Y.-L. Chen and Li 1995a; Li et al. 1997) that favored the development of deep convection.

Prior to the arrival of the Mei-Yu front, the LLJ impinges on the central mountain range (CMR) with a windward ridge/lee-side trough pressure pattern (Y.-L. Chen et al. 1989; Trier et al. 1990; Y.-L. Chen and Hui 1990, 1992). Island blocking and flow splitting occur off the southwestern coast of Taiwan (Y.-L. Chen and Li 1995b) in agreement with the theoretical studies of airflow for a low Froude-number [$Fr=U/Nh < O(1)$, where U is the basic wind speed, N the Brunt-Vaisala frequency, and h the mountain height] flow regime over an isolated mountain (Smith 1989; Smolarkiewicz et al. 1988; Sun et al. 1991; Lin et al. 1992). For flow past a mountain range with significant rotational effect, such as the CMR, the flow is characterized by the Burger number [$B = Ro/Fr = (N/f)/(h/L)$], where Ro is the Rossby number (Pierrehumbert and Wyman 1985; Overland and Bond 1995). For LLJs during TAMEX, $B > 1$ (Li and Chen 1998), the CMR is hydrodynamically steep. Based on TAMEX data, C.-S. Chen et al. (1991) and Akaeda et al. (1995) hypothesized that the movement of these pre-existing squall lines over the orography may have been dictated by the Froude number of the basic flow. In fact, Reeves and Lin (2006) have shown that squall line stagnation, which leads to copious accumulations of precipitation, is more prone to occur in flows with smaller Froude number. This leads to blocked and unblocked flow regimes, which can then strongly dictate precipitation

amounts and distribution. In addition, the extent of the lifting and precipitation growth in large Froude number and relatively stable flow is dictated by linear gravity wave theory (e.g., size and shape of the barrier, wind speed and stability)(e.g., Colle 2004; Smith and Barstad 2004). Frame and Markowski (2007) have also studied similar problems in a shear flow. Orographic precipitation in a stratified flow with embedded instability over moderate terrain has been examined using semi-idealized models (e.g., Kirshbaum and Durran 2004; 2005a; 2005b; Fuhrer and Schar 2005). These studies indicated that the thermal variations in the upstream incoming flow, vertical wind shear, and underlying terrain variability dictate the precipitation patterns (stratiform, band, and/or cellular) and amount. In fact, observations in the warm, moist, and relatively unstable environment are rare. *TiMREX will deploy resources (dropsonde, aerosonde, mobile, and ship soundings) to investigate these issues.*

Along the western coast, the northern branch of the deflected airflow accelerates northward with a large cross-contour wind component down the pressure gradient resulting in an orographically induced barrier jet (Y.-L. Chen and Li 1995a; Li and Chen 1998; Yeh and Chen 2003). The localized convergence between the barrier jet and the prefrontal airflow or the Mei-Yu front is favorable for the development of deep convection (Li et al. 1997; Yeh and Chen

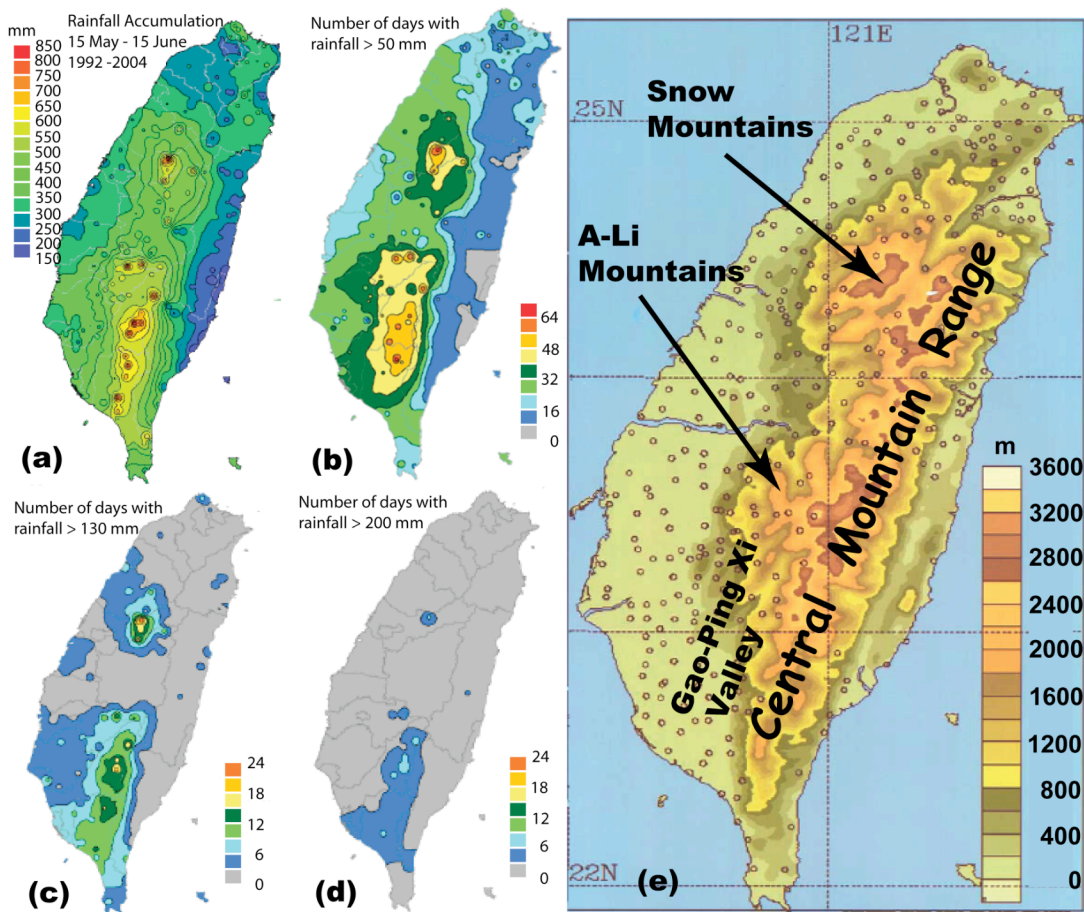


Figure 2. Rainfall statistics of 15 May-15 June from 1992-2004. The daily rainfall frequency in the 12 year period (a) is subdivided into three categories, >50 mm (b), >130 mm (c), and >200 mm (d). The right panel (e) illustrates the Taiwan topography and the locations of the ARMTS raingauges. The three peaks rainfall regions are Snow Mountains, A-Li Mountains, and Gao-Ping Xi valley.

2002; G. Chen et al. 2005). Due to a mismatch in both temporal and spatial scales, the mesoscale structures of the LLJ and barrier jet could not be observed from the operational rawinsonde network and only very limited aircraft data were collected during TAMEX. Therefore, details of the interactions between the LLJ and barrier jets, and their mesoscale structures could not be addressed. In addition to island blocking, the island-scale airflow and weather is strongly modulated by the diurnal heating cycle (e.g., Johnson and Bresch 1991; Li and Chen 1995b; Yeh and Chen 1998; Kerns 2003). However, due to insufficient data during TAMEX, local circulations under different large-scale settings have not been studied in sufficient detail. *TiMREX will deploy resources to address these issues.*

3. Rainfall climatology

A rainfall climatology using Taiwan's Automatic Rainfall and Meteorological Telemetry System (ARMTS, T.-C. Chen et al. 1999) from 1992 to 2004 is shown in Fig. 2. Nearly anywhere in Taiwan, especially the western slopes of the CMR, rainfall events exceeding 50 mm/day can be expected during the May-June period. In the Snow Mountains over central Taiwan and Gao-Ping Xi valley over southern Taiwan, daily rainfall >50 mm occurred 5-6 days during the one-month Mei-Yu season, consistent with events with daily rainfall exceeding 130 mm/day. Extreme rainfall events (rainfall exceeding 200 mm/day) are confined to southern Taiwan, west of the CMR. A pronounced afternoon maximum on the southwestern-facing slopes is consistent with the development of anabatic winds under the prevailing southwesterly monsoon flow (Yeh and Chen 1998; Chien and Jou 2004; C.-S. Chen et al. 2007). Peng (2006) identified 19 events with daily rainfall >200 mm from 1997-2005 including six events with daily rainfall > 400 mm. On average, these extreme events occurred twice during each Mei-Yu season in southern windward slope with year-to-year variability. Heavy rainfall could occur on either the western slope of CMR or the coastal plain under similar southwesterly flow regimes (Figure 3). However, low forecasting skills and inadequate model guidance for these heavy rainfall and the associated flooding events in southern Taiwan have been a significant challenge and will be the focus of TiMREX.

4. Scientific objectives

The overarching goals of TiMREX is to improve understanding of the physical process

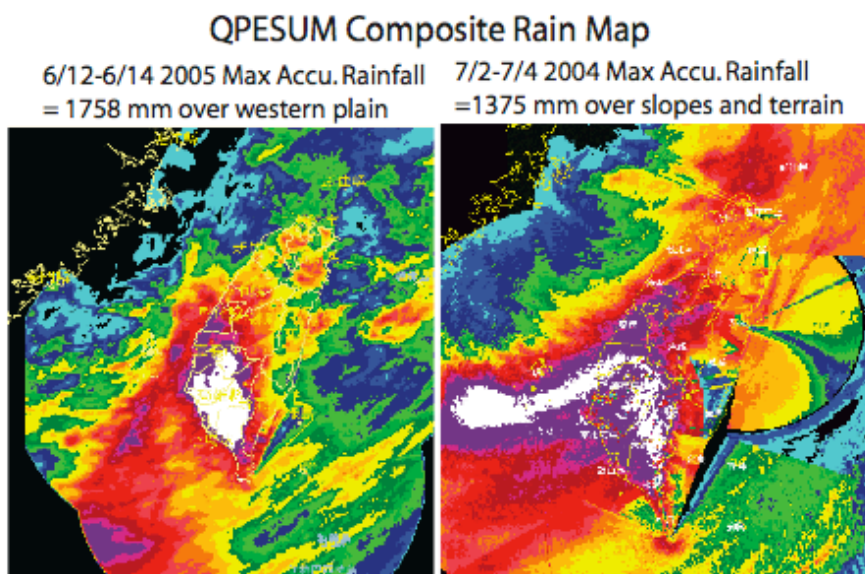


Figure 3. The 72 hours QPESUM (radar composite derived) rain map for two extreme heavy rain events in southern Taiwan. For the 2005 event (left panel), the maximum rain fell on the plains. For the 2004 event (right panel), the maximum rain fell on the western slopes of the CMR.

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. The NCAR S-Polka radar, when combined with two NOAA S-band rain profilers and a multitude of existing operational and research facilities in Taiwan (Section 6), will provide comprehensive observations to study the dynamical and microphysical processes and the environment conditions leading to the development of heavy rainfall. As an outgrowth of this work, model simulations of MCSs with data assimilation of high-resolution observations during TiMREX and their associated QPE/QPF should be improved as models begin to incorporate the improved physical processes leading to heavy rain.

TiMREX is organized around the following five broad scientific questions:

(1) What are the effects of orography and the characteristics of upstream monsoonal flow on rainfall distributions in southern Taiwan?

Recent WRF simulations have shown sensitivity between the precipitation patterns in the southern Taiwan area and the artificially perturbed sub-synoptic moisture and temperature fields in the upstream conditions (F. C. Chien 2006, personal communication), consistent with idealized simulations (e.g., Colle 2004). Based on TAMEX data, C.-S. Chen et al. (1991) and Akaeda et al. (1995) hypothesized that the movement of these pre-existing squall lines over the orography may have been dictated by the Froude number of the basic flow. For a nonrotating, 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; S.-H. Chen and Lin 2005a, b). These propagation characteristics can then dictate the precipitation distribution and amounts. In addition, the development of embedded convection and associated precipitation may strongly depend on small-amplitude upstream perturbations (Fuhrer and Schar 2005). These theories need to be further evaluated. The sounding data in TAMEX were not adequate to systematically evaluate the upstream flow characteristics. TiMREX will provide upstream conditions for determining the nondimensional control parameters for different flow regimes, which, in turn, will help predict the rainfall distribution. Dropsonde, aerosonde, and rawinsonde observations from the research vessel will be the key observations in this work. Also, the GPS radio occultation (RO) soundings from COSMIC will provide a good description of the thermodynamic characteristics of the upstream monsoon flow.

(2) What are the roles of Mei-Yu front and its mesoscale circulations in the development, maintenance and regeneration of heavy rain producing convection systems in southern Taiwan?

In TAMEX, dual-Doppler analysis in northern Taiwan examined the structures of MCSs associated with Mei-Yu front. Less known are the mesoscale kinematic and thermodynamic characteristics of the Mei-Yu front/LLJ in southern Taiwan and the adjacent oceans, and the effects of the CMR on Mei-Yu front/LLJ and heavy precipitation. TiMREX will provide a comprehensive dataset to examine the mesoscale characteristics of the barrier jet, island-induced flow, LLJ and Mei-Yu 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 Mei-Yu fronts. Doppler radars, surface, radiosondes, COSMIC GPS RO soundings, ISS, dropsonde, and boundary-layer wind profiler observations will be the key observations in this work.

(3) How do boundary layer processes, such as, surface moisture distributions, land-sea contrasts and mountain-valley circulations modulate 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 (e.g., Byers and Braham 1949; Wilson and Schreiber 1986; Lee et al. 1991; Wakimoto and Atkins 1994; Fankhauser et al. 1995; Atkins et al. 1995; Wakimoto and Kingsmill 1995; Kingsmill 1995; Laird et al. 1995; Weckwerth et al. 1996; Wilson and Megenhardt 1997; Weckwerth and Parsons 2006).

With the dense surface and advanced radar capability in TiMREX, we will investigate whether these convergence lines trigger MCSs in the vicinity of the Mei-Yu front or whether the influence of these convergence lines are overwhelmed by the Mei-Yu front, its associated LLJ, or by orographic features. 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 S-Polka, high resolution visible satellite imagery (e.g., Purdom 1982; Purdom and Marcus 1982), and surface stations. High-resolution water vapor fields will be obtained from surface stations, GPS integrated water vapor sensors and from radar refractivity measurements using the technique of Fabry et al. (1997). See Weckwerth et al. (2005) and Fabry (2006) for the potential of this technique.

(4) What are the microphysical processes within heavy rain producing convective systems influenced by the 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 TiMREX by retrieving ensemble microphysical properties using the polarimetric capabilities of the S-Polka 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. 1990, 1994, 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 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 was recently presented 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 1995a, b, c). The two sets of collocated NOAA S-band rain profiler and Ka-band rain radar will provide highly resolved reflectivity profiles at two locations on the windward slopes of the CMR, yielding important information on vertical structures and evolution of these precipitation systems.

(5) What is the potential for improving QPE/QPF skills 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; Liang 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. 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. 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.

5. Numerical modeling and data assimilation

5.1 Mesoscale modeling

Mesoscale numerical modeling will play an important role in TiMREX. Taiwan has the capability to run both WRF and the fifth-generation Penn State/NCAR Mesoscale Model (MM5, Grell et al. 1994) at the Central Weather Bureau (CWB) and various universities. Presently, WRF ensemble runs (for 36 hours forecast) with six different combinations of microphysical schemes and cumulus parameterization schemes at 15 km horizontal grid resolution are routinely performed (Chien and Jou 2004). The results are displayed on a centralized web page and provide QPF guidance to CWB forecasters. The ensemble forecast effort will be continued in real time during TiMREX to provide guidance for daily operation. The QPF results from the ensemble runs can be compared with polarimetric radar observations to further assess the performance and error characteristics of each ensemble member. The information can be used to guide the high-resolution research modeling efforts in post TiMREX.

High-resolution experimental numerical prediction is very important both for guiding the field operation in real time and for a careful verification (both subjective and objective) of the model with observations during post TiMREX. The WRF model will have the nested grid size down to 1 km in the TiMREX area. Such activity will lead to improvement of the model for future operational and research use. We will also perform sensitivity experiments to assess the impact of various physical processes (for example, the ice physics) on rainfall prediction. With the availability of polarimetric radar data, we can perform a careful comparison between cloud-scale model simulation and polarimetric radar observations (S-Polka and TEAM-R). This also provides a useful evaluation of the cloud microphysical parameterization in the model.

5.2 Data assimilation

Although we hope to gather a considerable amount of data from the experimental network including various observing platforms, there will be undoubtedly "data gaps" for a given case. This is partially remedied by assimilating observations into a high-resolution numerical model that optimally blends radar observations with other observations. The resulting numerical analysis can be extremely valuable in producing dynamically consistent four-dimensional data sets over extensive areas for various diagnostic, modeling, and nowcasting studies.

The MM5 and WRF data assimilation systems (3DVAR, 4DVAR, and ensemble Kalman Filter) have been developed in the MMM division of NCAR, and can be used for such purposes.

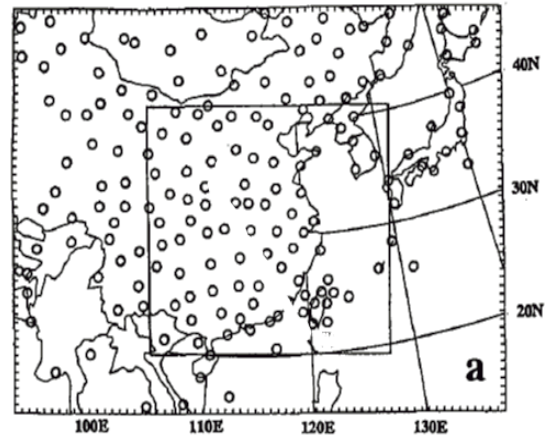


Figure 4: Upperair rawinsonde sites in East Asia.

We envision that the data assimilation studies will be performed at two different scales. On the mesoscale with a grid-resolution of ~ 12 km, we can assimilate observations taken by supplementary sounding, surface, upper-air networks and satellite data (e.g., cloud drift winds, COSMIC GPS RO soundings and AMSU). This can provide an excellent description of the regional atmosphere concerning the structure of the Mei-Yu front, the LLJs, the barrier jets, and MCSs. Embedded within this mesoscale data assimilation system, we can perform cloud scale data assimilation making direct use of the Doppler radar observations (e.g., Xiao et al. 2005, 2007; Xiao and Sun 2007). This will then provide a coherent four-dimensional description of the internal kinematic and thermodynamic structure of a given cloud systems. We envision that the cloud-scale data assimilation will be performed at a horizontal resolution of 1 km to 3 km. These data assimilation studies will be performed after the field campaign. The simulated model parameters, such as reflectivity, airflow, hydrometeor type, mass flux, and precipitation field, will be evaluated to confirm that the model captures the radar observed characteristics.

The results from mesoscale data assimilation can be used as the initial conditions for model sensitivity experiments to answer some of the scientific questions raised in the last section. We can also study the impact of supplementary data on the accuracy of forecast for convective systems and perform adjoint sensitivity analysis to test the idea of "targeted observations". Specifically, we will first run the high-resolution MM5 and/or WRF model without the use of supplementary data. We then run the MM5 and/or WRF

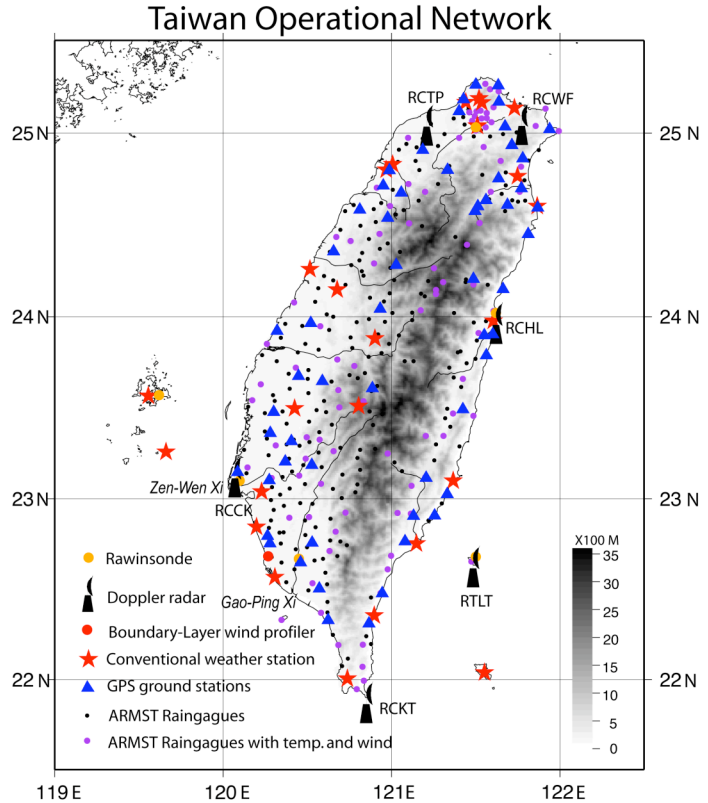


Figure 5. Operational network in Taiwan. Two major rivers (Gao-Ping Xi and Zen-Wen Xi) in the TiMREX domain are labeled at their entrance to the Taiwan Strait.

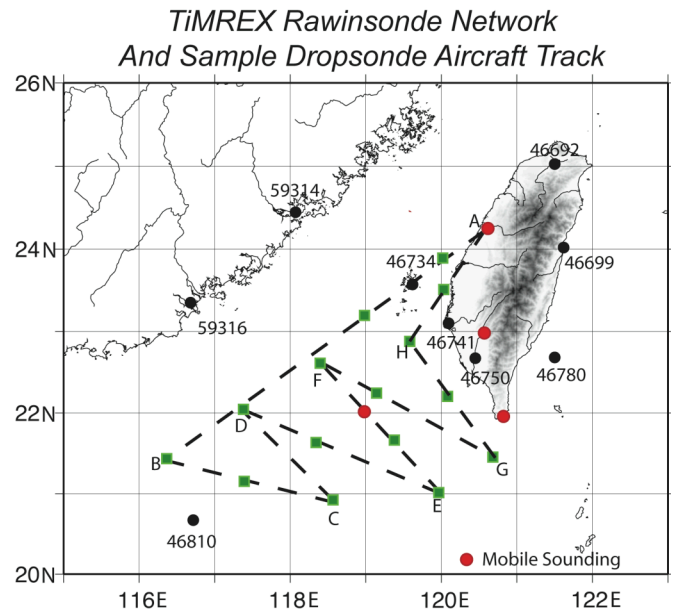


Figure 6. Operational rawinsonde network (black dots) and sample dropsonde aircraft track. Dropsonde locations are green squares. Mobile sounding locations are red dots including the one on research vessel at 22N, 119E.

adjoint model to determine the regions where the model prediction of convection will be most sensitive. We can then perform forecast experiments using supplementary observation within the "target" region and compare the new forecast with the control experiment. The current experiment design does not permit a "real-time" targeted observation study. But, many useful ideas can be tested using the experimental data after the field operation.

6. Experimental design and observing facilities

6.1 Overview

TiMREX will be conducted in the Taiwan area including the northern South China Sea. Figure 4 shows the distribution of surface stations and upper air rawinsonde stations in the synoptic observation region (108-123E and 18-30 N). The mean separation of existing surface/rawinsonde stations in southern China and the Taiwan area is ~ 150-250 km. The routine observations include 2 daily upper air rawinsondes and 8 surface reports on standard meteorological parameters daily. This network will provide invaluable background information of the synoptic environment. China is planning to hold a concurrent mesoscale experiment (CheREX) and the TIBET experiment near the TiMREX time frame and increase the routine sounding frequency from 2 to 4 times daily in southern China. TiMREX is working with China to obtain these data.

Other operational facilities in Taiwan include, six operational Doppler radars, one boundary layer wind profiler, 418 automatic raingauges, 57 GPS integrated water vapor sensors, ability to receive geostationary and polar orbiting satellite imageries (Fig. 5). The TiMREX observation region (115-123E, 20.0-26.0N) includes both the routine operation network and special observing stations and facilities. The operational and mobile rawinsonde stations are shown in Fig. 6. The special observing facilities include a ground-based S-band polarimetric research radar (NCAR S-Polka), an X-band mobile polarimetric research radar (TEAM-R), one integrated sounding system (ISS), a tethersonde, four mobile rawinsondes, a VHF wind profiler, two NOAA S-band rain profilers, two Ka-band rain profilers, one dropsonde aircraft, three aerosondes, one tethersonde, and one research vessel. A comprehensive list of the major research facilities and their proposed funding sources are listed in Table 1. During TiMREX, the observations will be divided into two categories, the special observation period (SOP) and the intensive observation period (IOP). During SOP periods, the surface observations will be hourly and the upper air rawinsondes will be 6 hourly for stations in Taiwan except Dongsha (46810, Fig. 6). During IOP periods, the soundings will be 3 (or 4) hourly. The local standard time (LST) in TiMREX is 8 hours behind UTC.

Table 1. Major observing facilities in TiMREX and the proposed funding source.

Facility	Quan.	Cost	Funding Source
NCAR S-Polka	1	\$700K	U.S. (National Science Foundation)
NOAA S-B Rain Prof.	2	\$250K	Taiwan (National Science Council)
Dropsonde Aircraft	90hrs	\$1M	Taiwan (Central Weather Bureau)
Dropsonde	300	\$300K	Taiwan (Central Weather Bureau)
Operation Sounding Supplement	1050	\$280K	Taiwan (Central Weather Bureau, Air Force)
ISS and Mobile Sounding	960	\$262K	Taiwan (National Science Council)
Research Vessel	1	\$155K	Taiwan (National Science Council)
Aerosonde	3	\$314K	Taiwan (Central Weather Bureau)
Cloud Videosonde	25	\$160K	Taiwan (Central Weather Bureau)
X-band Mobile Radar	1	\$277K	Taiwan (National Science Council)
Operation Center & Data Management		\$300K	Taiwan (Central Weather Bureau)

Taiwan: \$3300K (82.5%), US (NSF): \$700K (17.5%), Do not include routine operation cost.

Therefore, the 2 daily soundings are launched at 8 am and 8 pm LST. The IOP will be declared at least 24 hours before the predicted occurrence of MCSs in the domain in order to capture the development and evolution of Mei-Yu front, LLJ, barrier jet, and subsequent MCS development.

6.2 COSMIC and TiMREX

The atmospheric limb sounding technique making use of radio signals transmitted by the Global Position System (GPS) satellites has emerged as a powerful and relatively inexpensive approach for sounding the global atmosphere in all weather. On 15 April 2006, the joint U.S.-Taiwan COSMIC/FORMOSAT-3 (hereafter COSMIC) mission, a constellation of six microsattellites, was successfully launched from Vandenberg Air Force Base in California. By May and June 2008, COSMIC will be providing routinely more than 2,500 GPS radio occultation (RO) soundings per day uniformly distributed around the globe. With the use of advanced open-loop tracking technique, COSMIC GPS RO soundings can track through the tropical boundary layer, and can provide valuable information on the temperature and moisture structure associated with the Mei-Yu front, providing valuable information on the environmental conditions for mesoscale convective systems that develop along the Mei-Yu front. With the assimilation of COSMIC GPS RO soundings, we will also be able to improve the analysis and prediction of large-scale features such as the Western Pacific Subtropical High and the southwesterly flow. Figures 7 illustrate the actual COSMIC GPS RO soundings that were obtained during a one-week period in December 2006. When the COSMIC spacecrafts are fully deployed in 2008, these soundings will provide critical upstream thermodynamic and moisture information for TiMREX. The exact

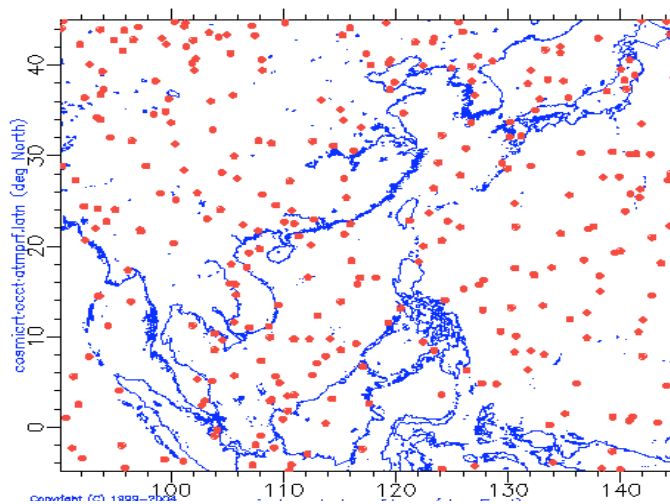


Figure 7. The COSMIC sounding distribution in east Asia during a one week period in December 2006.

locations of these COSMIC soundings can be predicted accurately weeks in advance. Therefore, TiMREX rawinsonde network and dropsondes can target the potential COSMIC sounding locations and provide comprehensive and critical validation datasets.

6.3 Experiment design and facilities

6.3.1 Upstream conditions

A research Vessel will be deployed to $\sim (22N, 119E)$ about 200 km west of the southern tip of Taiwan (Fig. 8) to routinely release upstream soundings, critical to document the evolution and characteristics (direction, intensity, and stability) of the incoming flow toward the mountain barrier. The mesoscale structure of the upstream conditions will be sampled by dropsondes released by a research aircraft (Astra SPX jet) and aerosondes offshore. The Astra SPX cruises at $\sim 750 \text{ km hr}^{-1}$ with maximum flight duration $\sim 6 \text{ h}$ and a ceiling of $\sim 14 \text{ km}$ (Wu et al. 2005). These offshore soundings across the LLJ are critical to document the kinematic and thermodynamic structures of the LLJ resulting in the upstream water vapor flux toward CMR in southern

Taiwan. A proposed sample flight track to sample LLJ is illustrated in Fig. 6 showing dropsondes released approximately every 100 km (green squares). This pattern will take about four hours to complete. It is expected to have 3-4 missions for each Mei-Yu front case. Three aerosondes, jointly operated by CWB and NTU, will continuously sample the mid-to-low level kinematic and thermodynamic structures of the upstream conditions to complement the ship sounding and dropsondes.

6.3.2 Precipitation structures and microphysics

The distribution and evolution of precipitation will be observed by six operational Doppler radars (RCWF, RCHL, RCKT, RCCK, RCTP, and RCLT), S-Polka and TEAM-R. Their characteristics are summarized in Table 2 and locations shown in Fig 6 and 8. These radars will be able to monitor convective development and precipitation systems up to 400 km off the coast of Taiwan with effective Doppler range ~ 200 km. The NCAR S-Polka will be strategically placed ~ 60 km from the RCCK (Fig. 8) to form the primary dual-Doppler radar pair to sample the mesoscale kinematic and microphysical structures of heavy precipitation systems in the primary TiMREX study area. Smaller dual-Doppler radar domains can be formed by pairing the TEAM-R with either the RCCK, S-Polka or RCKT radars, yielding baselines as small as 30 km to better sample convective scale structures. TEAM-R can also be deployed between S-Polka and RCKT to form two additional dual-Doppler radar lobes with baselines about 45-60 km. This configuration can be adjusted in real-time to resolve low-level, high resolution, 4-D air motions along the western slopes of the CMR and adjacent plains. An example of the dual Doppler lobes formed between RCCK and S-Polka (solid circles), S-Polka and TEAM-R (solid circles), and S-Polka and RTKT (dash circles) are indicated in Fig. 8.

The polarimetric capability of NCAR S-Polka and the TEAM-R will provide simultaneous polarimetric measurements from which microphysical processes can be inferred. In addition, the surface moisture patterns derived from the S-Polka refractivity data will be important in assessing the relative importance of low-level moisture variations in convection initiation.

Prior to the occurrence of deep convection the S-Polka will conduct low elevation scans to map boundary layer winds, radar refractivity and convergence lines to examine their role in triggering convective storms. These scans will also be used to monitor the development of cumulus clouds prior to the development of precipitation. Once deep convection begins (> 30 dBZ in reflectivity) in the primary dual-Doppler lobe, scans through the entire depth of the storms will be conducted and will remain in effect during the entire storm evolutionary process.

Table 2 Characteristics of Doppler radars in TiMREX.

Radar	Wavelength	Pulse Duration	PRF	Peak Power	Beamwidth	Ant. Gain	Scan rate
RCWF	10 cm	1.6 & 4.7 μ s	318-1304 Hz	750 Kw	0.95°	45.6 dB	0-36°s ⁻¹
RCHL, RCCK,R CKT	10 cm	0.5 & 3.3 μ s	250-1302 Hz	750 Kw	0.95°	45.5 dB	0-36°s ⁻¹
RCTP	5 cm	0.5 & 2 μ s	900 & 1200 Hz	250 Kw	0.857°	43dB	12-36°s ⁻¹
RCLT	5 cm	0.7 & 2 μ s	250 & 1200 Hz	250 Kw	1.02°	44.5 dB	0-36°s ⁻¹
TEAM-R	3 cm	0.2 – 2 μ s	0 – 3000 Hz	50 Kw	1.15°	42.5 dB	0-36°s ⁻¹
S-Polka	10 cm	0.3-1.4 μ s	0-1300 Hz	>1Mw	0.91°	44.05dB	0-18°s ⁻¹

A combination of scan sequence including sector scans, VAD surveillance scans, and a set of RHI scans will be implemented based on the storm locations and lifecycles. The objectives in this mode include the need for high space and time resolution dual-Doppler, polarimetric sampling, boundary layer monitoring, and rainfall mapping. Scan strategies will consider the applied scientific objectives of field-testing precipitation algorithms, model verification, and assimilation of radar data into high-resolution numerical models.

7. Project and data management

Scientific planning and coordination will be carried out by the TiMREX Scientific Steering Committee (SSC). The SSC is responsible for the design, operation, and management of TiMREX. The data management committee (DMC) will be organized to oversee the collection, archival and access to all project data. The DMC will report to the SSC on a regular basis. Field operation control will be an EOL/Taiwan collaboration.

7.1 Scientific Steering Committee

The SSC members (Table 3) consists of principal investigators and will be co-chaired by Wen-Chau Lee (U.S.) and Ben J.-D. Jou (Taiwan). The SSC will be responsible for the overall planning, scientific objectives, and coordination of the TiMREX program prior to the field experiment, including preparation of a TiMREX Field Program Operations Plan. During the field phase, the SSC will also be responsible for the daily operation of TiMREX and assessing how well the experimental objectives are being met.

7.2. Field operation center

The primary field operation center (OC) will be located at the CWB southern forecast center near RCCK in Tainan, Taiwan. The Operations Director (OD) and SSC will be responsible for the overall execution of TiMREX field activities and declaring IOPs. The OD will work with the radar coordinator to determine the best strategy for using the research radars and the sounding coordinator on the deployment of the dropsonde aircraft, mobile, operational,

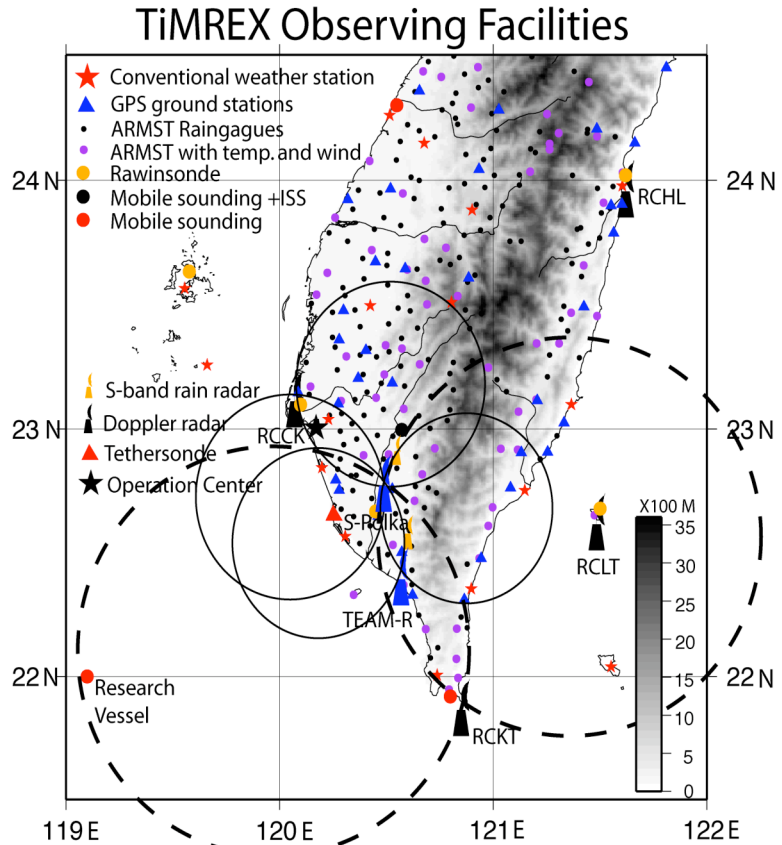


Figure 8. TiMREX observing facilities.

ISS, and shipboard soundings. The sounding coordinator will also work with OD and SSC on the dropsonde flight patterns. The OD will facilitate a daily planning meeting, prepare a daily operations summary and make sure proper operations documentation is provided. The radar coordinator will be responsible for (1) coordinating the scanning strategy among S-Polka, RCCK, RCKT, and the TEAM-R, (2) deploying and adjusting the position of the TEAM-R, and (3) operations of the S-band and Ku-band vertical pointing radars.

The OC will have access to all synoptic, satellite, and raingauge data as well as numerical weather prediction output and operational radar data via existing CWB facilities. It is proposed to transmit S-Polka radar images, refractivity, particle ID, and rainfall products to the OC via high-speed communications link. Overlays of satellite imagery and model output will be included as an aid to operations coordination of ground-based mobile and airborne facilities. CWB will work with EOL staff to implement a TiMREX Field Catalog to help 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 plans. The OD and SSC will be responsible for the overall execution of TiMREX.

7.3. Data Management and Data Policy

TiMREX, like other multi-agency sponsored international programs, relies on diverse datasets. These datasets include routine observations and data generated by university research laboratories and special field experiment networks. Proper management and access to these diverse datasets will be one of the critical factors in the success of TiMREX. CWB will work with EOL to develop a comprehensive data management plan, including data policies consistent with NSF (U.S.) and other agencies (U.S. and Taiwan), and maintain and manage a distributed archive at CWB. This will be similar to the existing archive and distribution system in EOL. The goal is to make the TiMREX data available to the PIs and greater scientific community.

The TiMREX DMC will be responsible for assisting in the development of the project data management plan, the coordination of data collection during the field phase and data quality control and distribution after the field experiment. The DMC will be primarily staffed by CWB and will work closely with EOL staff on the development of effective data management strategies. TiMREX proposes to (1) set up and maintain a project website at CWB, (2) collect special high-resolution data in real time and post field phase when available, and (3) perform uniform quality control procedures on operational data and research data (e.g., surface and sounding data, radar data calibration, etc).

Table 3. TiMREX Scientific Steering Committee members.

TiMREX Scientific Steering Committee	
U.S. members	Taiwan members
Yi-Leng Chen (U. of Hawaii)	Shui-Shang Chi (CWB)
Robert Fovell (UCLA)	Ben Jong-Dao Jou (NTU) – Co-Chair
Bill Kuo (NCAR)	Tai-Chi Chen Wang (NCU)
Wen-Chau Lee (NCAR) – Co-Chair	Feng-Ching Chien (NTNU)
Yuh-Lang Lin (North Carolina State Univ.)	Cheng-Ku Yu (CCU)
Jim Moore (NCAR)	Yu-Chieng Liou (NCU)
Tammy Weckwerth (NCAR)	
Jim Wilson (NCAR)	

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