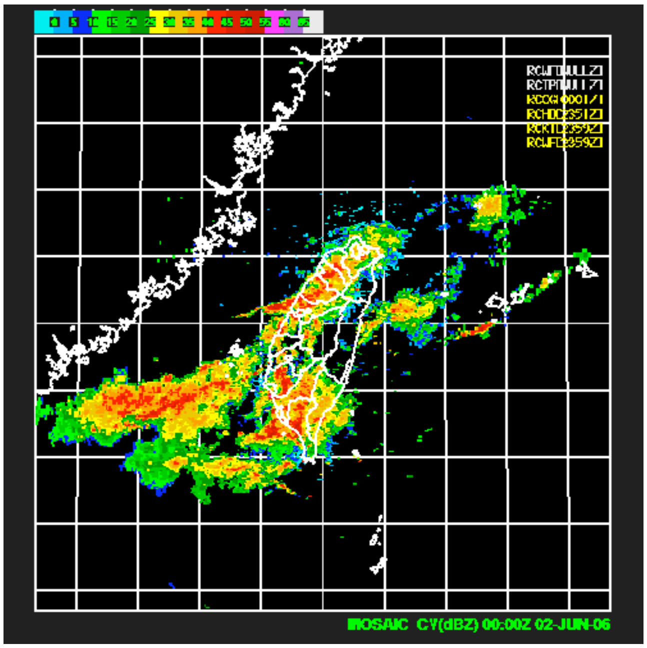
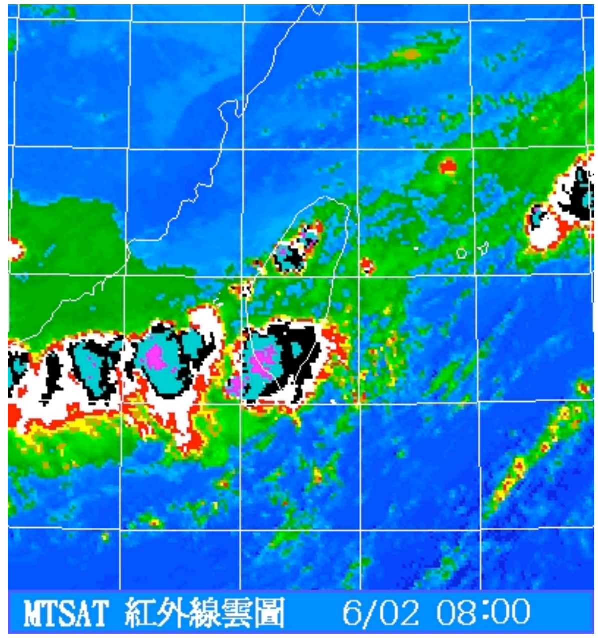
SCIENTIFIC OVERVIEW DOCUMENT

TiMREX

Terrain-influenced Monsoon Rainfall Experiment





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7 February 2007

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1. Project Summary

The second Taiwan Area Mesoscale Experiment (TAMEX II) 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 western coastal plain and mountain slope regions of southern Taiwan. The goal of TAMEX II is to improve understanding of the physical process associated with the heavy precipitation systems and the environment in which they are embedded through intensive observations and numerical model studies. The knowledge gained in TAMEX II will form the basis to advance our ability to predict heavy precipitation events and the skills of quantitative precipitation forecasts. TAMEX II 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 low-level jet (LLJ), approaching front, land-sea breeze and steep terrain. TAMEX II will sample the mesoscale environment and its variability (in moisture, stability and thermodynamic properties) of the upstream conditions and the Mei-Yu front, 3-D microphysical and kinematic structures of mesoscale convective systems (MCSs) and the morphology of orographic precipitation (spatial distribution, timing, intensity, structure, and microphysical processes).

Taiwan operates one of the highest density meteorological observing networks in the world. S-Polka will be deployed in conjunction with research facilities from U.S., Taiwan, and Japan to create a large-scale, research quality network that will permit coordinated observations of convective systems that propagate into or develop near Taiwan. TAMEX II will focus its observational resources over southwestern Taiwan and the adjacent oceans to study orographic precipitation on the southwestern windward slopes where heavy orographic precipitation is most frequent during the Mei-Yu season. The observing facilities to be deployed by Taiwan include dense routine and special surface, rawindsonde, Doppler radar networks supplemented by shipboard sounding and dropsonde observations from a research aircraft, ISS, boundary-layer wind profiler, and vertical pointing rain profilers. The primary proposed U.S. observational facilities to be deployed are the NCAR 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 two dual-Doppler networks.

TAMEX II 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 (e.g., research vessels, soundings, dropsonde aircraft, operational, and research Doppler radars, etc.) 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 TAMEX II will be provided 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).

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 convection), poorly understood microphysics and complicated topography have been suggested as the main sources for the lack of skills in predicting heavy orographic precipiation, and have motivated Improvement of Microphysical Parameterization through Observational Verification Experiments I and II (IMPROVE, 2001, Stoelinga et al. 2003) and other field campaigns (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. TAMEX II 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 orographic precipitation: the Taiwan Area Mesoscale Experiment (TAMEX, 1987; Kuo and Chen 1990), The Coastal Observation and Simulation with Topography Experiment (COAST, Bond et al. 1997), Mesoscale Alpine Program (MAP, 1999; Bougeault et al. 2001), , IMPROVE I, and II, and the North American Monsoon Experiment (NAME, 2004, Higgins et al. 2006). Yet TAMEX II is unique in the following four aspects:

(1) Flash floods are extreme hazards in the U. S. However, they occur so infrequently such that 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.

(2) Heavy rain producing convective systems are frequently embedded within the Mei-Yu front and influenced by southwesterly monsoon flow, land-sea thermal contrast, and orography. Taiwan is a natural laboratory for the study of physical process leading to the heavy orographic precipitation during the Mei-Yu season.

(3) Past orographic precipitation experiments (e.g., MAP, COAST, IMPROVE I and II), except NAME, which was carried out in Mexico during the summer monsoon, and the forthcoming COPS (http://www.uni-hohenheim.de/spp-iop/),which will be carried out in continental Europe during summer 2007, were conducted during the winter season in mid-latitudes with a relatively stable environment. TAMEX II will be conducted in a subtropical, warm, and potentially unstable flow regime with an isolated, steep mountain range with large diurnal variations in airflow and weather. For NAME, convection typically forms 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.

1.2 Broader impacts

Better understanding of the physical processes related to orographic precipitation in TAMEX II 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 southwesterly LLJ associated with the Mei-Yu front is a component of the summer Asia monsoon circulation. TAMEX II will advance our understanding on this important component of the global circulation system. The focus on convective scale precipitating system structure and microphysical processes will improve QPE/QPF in mesoscale numerical models. The localized heavy rainfall events during the Mei-Yu season over Taiwan frequently lead to floods and landslides result in casualty, heavy property damage and impede agricultural production in a populous, developing country. TAMEX II will have significant societal impact because knowledge gained from these studies is important to the downstream hydrological modeling of river runoff, flooding, and real-time forecasts of landslides and debris flows, which are critical for local government, emergency managers and general public. Furthermore, the research results will be translated into improved numerical models, forecasting tools and nowcasting systems for heavy rainfall forecasts and QPF/QPE. TAMEX II 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 for years to come.

2. Background

The Mei-Yu (plum rain) season is a climate regime characterized by frequent MCSs that occur along a semi-permanent convergence zone (or Mei-Yu front), extending from Okinawa to southern China. Climatologically, the Mei-Yu rainy season in the vicinity of Taiwan lasts from mid-May to mid-June (Chen and Chen 2003). It first appears in southern China during May, affects Taiwan and southeastern China from mid-May to mid-June, 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. The Mei-Yu front is slow-moving and occasionally quasi-stationary, which often produces a long, narrow cloud band with embedded vigorous and organized convection (Fig. 1, Wang et al. 1990). These MCSs move from west to east along the Mei-Yu front and as the MCSs move across the Taiwan Strait, they often interact with the steep topography in Taiwan and produce extremely heavy precipitation (Kuo and Chen 1990; 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 (Houze and Betts 1981; Chong et al. 1987; Houze 1989, 1993; Houze et al. 1989; Kingsmill and Houze 1999a, b). Mei-Yu season over Taiwan is an ideal laboratory to study the physical processes leading to the development of heavy orographic precipitation in a warm, moist, and conditionally unstable subtropical environment under the influence of Mei-Yu front and steep terrain.

The climatological and synoptic characteristics of the Mei-Yu front have been extensively studied by meteorologists in Taiwan, China, Japan and elsewhere (e.g., Chen and Chi 1980; Chen 1983; Matsumoto et al. 1971; Ninomiya 1984). On average, 4-5 frontal systems affect Taiwan during the Mei-Yu season each year (Chen 1983). Analysis of a Mei-Yu front (Chen and Chang 1980) suggested that the western section of the Mei-Yu front over southern China resembled an equivalent barotropic system. TAMEX (1987) used three ground-based C-band Doppler radars over the northwestern coast, 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 in southern Taiwan.

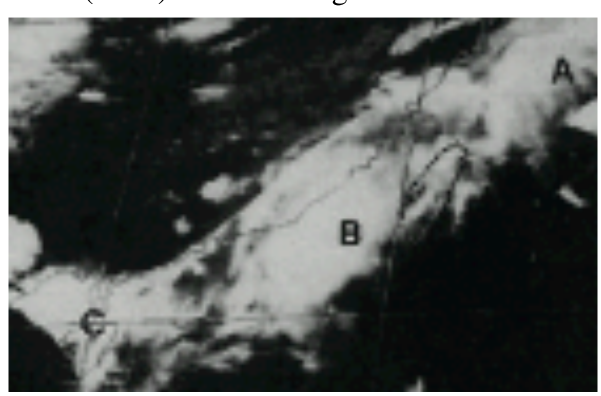

Figure 1. An IR satellite images at 20 LST (12 UTC) 16 May 1987. The separate organized MCSs are labeled A, B and C. (Wang et al. 1990)

A LLJ is frequently observed on the warm side of the Mei-Yu front (Chen 1977, 1983). 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. A LLJ often precedes heavy rainfall events over northern Taiwan by as much as 12 hours (Chen and Yu 1988; Chen et al. 2005). Chen et al. (1994) and 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 (Chen 1993). The feedback effects by convective heating on the jet/front circulation are also important (Hsu and Sun 1994; Chen et al. 1997; 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 (Chen and Tseng 2000; Chen et al. 2006). TAMEX studies found that heavy rainfall events are frequently related to a coupling between the LLJ and upper-level forcing (Chen and Li 1995a; Li et al. 1997).

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 (see Lin et al. 2001; Lin 2005; Witcraft et al. 2005). Prior to the arrival of the Mei-Yu front, the subsynoptic LLJ impinges on the central mountain range (CMR) with a windward ridge/lee-side trough pressure pattern (Chen et al. 1989; Trier et al. 1990; Chen and Hui 1990, 1992). Island blocking and flow splitting occur off the southwestern coast of Taiwan (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 effects, such as the CMR, the flow is characterized by the Burger number [$B = Ro/Fr = (N/f)/(h/L)$], where Fr is the Froude number and 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, 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. Frame and Markowski (2007) have also studied similar problems in a shear flow. TAMEX II will deploy resources (dropsonde 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 (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 2002; 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 synoptic flow patterns, the LLJ and barrier jets, and their mesoscale structures could not be addressed. TAMEX II will deploy resources to address these issues. 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.

3. Rainfall climatology

A rainfall climatology using Taiwan's Automatic Rainfall and Meteorological Telemetry System (ARMTS, 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. Daily rainfall exceeding 130 mm/day is more concentrated near the Snow Mountains and southern Taiwan. Extreme rainfall events (defined as rainfall exceeding 200 mm/day) essentially are confined to southern Taiwan, west of the CMR. A recent study (Peng 2006) identified 19 daily rainfall >200 mm events from 1997-2005 where six of these events had daily rainfall > 400 mm. On average, these extreme events occurred twice during each Mei-Yu season in southern windward slope, but year to year variability can be large. Examining extreme rainfall cases revealed that the heavy rainfall can occur on either the 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

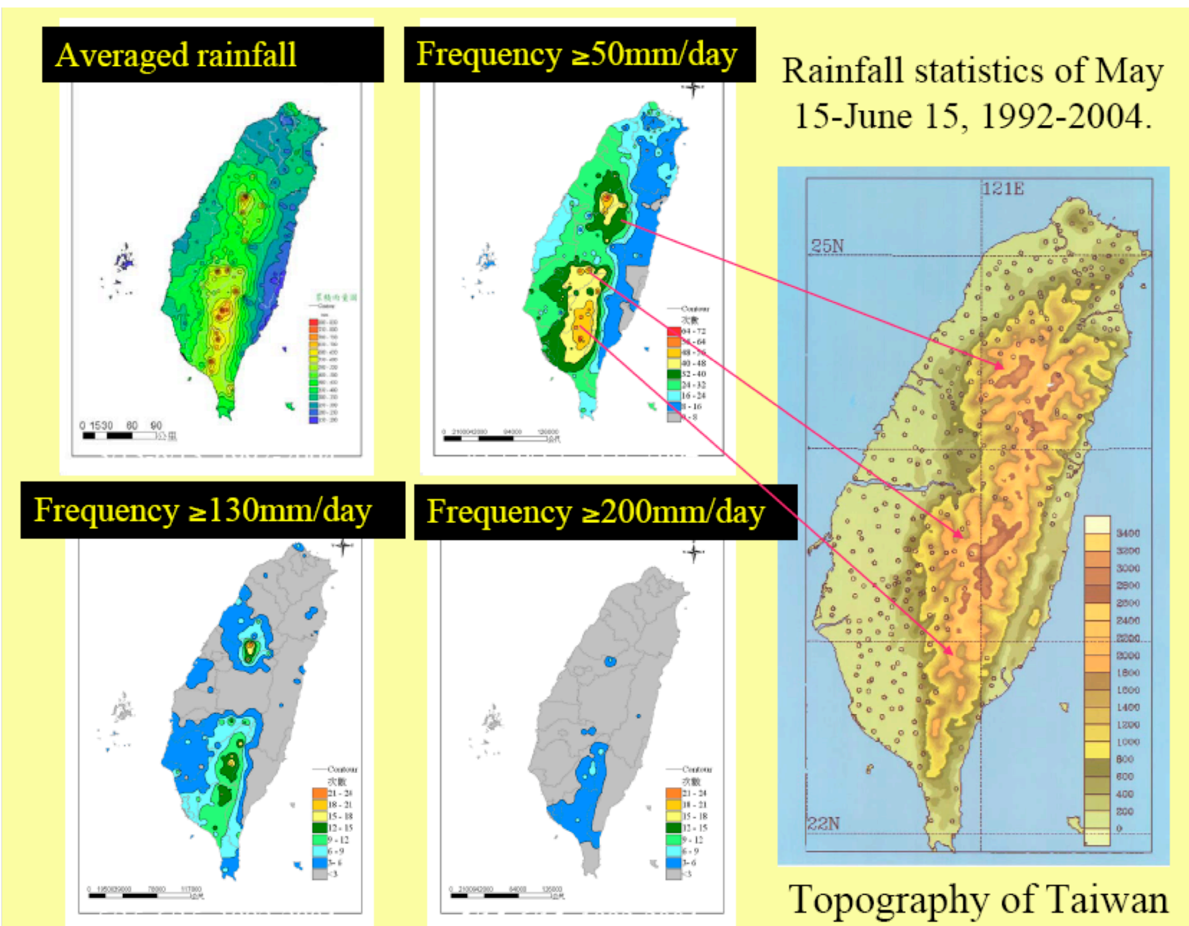

Figure 2. Rainfall statistics of 15 May-15 June from 1992-2004. The daily rainfall frequency in the 12 year period is subdivided into three categories, >50 mm, >130 mm, and >200 mm. The right panel illustrates the Taiwan topography and the locations of the ARMTS raingauges. The three arrows point to Snow Mountains (top), A-Li Mountains (middle), and Gao-Ping Xi valley (bottom).

southern Taiwan have been a significant challenge.

Both the hourly rainfall frequencies during TAMEX (Yeh and Chen 1998) and climatological heavy rainfall occurrences during the Mei-Yu season (hourly rainfall rate > 15 mm h^{-1}) (e.g., Chien and Jou 2004; Chen et al. 2007) indicate a pronounced afternoon maximum on the southwestern-facing slopes due to the development of anabatic winds under the prevailing southwesterly monsoon flow. The dense observing network in TAMEX II will allow us to study the evolution of island-induced airflow during the diurnal cycle under different synoptic settings, and the interactions between the island-induced airflow and the prevailing flow.

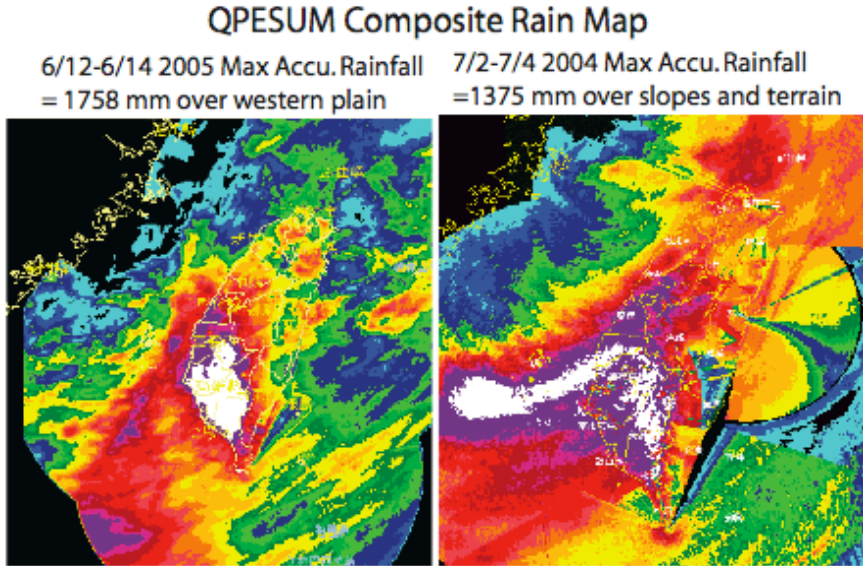

Figure 3. The 72 hours QPESUM (radar composite derived) rain map for two extreme heavy rain events in southern Taiwan. For the 2005 event (left panel), the maximum rain fell on the plains. For the 2004 event (right panel), the maximum rain fell on the western slopes of the CMR.

4. Scientific objectives

The main goals of TAMEX II are: (1) to investigate the effects of the large-scale (Mei-Yu front, LLJ), mesoscale (MCSs, orographic effects), local-scale and microphysical processes on the formation, development, maintenance, and regeneration of heavy rain events in southern Taiwan, and (2) to advance the 0-36 hour QPE/QPF skills in complex terrain. The NCAR S-Polka radar, when combined with two NOAA S-band rain profilers and existing operational and research facilities in Taiwan (Section 6), will provide comprehensive observations to study the dynamical and microphysical processes leading to the development of heavy rainfall. As an outgrowth of this work, model simulations of MCSs and their associated QPE/QPF should be improved as models begin to incorporate the improved physical processes leading to heavy rain. TAMEX II is organized around five scientific objectives as follows.

(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 LLJ. 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; Chen and Lin 2005a,b). These propagation characteristics can then dictate the precipitation distribution and amounts. These theories need to be further evaluated. The sounding data in TAMEX were not adequate to systematically evaluate the upstream flow characteristics. TAMEX II will help 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.

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

In TAMEX, dual-Doppler analysis in northern Taiwan explored 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. Furthermore, the island flow response and the rainfall distributions are sensitive to the upstream conditions and vary throughout the diurnal cycle. The TAMEX sounding network was not designed to study these features in detail. TAMEX II 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, 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. These boundary layer convergence zones or boundaries are important factors in the convective initiation and evolution process (e.g., Byers and Braham 1949; Wilson and Schreiber 1986; Lee et al. 1991; Wakmoto 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 TAMEX II, 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 low-level jet, or by orographic features. These results can then be compared to regions without the role of topographical forcing, such as Florida. The boundary-layer convergence lines over land will be characterized by the NCAR S-Polka and high resolution visible satellite imagery (e.g., Purdom 1982; Purdom and Marcus 1982), providing moisture information derived from the radar refractivity estimates (e.g., Fabry et al. 1997; Weckwerth et al. 2005; Weckwerth 2006), in addition to the reflectivity and Doppler velocity measurements.

(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 TAMEX II by retrieving ensemble microphysical properties using the polarimetric capabilities of the S-Polka and TEAM-R (Taiwan's mobile X-band, polarimetric) radars (e.g., Bringi et al. 1986; Seliga et al. 1986; Vivekanandan et al. 1990, 1994). Our approach to microphysical studies will consider a water budget perspective. We are particularly interested in determining the relative contribution that ice and warm rain processes make 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 TAMEX II. Our microphysical studies will be developed within a dynamical framework (afforded by dual-Doppler observations), as couplings between dynamics and microphysics are paramount in orographic precipitation. A framework for this analysis was recently presented by Medina et al. (2005) and Houze and Medina (2005). These two studies, from MAP and IMPROVE II, respectively, identified the role of small-scale convective cells, rich with liquid water, in enhancing precipitation via accretion growth. These convective scale cells were generated between highly sheared, stable, horizontal flows impinging on a topographic barrier (The Alps in the case of MAP, and the Cascade Mountains in IMPROVE II). We seek to investigate these mechanisms in TAMEX II, in particular, to see if this low level enhancement is present, or if the highly unstable upslope flow in the Taiwan area produces deeper convection, causing precipitation to grow over a deeper layer. 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 NOAA S-band rain profiler observations 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 are the impacts of scientific advancement in TAMEX II (e.g., upstream conditions, physical and microphysical processes of the orographic heavy precipitation systems, boundary layer processes) and data assimilation (e.g., radar, COSMIC, satellite, dropsonde, etc) on improving the predictability of heavy rainfall events, rainfall distributions, and the associated QPE/QPF skills in 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 be, to a large degree, attributed to the inadequate representation of microphysical processes and the lack of knowledge of the cloud and mesoscale structures of the environment in the numerical model. 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. TAMEX II 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. Scientific advancement through the TAMEX II field campaign and the subsequent analyses and modeling efforts is expected to provide an important framework for improving warm season QPF skill.

5. Numerical modeling and data assimilation

5.1 Mesoscale modeling

Mesoscale numerical modeling will play an important role in TAMEX II. Taiwan has the capability to run both Weather Research and Forecasting (WRF, Skamarock et al. 2005) and the fifth-generation Penn State/NCAR Mesoscale Model (MM5, Grell et al. 1994) at Central Weather Bureau (CWB) and various universities. At present time, 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 for QPF purposes (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 TAMEX II to provide guidance for daily operation including declaring IOP's, designing flight plan for the dropsonde aircraft, activating radar, rawinsonde, operational and research facilities, and TEAM-R deployment, etc. 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 TAMEX II.

High-resolution experimental numerical weather 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 TAMEX II. The high-resolution model will have the nested grid size down to 1 km in the TAMEX II area. Such activity will lead to improvement of the model for future operational 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

The initiation, development, internal kinematic and thermodynamic structures of mesoscale convective systems embedded within the Mei-Yu front and their interaction with the island orography of Taiwan is the key focus of this experiment. 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. The extensive coverage of dual-Doppler radar network can only provide 3D kinematic fields and limited thermodynamic information via dynamic retrieval. Therefore, radar data assimilation with a high-resolution model that optimally blends radar observations with other observations can be extremely valuable in producing dynamically consistent four-dimensional data sets for various diagnostic, modeling, and nowcasting studies.

The MM5 and WRF data assimilation systems (3DVAR, 4DVAR, and ensemble Kalman Filter) have been developed at the MMM division of NCAR, and can be used for such purposes. 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 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 3 km to 1 km. These data assimilation studies will be performed after the field operation. The simulated model parameters, such as reflectivity, air flow, hydrometer 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 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.

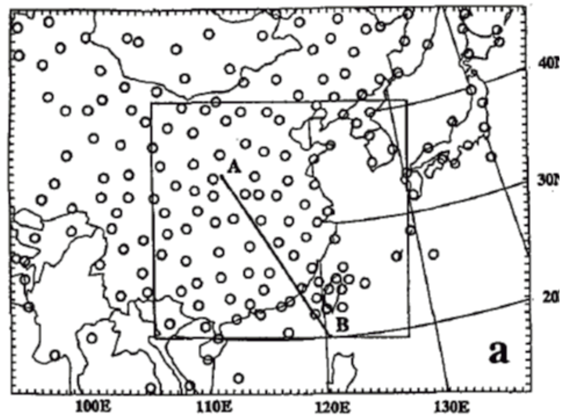

Figure 4. Upper air rawinsonde sites in East Asia.

6. Experimental design and observing facilities

6.1 Overview

TAMEX II 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 about 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 of the Mei-Yu front and MCSs. China is planning to hold a concurrent mesoscale experiment (CheREX) and the TIBET experiment near the TAMEX II time frame and increase the routine sounding frequency from 2 to 4 times daily in southern China. TAMEX II is working with China to obtain these data.

The operational facilities in Taiwan include surface stations, upper air stations, six operational Doppler radars, one boundary layer wind profiler, 418 automatic raingauges, 57

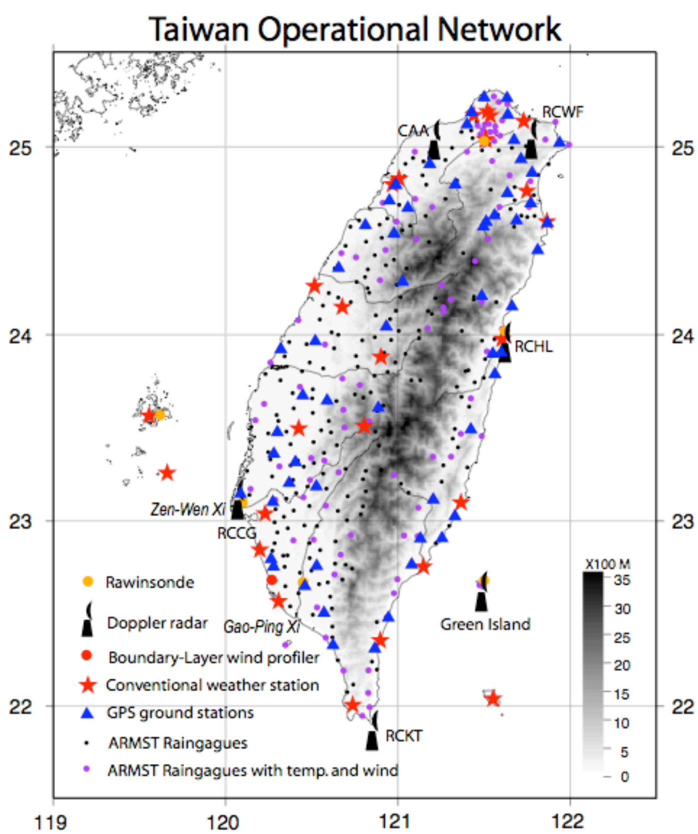

Figure 5. Taiwan operational network. Two major rivers are labeled at their entrance to the Taiwan Strait.

GPS integrated water vapor sensors, geostationary and polar orbiting satellites (Fig. 5). The TAMEX II observation region (115-123E, 20.0-26.0N) includes both the routine operation network and special observing stations and facilities. The routine operational 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 radars, one dropsonde aircraft, three aerosondes, one tethersonde, and one research vessel. A comprehensive list of the major research facilities are in Table 1. During TAMEX II, 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 TAMEX II is 8 hours behind UTC. 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.

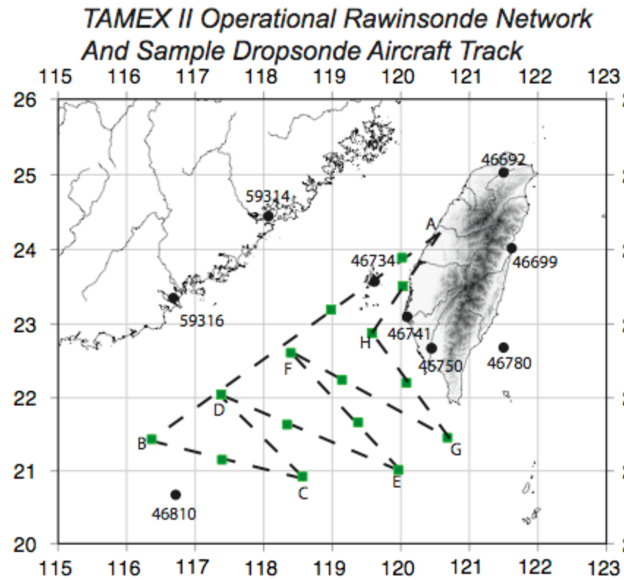

Figure 6. Operational rawinsonde network and sample dropsonde aircraft track. Dropsonde locations are green squares.

6.2 Experiment design and facilities

6.2.1 Upstream conditions

A research Vessel will be deployed to ~ (22N, 119E) about 200 km west of the southern tip of Taiwan (Fig. 7) 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 ~750 km hr^{-1} with maximum flight duration ~6 h and a ceiling of ~14 km. 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 that will be used in TAMEX II is illustrated in Fig. 6 in a racetrack segment ~300 km with dropsonde 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.

Table 1. Major observing facilities in TAMEX II 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 Managment		$300K	Taiwan (Central Weather Bureau)

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

6.2.2 Precipitation structures and microphysics

The TAMEX II outer radar domain consists of six operational Doppler radars in Taiwan (RCWF, RCHL, RCKT, RCCG, CAA, and Green Island) and a research C-band, polarimetric Doppler radar. Their characteristics are summarized in Table 2. These radars will be able to monitor convective development and precipitation systems up to 200 km off the coast of Taiwan, covering the entire Taiwan Strait. The NCAR S-Polka will be strategically placed ~60 km from the RCCG (Fig. 7) to form the primary dual-Doppler radar pair to sample the kinematic and microphysical structures of heavy precipitation systems in the primary TAMEX II study area. Smaller dual-Doppler radar domains can be formed by pairing the TEAM-R with either the RCCG, 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 and 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 RCCG and S-Polka (solid circles), S-Polka and TEAM-R (solid circles), and S-Polka and RTKT (dash circles) are indicated in Fig. 7

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.

Table 2 Characteristics of Doppler radars in TAMEX II.

Radar	Wavelength	Pulse Length	PRF	Peak Power	Beamwidth	Ant. Gain	Scan rate
RCWF	10 cm	1.57 &4.7 μs	318-1304 Hz	750kw	0.95	45dB	0-36°/s

RCHL, RCCG,RCKT	10 cm						
CAA	5.31 cm	1 & 2 μs	900 & 1200 Hz	250kw	1	43dB	12-36°/s
CCK	5 cm	0.8 & 2 μs	250 &1200 Hz	250kw	1.1	44dB	0-36°/s
Green Is.	5 cm	0.8 & 2 μs	250 &1200 Hz	250kw	1.1	44dB	0-36°/s
TEAM-R	3 cm						
S-Polka	10 cm	0.3-1.4μs	0-1300 Hz	>1Mw	0.91	44.05dB	0-18°/s

The clear-air mode will be in effect prior to the onset of deep convection (<30 dBZ in reflectivity). The objectives of this strategy are to characterize boundary layer circulations and their role in triggering convection by boundary-layer convergence. The scan sequence of ~6 minutes will involve a high-resolution dual-Doppler volume and a set of surveillance scans suitable for VAD analysis. During these scans, S-Polka will be operating in a non-polarimetric mode.

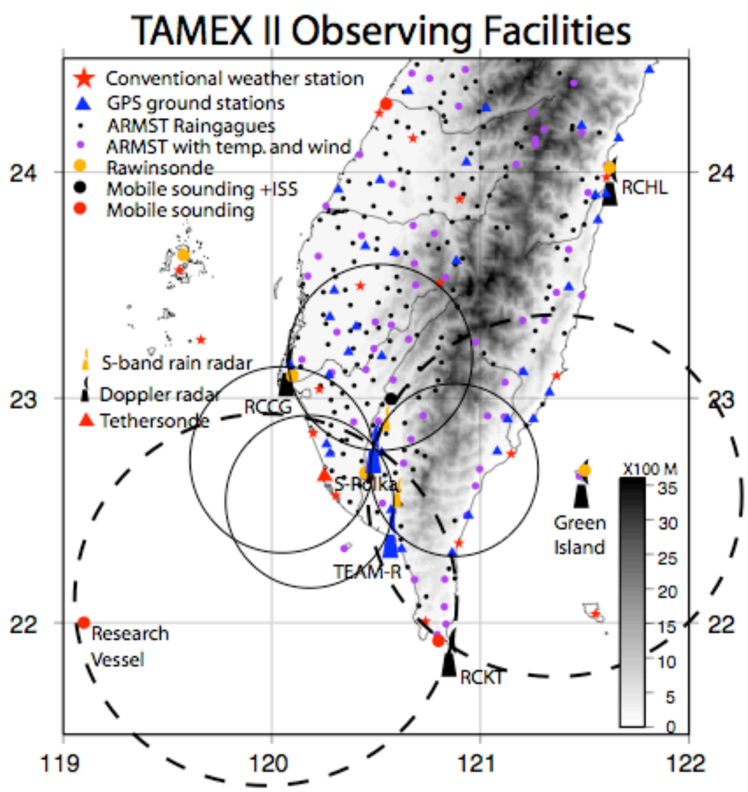

Figure 7. TAMEX II observing facilities.

The convective mode will be in effect once deep convection becomes established (> 30 dBZ in reflectivity) in the primary dual-Doppler lobe and will remain in effect during its entire evolutionary process. The objectives in the convective mode are more numerous and include the need for high space and time resolution dual-Doppler, polarimetric sampling, boundary layer monitoring, and rainfall mapping. The scan sequence of ~15 minutes will first involve a 3-4 minute high-resolution dual-Doppler volume where S-Polka is in a non-polarimetric mode[1]. Then, for the next 7-8 minutes, S-Polka will execute polarimetric scans over the same volume examined by the preceding dual-Doppler scans. For the remaining three minutes of the cycle, S-Polka will execute boundary layer monitoring and rainfall mapping scans in polarimetric mode. These scans will focus their attention over the land and the associated raingauge network. Both of these scan strategies allow for the applied scientific objectives of field testing precipitation algorithms, model verification, and assimilation of field data into high-resolution numerical models.

[1]It was determined that a meaningful dual-Doppler analysis could not be obtained if S-pol were scanning in its slower polarimetric mode.

7. Project and data management

Scientific planning and coordination will be carried out by the TAMEX-II Scientific Steering Committee (SSC). The SSC is responsible for the design, operation, and management of TAMEX II. 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. NCAR EOL will provide advice and some assistance in operations and data management activities during the project. Project Operations and Data Management Plans will be prepared.

7.1 Scientific Steering Committee

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

TAMEX II 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)
Jim Wilson (NCAR)	

7.2. Field operation center

The primary field operation center (OC) will be located at the CWB southern forecast center near RCCG in Tainan, Taiwan. The Operations Director (OD) and SSC will be responsible for the overall execution of TAMEX II field activities. 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, ISS, and shipboard soundings. The sounding coordinator will also work with OD and SSC on the dropsonde flight patterns. A sample proposed dropsonde aircraft track is given in Fig. 6. 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, RCCG, RCKT, and the TEAM-R, (2) deployment 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 potentially model output will be included as an aid to operations coordination of ground based mobile facilities. CWB will work with EOL staff to implement a TAMEX-II 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 TAMEX II.

7.3. Data Management and Data Policy

TAMEX II, 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 TAMEX II. CWB will work with EOL to develop a comprehensive data management plan, including data policies consistent with NSF (US) and other agencies (US 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 TAMEX II data available to the PIs and greater scientific community soon after the field phase.

The TAMEX-II 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.

TAMEX II proposes to (1) set up and maintain a project website in 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).

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