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Taiwan area heavy rain observation and prediction experiment (TAHOPE): overview and some scientific results

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Abstract

"Taiwan Area Heavy rain Observation and Prediction Experiment" (TAHOPE) was originally planned to be conducted from August 2019 to July 2022 to study Mei-Yu fronts, mesoscale convective systems (MCSs), landfalling typhoons and afternoon thunderstorms near Taiwan. The Prediction of Rainfall Extremes Campaign In the Pacific (PRECIP) team in the United States of America (USA) and the Tropical cyclone-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts (T-PARCII) team in Japan joined the TAHOPE team to conduct an international field experiment over northern Taiwan and Yonaguni Island from late May to early August 2020. The main themes of TAHOPE range from large-scale environmental influence, mesoscale convective systems as well as microscale cloud physics processes, under the special topography of Taiwan Island with steep terrain. To accomplish this international observation and forecast experiments, the TAHOPE project office was established to integrate the available observation instruments in Taiwan under the support from the Ministry of Science and Technology (MOST). The observation platforms (NOAA P3-aircraft, NCAR S-Pol radar, and CSU SEA-Pol radar) from the USA will combine with the Central Weather Bureau (CWB; Central Weather Administration, official name updated after 2024) operational facilities (radars, radiosondes, and DOSTAR dropsondes), and the atmospheric measurement (wind profiler) from the National Applied Research Laboratory (NARL) to perform intense field observations. However, due to the outbreak of the COVID-19 pandemic after February 2020, the deployment of S-Pol radar observation and intense upper-air measurements were delayed for two years. The field observations were conducted in Taiwan from 25 May

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[^]Cheng-Shang Lee: Deceased.

The institution's name "Central Weather Bureau" is changed to the Central Weather Administration after 15 September 2023.



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to 10 August of 2022, but the NOAA P3 aircraft observations were cancelled due to the COVID-19 pandemic and unforeseen aircraft mechanic issues.

Keywords TAHOPE · Mei-Yu front · Mesoscale convective system (MCS) · Afternoon thunderstorm

1 Introduction

During late spring to early summer (from mid-May to mid-June or July), East Asia experiences a climatological rainfall maximum outside the summer typhoon season, referred to as "Mei-Yu" in China and Taiwan, "Baiu" in Japan, and "Changma" in Korea (Chen and Chang 1980; Chen 1983). In this period, a quasi-stationary Mei-Yu front, oriented in the northeast-southwest or east-west direction and most pronounced at low levels, forms and extends from eastern China to southern Japan (Yang et al. 2000; Zhou et al. 2004).

From a synoptic perspective, the Mei-Yu front coincides with the early summer monsoon trough in East Asia, and its existence may be viewed as a manifestation of that monsoon trough (Chen 1983). A Mei-Yu front typically undergoes repeated development and decay, resulting in the successive formation of frontal cloud bands, and the cloudy zone can persist for several days to even a few weeks (Chen and Chang 1980; Hu et al. 2021). Along a Mei-Yu front, there are frequent occurrences of mesoscale convective systems (MCSs) within the frontal zone, resulting in heavy rainfall and flash floods (Chen et al. 2022; Miao et al. 2025, 2026).

Heavy rainfalls on Taiwan are mainly produced by the MCSs associated with Mei-Yu fronts, landfalling typhoons, and afternoon thunderstorms. Because of the steep terrain over the Central Mountain Range on Taiwan, extreme rainfalls over the mountain areas often induce floods, land- and mudslides, resulting in severe property damage and human casualties. Due to the increase of computational power for numerical models, improvement of physical parameterizations, and advancement of data assimilation systems, the quantitative precipitation forecast (QPF) skill of numerical models has been increased consistently. However, there are still deficiencies in the model QPF, largely because of the limited observational data and the lack of scientific understanding on the complex physical mechanisms producing the heavy rainfalls. In order to enhance the observational and prediction capability for the heavy rain-producing weather systems, a team of scientists with expertise in severe weather research in Taiwan was formed, including experts in academic and operational sectors, to propose an integrated proposal of Taiwan Area Heavy rain Observation and Prediction Experiment (TAHOPE) for 3 years from August 2019 to July 2022 (e.g., Yang 2020) to execute an international large-scale observation and prediction field campaign (and later the TAHOPE Phase II from August 2022 to July 2025).

The research topics of TAHOPE were quite extensive. These topics included the large-scale and synoptic-scale environmental influence (Chen 1983; Sui et al. 2020), MCS (Kuo and Chen 1990; Yang and Houze 1995a; b; Chien et al. 2002; Jou et al. 2011), typhoon circulation (Wu and Kuo 1999; Wu et al. 2005, 2022; Houze et al. 2007; Liou et al. 2016; Yang et al. 2018; Tsujino and Kuo 2020; Fang et al. 2024), convective-scale afternoon thunderstorm (Lin et al. 2011; Miao and Yang 2018, 2020, 2022; Miao et al. 2025, 2026), and cloud microphysics (Yang and Houze 1995b; Tao et al. 2011; Tsai and Chen 2020).

International cooperation with the TAHOPE team in Taiwan included the Prediction of Rainfall Extremes Campaign In the Pacific (PRECIP) team from the United States of America (USA), and the Tropical cyclone-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts (T-PARCII) from Japan. There were 18 scientists in TAHOPE team, 12 scientists in PRECIP team, and 4 scientists in T-PARCII team, respectively; in addition, two senior scientists served as the experiment consultants to provide comments and suggestions for the experiment design and scientific goals. A list of all experiment personnel and affiliation is given in Table 1.

The PRECIP team from the USA planned to deploy the NCAR S-Pol radar over the Hsinchu coast on Taiwan and the CSU SEA-Pol radar on Yonaguni Island (Japan); the NOAA P3 based on Kadena Air Base in Okinawa planned to conduct intra-typhoon penetration observations (IFEX-West). The additional observation platforms

Table 1 A list of all experiment personnel and affiliation

Team	Affiliation	Name
TAHOPE	National Taiwan University (NTU)	Ming-Jen Yang, Hung-Chi Kuo, Po-Hsiung Lin, Cheng-Shang Lee,
	Central Weather Bureau (CWB)	Ming-Dean Cheng, Kuo-Chen Lu, Po-Liang Chang, Tseng-Shi Huang
	National Central University (NCU)	Yu-Chieng Liou, Pay-Liam Lin, Ching-Yuang Huang, Kao-Shen Chung, Wei-Yu Chang, Shu-Chih Yang
	National Taiwan Normal University (NTNU)	Chung-Chieh Wang
	National Defense University (NDU)	Jou-Ping Hou
	Chinese Culture University (CCU)	Ching-Hwang Liu, Shih-Hao Su
PRECIP	Colorado State University (CSU)	Michael Bell, Kristen Rasmussen
	University of Hawaii (UH)	Yi-Leng Chen, Alison Nugent
	University of Wisconsin (UW) at Madison	Angela Rowe
	North Carolina A&T (NCAT)	Yuh-Lang Lin
	University of California (UC) at Davis	Shu-Hua Chen
	Penn State University (PSU)	Anthony Didlake
	University of Oklahoma (OU)	James Ruppert
	NSF National Center for Atmospheric Research (NCAR)	Wen-Chau Lee, Rosimar Rios-Berrios
	National Oceanic and Atmospheric Administration (NOAA)	Robert Rogers
TAPRC-II	Nagoya University	Kazuhisa Tsuboki, Taro Shinoda
	University of Ryukyus	Hiroyuki Yamada
	Kyoto University	Kosuke Ito
Consultants	National Taiwan University (NTU)	Jon-Dao Ben Jou
	NSF National Center for Atmospheric Research (NCAR)	Ying-Hwa Bill Kuo

from PRECIP and T-PARCII would incorporate with the operational observation facilities (radars, soundings, surface measurements, and dropsondes by DOTSTAR aircraft missions) in the Central Weather Bureau (CWB) and the wind profiler of the National Applied Research Laboratories (NARL) to jointly conduct an international observation field campaign (between Taiwan, Japan, and USA) over northern Taiwan and Yonaguni Island (Japan) in late May to early August of 2020. Any COSMIC-II satellite coverage periods overlap with some intense observational periods (IOPs) in TAHOPE, observational data could be used to calibrate the satellite retrieval algorithm and evaluate the data-assimilation and forecast impact of satellites launched by Taiwan's COSMIC-II satellite mission.

The TAHOPE project office had included six other sub-projects related to the observation analysis and data-assimilation impact studies, and other sub-projects related to real-time forecasts and evaluation had been included in the integrated project of Taiwan-Area Heavy rainfall Prediction Experiment (TAHPEX; Wang et al. 2026). TAHPEX was led by Chung-Chieh Wang at National Taiwan Normal University (NTNU). Both projects would support each other. Due to the global COVID-19 pandemic outbreak that occurred in February 2020, the international campaign of intense radar observation and sounding releases was postponed for two years until 25 May to 10 August 2022. The NOAA P3 aircraft observation was stopped due to the pandemic and mechanical issues.

2 Scientific hypotheses

The scientific hypotheses to be tested and verified in the TAHOPE field campaign include the following:

1. H1: The frontal lifting and thermodynamical instability associated with the Mei-Yu front play a key role in the generation of MCSs.

2. H2: The multiscale interactions of MCSs and Mei-Yu fronts are important for the heavy rainfall on Taiwan.
3. H3: Steep terrain on Taiwan enhances the coalescence-collision microphysics processes within the MCSs.
4. H4: Complex topography on Taiwan significantly affects the tracks, wind gusts, and accumulated rainfalls of landfalling typhoons.
5. H5: Cell mergers produced by prefrontal southwesterly flow and outflow from previous convective cells enhance convection intensity and cell duration.
6. H6: The highest rainfall accumulations come from moderate rates in long-lived MCSs supported by Mei-Yu frontal ascent, not from cells with high rain rate or weak widespread rain.

Although some of the hypotheses were examined in previous field experiments on heavy rainfall in Taiwan, such as the TAMEX in 1987 (Kuo and Chen 1990) and the SoWMEX/TiMREX in 2008 (Jou et al. 2010), none of the six scientific hypotheses were investigated in great details. In addition, the duration of TAHOPE lasted for 78 days, which were longer than those in TAMEX (60 days) and SoWMEX/TiMREX (47 days), so a wider spectrum of severe weather features (Mei-Yu front, MCS, afternoon thunderstorm, tropical depression, and typhoon) was observed and studied in TAHOPE.

3 Observational facility

To maximize the observation capability, after a series of meetings and discussions, scientists from Taiwan, Japan, and the USA reached an agreement on the setup and configuration (Fig. 1) of observational facilities as follows; the available observational instruments to be used to verify the scientific hypotheses are given in Table 2:

1) Yonaguni Island: CSU Sea-Pol C-band radar and Nagoya University Ka-band radar were located, upper-level Vaisala sounding was released, and surface measurement was observed.
2) Penjiayu CWB station: Upper-level Vaisala sounding and Storm-Tracker sounding were leased, and surface measurement was observed.
3) Benqiao CWB sounding station: Upper-level Vaisala sounding and Storm-Tracker sounding were leased.
4) Yilan Science Park: NTU X-Pol radar was operating. Unfortunately, data was not available due to hardware problem.

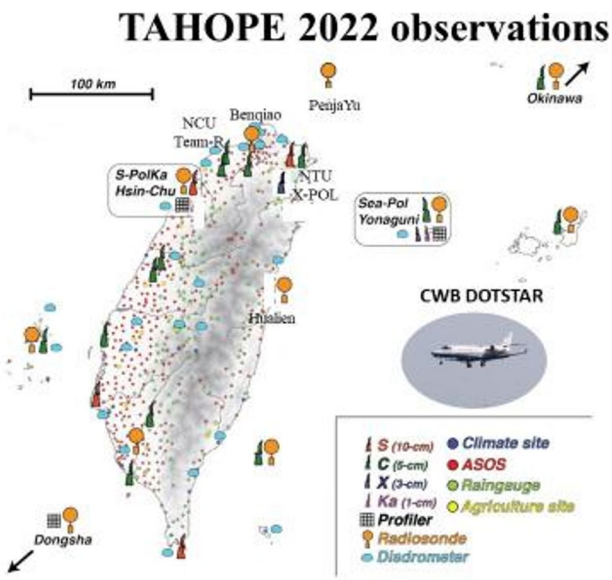


Fig. 1 The setup and configuration of TAHOPE observation facilities

Table 2 A list of all science hypotheses and observational instruments to be used to verify the hypotheses

Index	Science hypothesis	Observational instruments
H1	The frontal lifting and thermodynamical instability associated with the Mei-Yu front play a key role in the generation of MCSs	Satellite image, operational radars, two research radars (S-Pol and Team-R), sounding, surface observation
H2	The multiscale interactions of MCSs and Mei-Yu fronts are important for the heavy rainfall on Taiwan	Operational radars, two research radars (S-Pol and Team-R), sounding, surface observation, MPD profilers, rain gauges
H3	Steep terrain on Taiwan enhances the coalescence-collision microphysics processes within the MCSs	Operational radars, two research radars (S-Pol and Team-R), rain gauges
H4	Complex topography on Taiwan significantly affects the tracks, wind gusts, and accumulated rainfalls of landfalling typhoons	Satellite image, operational radars, two research radars (S-Pol and Team-R), sounding, wind profilers, surface observation, rain gauges
H5	Cell mergers produced by prefrontal southwesterly flow and outflow from previous convective cells enhance convection intensity and cell duration	Operational radars, two research radars (S-Pol and Team-R), sounding, wind profilers, surface observation, rain gauges
H6	The highest rainfall accumulations come from moderate rates in long-lived MCSs supported by Mei-Yu frontal ascent, not from cells with high rain rate or weak widespread rain	Operational radars, two research radars (S-Pol and Team-R), MPD profilers, surface observation, rain gauges

5) Yilan CWB station: Upper-air Vaisala sounding and Storm-Tracker sounding were leased, and NCAR MPD water vapor profiler was operating.
6) Hsinchu coast: the NCAR S-Pol radar and NDU radiometer were operating.
7) Hsinchu CWB station: The Auto Sound system was located to release upper-level Vaisala sounding and Storm-Tracker sounding, and the NCAR MPD water-vapor profiler was operating.
8) Taoyuan coast (Yongan fishing harbor): the NCU Team-R X-band radar, MRR radar, and raindrop disdrometer were operating.
9) NCU campus: the NCAR MPD water vapor profiler, NARL wind profiler, and surface measurement were operating.
10) Hualien CWB station: Upper-level Vaisala sounding and surface measurement were observed.
11) Pingtung CAF airport: Upper-level Vaisala sounding and surface measurement were observed.
12) Penghu CAF airport: Upper-level Vaisala sounding and surface measurement were observed.
13) Dongsha Island: Upper-level Vaisala sounding and surface measurement were observed.
14) CWB DOTSTAR flight: ASTRA aircraft would conduct dropsonde observation near typhoons (for 15 h). Unfortunately, the actual DOTSTAR flight did not execute in 2022 because of aircraft mechanical problems.

Note that the uniqueness of the TAHOPE field campaign is the availability of high-resolution MPD water-vapor vertical profiler, which was the first-time to be operated in the subtropics, and the unprecedented large-amounts of vertical profiles (more than 176,000 RHIs) for dual-polarimetric parameters, which could be used to infer the active microphysical processes.

4 Intensive operation period

The extensive operational period (EOP) for the TAHOPE/PRECIP/T-PARCII field campaign was from 25 May to 10 August 2022. The schedule of intense observation period (IOP) is shown in Table 3, and the schedule of special observation period (SOP) is shown in Table 4, respectively. The IOP stands for the period for severe weather and heavy rainfall with intense soundings released (every three or six hours), and the SOP stands for the period for severe weather and heavy rainfall but without extra soundings released (only the routine soundings at 00 UTC and 12 UTC). During the EOP, the TAHOPE operational center was located at the CWB headquarters; the TAHOPE team members met at 9:50 LST every day to have a weather briefing and future weather outlook,

Table 3 A list of IOPs during TAHOPE

Event	Period	Weather regime
IOP1	5/26 00 UTC – 5/28 00 UTC	Mei-Yu front and back-building MCS
IOP2	5/31 00 UTC – 5/31 12 UTC	Afternoon thunderstorm (radar echo top reached 16-km height over Yilan)
IOP3	6/06 06 UTC – 6/12 12 UTC	Quasi-stationary Mei-Yu front over Taiwan; backbuilding MCS over Miaoli; squall lines approached on 6/6 and 6/10
IOP4	6/15 00 UTC – 6/16 00 UTC	Southwesterly flow ahead of a weakening Mei-Yu front
IOP5	6/25 00 UTC – 6/25 15 UTC	Afternoon thunderstorm (deep convective cells over Taipei, Taoyuan, and Miaoli)
IOP6	7/01 00 UTC – 7/04 00 UTC	Heavy rainfalls associated with Typhoons Chaba and Aere in Japan (also heavy rainfalls over eastern and southern Taiwan)
IOP7	7/05 00 UTC – 7/05 04 UTC	Typhoon Area approached Kyushu (heavy rainfalls and floods in Kyushu and Honshu)
IOP8	7/13 06 UTC – 7/16 06 UTC	TD 90 W approached (heavy rainfalls in eastern and southern Taiwan)
IOP9	7/29 00 UTC – 7/29 12 UTC	TD approached (thunderstorms and lightning in northern Taiwan)
IOP10	8/01 00 UTC – 8/03 18 UTC	TD approached (heavy rainfalls over Taipei Basin, central and southern Taiwan)
IOP11	8/04 00 UTC – 8/04 12 UTC	Afternoon thunderstorm (Taipei Basin)

The IOP stands for the period for severe weather and heavy rainfall with extra intense soundings released. See Schumacher and Johnson for the definition of back-building MCS

Table 4 A list of SOPs during TAHOPE

Event	Period	Weather Regime
SOP1	5/25 00 UTC – 5/26 00 UTC	Mei-Yu front and MCS
SOP2	6/23 00 UTC – 6/24 00 UTC	Afternoon thunderstorm
SOP3	6/24 00 UTC – 6/25 00 UTC	Afternoon thunderstorm (hailstones in Taipei City)
SOP4	6/29 00 UTC – 6/30 00 UTC	Afternoon thunderstorm
SOP5	7/05 00 UTC – 7/06 00 UTC	Afternoon thunderstorm (Taipei Basin)
SOP6	7/06 00 UTC – 7/07 00 UTC	Afternoon thunderstorm (Taipei Basin)
SOP7	7/19 00 UTC – 7/20 00 UTC	Afternoon thunderstorm (Taipei Basin)
SOP8	7/20 00 UTC – 7/21 00 UTC	Afternoon thunderstorm (Taipei Basin)

The SOP stands for the period for severe weather and heavy rainfall but without extra soundings released (only the routine soundings at 00 UTC and 12 UTC)

and to discuss with scientists in PRECIP and T-PARCII teams in person and online to decide whether to call for an IOP on that day or the next day (Fig. 2). Once an IOP mission was decided after the online meeting, the CWB sounding stations on Penjiayu, Banqiao, Hsinchu, Yilan, and Hulein would launch extra soundings every 3–6 h, and research radars of S-Pol and Team-R would execute specific scanning strategies for target weather systems, and operational radars on Wufenshan (RCWF) and Taoyuan Airport (RCTP) would also adjust their scanning strategies accordingly if possible.

On 21 June 2022, CWB Director-General Dr. Ming-Dean Cheng led a group of CWB staff and TAHOPE/PRECIP scientists and students to visit the CWB Hsinchu weather station, S-Pol radar site at Hsinchu coast, and the Team-R radar site at Taoyuan coast (Fig. 3). On 5 July 2022, the Deputy Minister of Ministry of Science and Technology (MOST), Dr. Minn-Tsong Lin, led a group of MOST officials and media people to visit the S-Pol radar site and Team-R radar site, and provided comments and suggestions for the management plan of key observation platforms in the Atmospheric Science Department of MOST (Fig. 4).

The lists of IOPs in Table 3 and SOPs in Table 4 summarized various severe weather regimes during TAHOPE, including Mei-Yu front, MCS, afternoon thunderstorm, typhoon, and tropical depression (TD). Among the EOP of TAHOPE (25 May to 10 August 2022), most of typhoons and TDs either moved northward to Japan or westward to the Philippines, rather moved toward Taiwan directly. A noteworthy fact was that more active afternoon thunderstorms occurred during TAHOPE than in previous two years. Hailstones were even observed in the center of Taipei City (SOP3), a very rare event in the observation record in Taiwan.



Fig. 2 Daily weather briefing at the TAHOPE operational center in CWB headquarters. Photo taken on 13 June 2022. Note that scientists were wearing masks due to COVID regulation



Fig. 3 A group photo taken in front of the Auto Sound when CWB Director-General Dr. Ming-Dean Cheng (the fifth one from the right) was visiting the CWB Hsinchu weather station on 21 June 2022



Fig. 4 A group photo taken when MOST Deputy Minister Dr. Minn-Tsong Lin (the fifth one from the left) was visiting the S-Pol radar station at Hsinchu coast on 5 July 2022

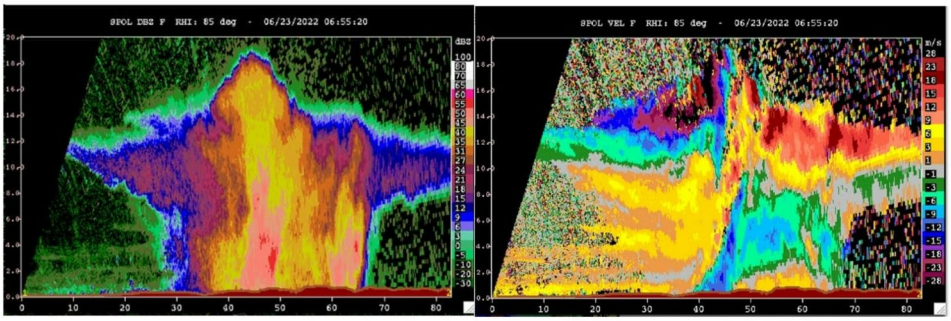


Fig. 5 RHI of radar reflectivity (in units of dBZ; left panel) and radial velocity (in units of m s^{-1}; right panel) along the 85-degree azimuth angle from S-Pol radar at 0655 UTC 23 June 2022 (SOP2)

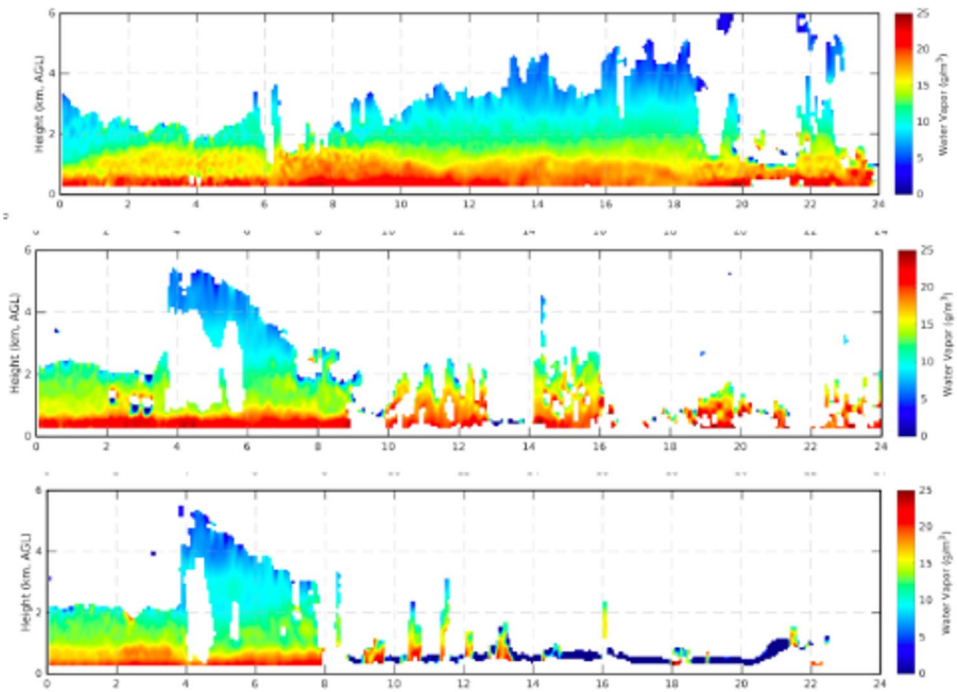


Fig. 6 The 24-h time series of low-level (below 6 km) water vapor profiles from MPD observations on 6 June 2022 (upper panel for Yilan station, middle panel for Hsinchu station, and lower panel for NCU campus)

The NCAR S-Pol radar observed many distinct weather features during TAHOPE. Figure 5 displays the vertical cross-sections of S-Pol observed radar reflectivity and radial wind for the afternoon thunderstorm systems above the Snow Mountain Range in SOP2. The 20-dBZ radar echo top reached 18-km height, overshooting cloud tops were observed on both sides of anvils (left panel of Fig. 5). Strong convergence occurred at low levels and divergence at upper levels for radial wind (right panel of Fig. 5). Similar radar features for thunderstorms with over-shooting echo tops were also found in other SOPs and IOPs, like the IOP2, SPO3, IOP5, SOP5, SOP7, IOP10, and IOP11. However, none of the CWB operational radars in Taiwan observed thunderstorms with such overshooting echo tops, possibly because of their fixed PPI scanning mode.

Figure 6 is the time series of vertical profile of moisture in low levels (below 6 km) observed by the NCAR MPD water-vapor profiler on 6 June during IOP3 at Yilan station (upper panel), Hsinchu station (middle panel), and NCU campus (lower panel), respectively. The time series show the evolution of low-level moisture when a Mei-Yu front approached Taiwan. The missing data indicates the observation period affected by rainfall. At 06 UTC, the water vapor amount at low levels (below 2 km) started to increase over Yilan (upper panel), implying the approach of a Mei-Yu front; at 08 UTC, missing date of moisture indicated the rainfall over NCU campus (lower panel); at 09 UTC, missing date of moisture indicated rainfall over Hsinchu station (middle panel). Comparing the moisture evolution between the Yilan (upper panel) and NCU campus (lower panel), the MPD data revealed that the signal of low-level moisture increase was ahead of precipitation observation by approximately

2 h. Because the MPD water-vapor profiler was first time operated in Taiwan (this TAHOPE field campaign in particular), more MPD observations would be needed to confirm whether the 2-hour lead-time between moisture increase and resulting rainfall was appropriate. Although we need more case studies to verify this 2-hour lead time in Taiwan, the MPD data is of great use for heavy rain monitoring and warning in real time.

Figure 7 displays the sounding data at CWB Hsinchu station at 00 UTC and 12 UTC of 3 July 2022 (IOP 6 case). On this day (3 July), Typhoon Aere was near Taiwan, and the thermodynamic condition was quite unstable; the convective available potential energy (CAPE) calculated from the 00 UTC sounding was 3100 J kg^{-1}, and the CAPE calculated from the 12 UTC sounding even reached 4000 J kg^{-1}. However, there were only minor scatter showers in Hsinchu. These facts suggested that when Typhoon Area was nearby Taiwan, the subsidence by the typhoon outer circulation suppressed the development of convection and reduced the chance for heavy rainfall on Taiwan, despite the high instability in the thermodynamic indices. Thus, the convection-triggering mechanism (either the Mei-Yu frontal lifting or the mesoscale convergence between the southwesterly monsoon flow and the land breeze or mountain breeze) is highly important; organized deep convection will only occur when the convection-triggering mechanism exists in a thermodynamically unstable environment.

The closing ceremony of TAHOPE/PRECIP/T-PARCII field campaign was held at the CWB head quarter in the morning of 10 August 2022; certificates and awards were presented to the volunteer weather forecasters (all undergraduate students from NTU, NCU, NTNU, and CCU). The lead-PI of TAHOPE, Ming-Jen Yang, was giving an overview summary for all the executed IOPs and SOPs; scientists (in Taiwan, Japan, and USA) participating the field campaign shared their thoughts and comments; students who volunteered as weather forecasters shared what they had learned from the daily weather briefings. Finally, a group photo was taken at the closing ceremony (left panel of Fig. 8) with all the scientists, students, and CWB employee in Taiwan; PIs from Taiwan, USA, and Japan (some of them participating online) took another group photo (right panel of Fig. 8).

5 Some scientific results

Some scientific results from the TAHOPE/PRECIP IOPs and SOPs have been published or are in the review for publication in academic journals and conferences. The main results are briefly summarized as follows:

1) IOP2 case: In response to H5 (see Table 2), Miao et al. (2025) examined the S-Pol radar data for the convection organization of the IOP2 heavy-rain case and found multiple cell merger (MCM) favored by terrain-induced circulation over the Snow Mountain Range. Around the time of MCM, the enhanced Z_{DR} region (> 1

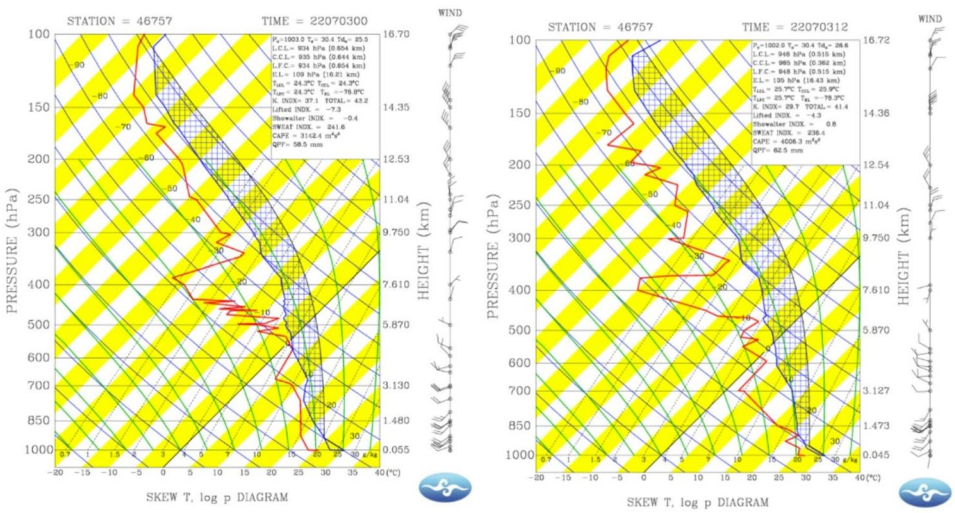


Fig. 7 The soundings with thermodynamic indices at the CWB Hsinchu station at 00 UTC and 12 UTC of 3 July 2022 (IOP 6 case)



Fig. 8 A group photo with all scientists, students, and CWB staff at the closing ceremony on 10 August 2022 (left panel); another photo of TAHOPE PIs with the PIs in PRECIP and T-PARCII (right panel)

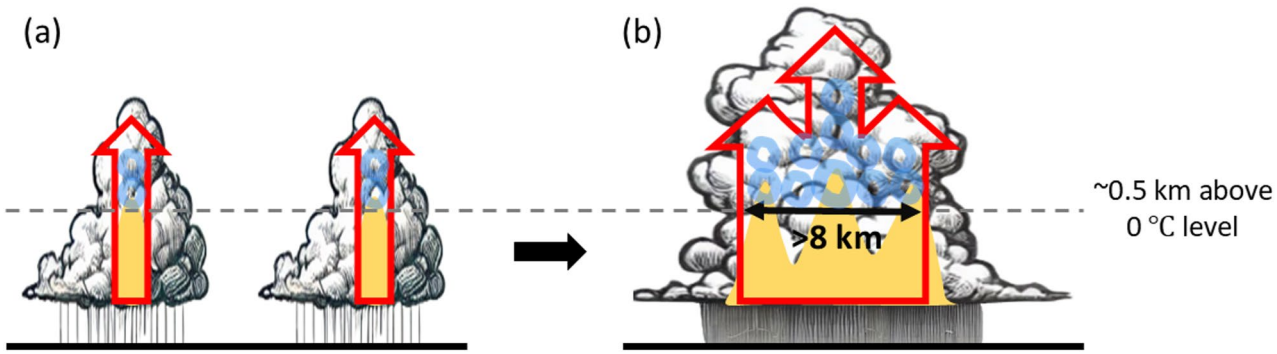


Fig. 9 Conceptual diagram illustrating changes in Z_{DR} column structure associated with multiple cell mergers in IOP2 case. (**a**) Before the merger, individual convective cells contain distinct Z_{DR} columns (yellow), each associated with localized updrafts (red). (**b**) After multiple cell mergers, the updrafts merge, along with the development of a wide (> 8 km) enhanced ZDR region (> 1 dB) at 5.5 km altitude (~ 0.5 km above the 0 °C level). From Miao et al. (2025)

dB) broadened horizontally to ~ 8 km in width at 5.5 km above mean sea level (about 0.5 km above the melting level; see Fig. 9). Afterward, maximum vertical velocity increased dramatically to ~ 20 m s^{-1} and graupel particles could reach up to 12-km height.

Miao et al. (2026) further examined the moist absolutely unstable layer (MAUL) and terrain effect of this case, in response to H2 and H3. Through high-resolution numerical sensitivity experiments (nested-down to 1.5-km horizontal grid spacing) with and without the Taiwan terrain, they found that terrain could induce MAULs and enhance extreme rainfall in mountainous areas over northern Taiwan. The terrain-driven moisture convergence and layer lifting promoted deeper and more persistent MAULs (Fig. 10); removing the terrain substantially limited the MAUL development, resulting in weaker less rainfall (see their Fig. 3).

2) IOP3 case: Yang et al. (2024) investigated the physical mechanism of a heavy rainfall event on 6–7 June during IOP3, which could address H2 in Table 2. A multiscale radar ensemble data assimilation system was used to derive a high-resolution analysis for forecasts. Two numerical experiments were conducted with the use of convective-scale (RDA) or multiscale (MRDA) corrections in the assimilation of the radial velocity from the CWB's Chigu (RCCG) and Wufenshan (RCWF) radar and NCAR S-Pol radar. Comparisons between two experiments showed that the MRDA had large-scale wind corrections, reshaped and relocated a low-level mesoscale vortex, resulting in a better 6-h rainfall prediction (compared to RDA). This study demonstrated the added-value of assimilating winds from CWB Chigu and NCAR S-Pol radar to better represent low-level mesoscale vortex, convergence zone, and surface rainfall (Fig. 11).

Liao and Yang (2025) analyzed a squall line event which developed over the Taiwan Strait and made landfall on northern Taiwan at 06–07 UTC on 6 June during IOP3, also in response to H2. Using the wind retrieval method of

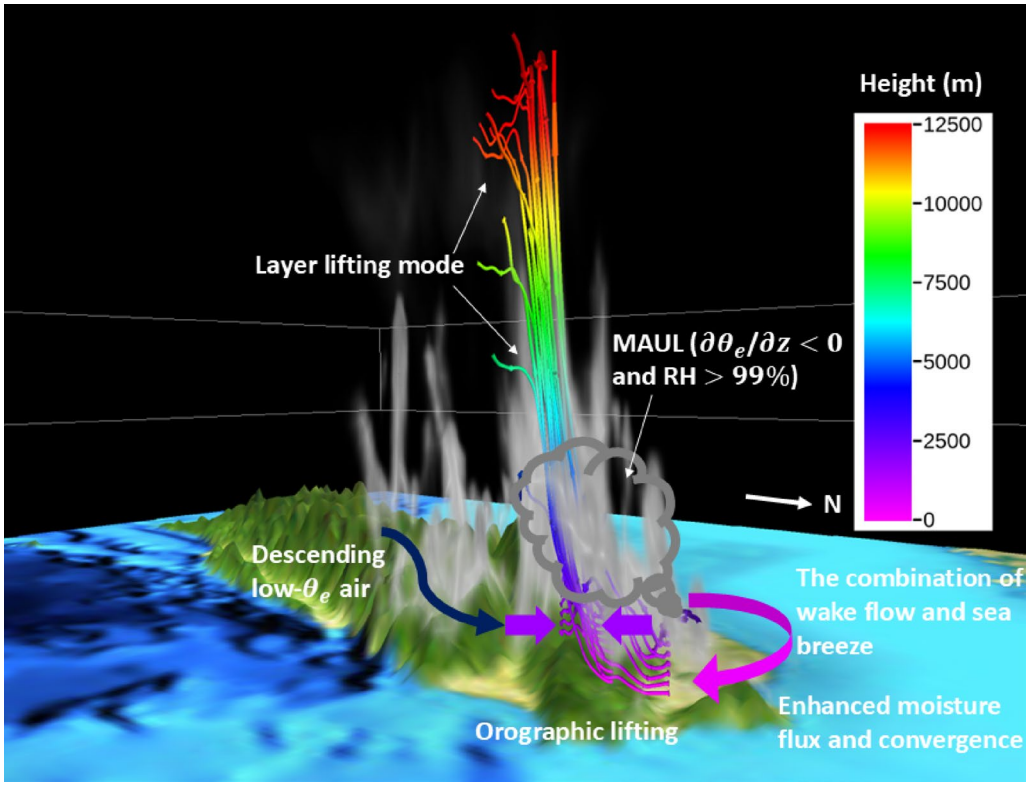


Fig. 10 Conceptual model illustrating the formation of terrain-induced MAUL and the enhancement of orographic rainfall in IOP2 case. From Miao et al. (2026)

the Spline Analysis at Mesoscale Utilizing Radar and Aircraft Instrumentation (SAMURAI; Bell et al. 2012; Cha and Bell 2023) with data from radars at S-Pol, Taoyuan airport (RCTP), and Shu-Ling (RCSL), a strong southwesterly flow with an evident barrier jet ahead of the squall line, and westerly and northwesterly flows behind the squall line were found (Fig. 12). Numerical sensitivity experiment with half and no Taiwan terrain showed that there would be weaker barrier jet and less convection development, compared to the simulation with full Taiwan terrain (figure not shown).

To examine H1 and H2 in Table 2, Zhu and Yang (2026) compared the synoptic and mesoscale forcing conditions for Mei-Yu fronts during the SOP1 and IOP3 cases. Two Mei-Yu fronts at 975 hPa were similarly positioned over the central to northern Taiwan Strait, but the total precipitation over northern Taiwan in SOP1 was three times that in IOP3. The IOP3 case exhibited a steeper frontal slope, greater front intensity, and strong synoptic forcing. Moreover, the SOP1 event had more favorable thermodynamic condition, stronger mesoscale kinematic structure, and higher low-level liquid water content (table not shown). Consequently, these factors resulted in higher accumulated rainfall in SOP1 than that in IOP3, suggesting that the resultant rainfall was not solely determined by the structure and intensity of the synoptic-scale Mei-Yu front, but rather the combined effects of environmental moisture and mesoscale-to-convective scale processes.

3) IOP1 and IOP3 cases: To address H6 in Table 2, DeHart and Bell (2025) investigated the relationships between dynamics and rainfall intensity in two Mei-Yu frontal periods (IOP1 and IOP3) during the TAHOPE/PRECIP. Observation statistics from oceanic rainfalls over the Taiwan Strait showed a mean increase and a positive shift of the distributions of vertical vorticity, vertical motion, and divergence with increasing rainfall (Fig. 13). Stratiform rainfall points were frequent in light rain rates below 5 mm h^{-1} but contributed little to the total rainfall. Convective (heavy) rainfall rates at 10–50 mm h^{-1} existed for only 6% of the total observed raining points over the Taiwan Strait, but contributed more than 45% of the total volumetric rainfall.

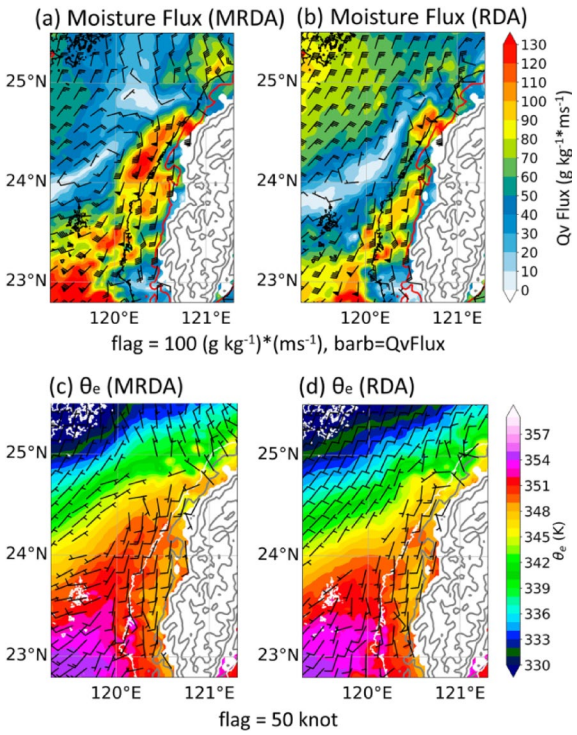


Fig. 11 (**a**) MRDA and (**b**) RDA moisture fluxes at 975 hPa at 03 UTC 7 June of IOP3. The wind barbs and equivalent potential temperature of (**c**) MRDA and (**d**) RDA analyses at 03 UTC 7 June. From Yang et al. (2024)

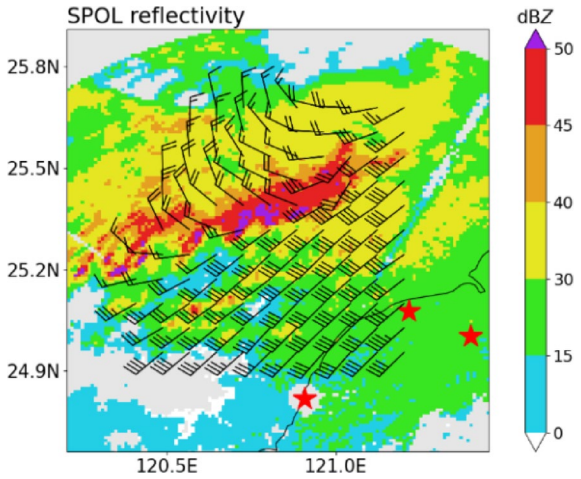


Fig. 12 Radar reflectivity (colored; in units of dB*Z*) observed by S-Pol and the derived horizontal winds at 1-km height at 0548 UTC 6 June of IOP3. Stars indicated the radar locations of S-Pol, RCTP, and RCSL. From Liao and Yang (2025)

4) SOP4 case: To verify H2 and H3 in Table 2, Liu et al. (2026) examined the evolution and characteristics of a quasi-linear MCS over central Taiwan during SOP4. Using the dual-polarization Doppler radar data from S-Pol, surface observation, and the SAMURAI wind retrieval technique, this study investigated storm structure evolution, vorticity development, and microphysics. Observational analysis showed that this 90-km-long line-type MCS exhibited a bow-shaped echo with enhanced rainfall and a pronounced cold pool. The bow-shaped echo was produced by the cold-pool-induced horizontal buoyancy gradients, which generated horizontal vorticity that was further tilted and stretched by low-level updrafts into vertical vorticity couplets (Fig. 14).

6 Concluding remarks

The TAHOPE/PRECIP/T-PARCII field campaign was conducted successfully from 25 May to 10 August 2022, despite the two-year delay due to the COVID-19 pandemic. The unique features of the TAHOPE/PRECIP/T-PARCII field experiment include:

- First deployment of NCAR MPD water-vapor profiler in Taiwan.
- First land-based deployment of CSU SEA-Pol radar on Yonaguni Island, Japan.
- First international field campaign on Mei-Yu fronts, MCSs, afternoon thunderstorms, and typhoons.

All six proposed scientific hypotheses (see Table 2) were verified by detailed examination and analyses of the collected observation data within 11 IOPs (Table 3) and 8 SOPs (Table 4) during the TAHOPE/PRECIP/T-PARCII field campaign, except for hypothesis H4 because there were no landfalling typhoons to Taiwan during the field

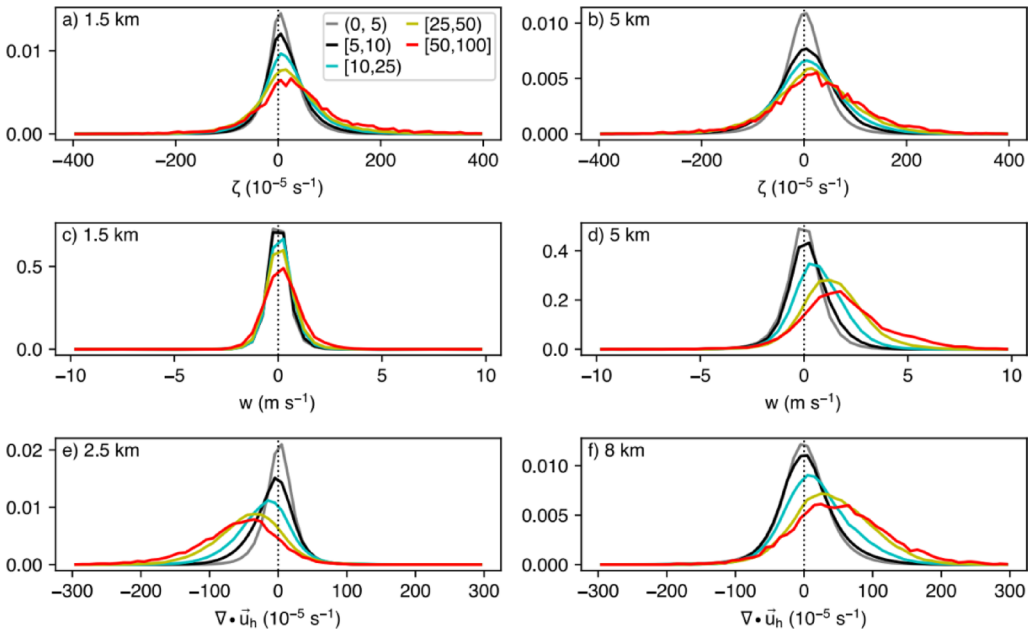


Fig. 13 (**a**) Normalized probability distributions of vertical vorticity (10^{-5} s^{-1}) for rain rates between 0–5, 5–10, 10–25, 25–50, 50–100 mm h^{-1} at 1.5-km altitude. (**b**) As in (**a**), but at 5 km. (**c**, **d**) As in (**a**, **b**), but for vertical velocity (m s^{-1}). (**e**, **f**) As in (**a**, **b**), but for divergence (10^{-5} s^{-1}) at 2.5 and 8 km. From DeHart and Bell. (2025)

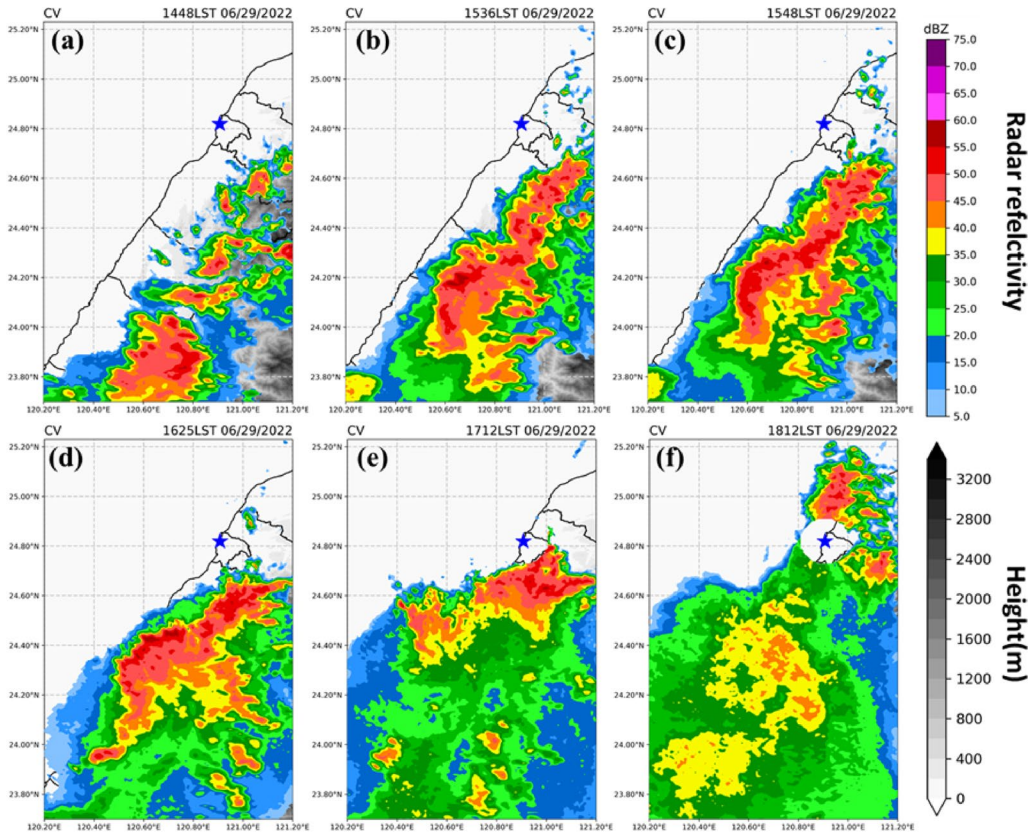


Fig. 14 Composite radar reflectivity from the S-Pol at 2-km altitude. The blue star indicates the location of the S-Pol radar site. Panels: (**a**) 1448, (**b**) 1536, (**c**) 1548, (**d**) 1625, (e) 1712, and (**f**) 1812 UTC. From Liu et al. (2026)

experiment. One unique finding was that the boundary-layer lifting in moisture-rich environment surrounding Taiwan played a critical factor (Miao et al. 2025, 2026). When the southwesterly flow accompanying with abundant moisture encountered the cold-air outflow by previous convection over the mountain slope, continuous triggering and merging of deep convective cells resulted in heavy rainfall and flash floods. The strength and position of the Mei-Yu frontal forcing were essential, but the combined effects of environmental moisture and mesoscale to convective processes determined the local accumulated rainfall amount (Zhu and Yang 2026). Formation of a quasi-linear convective system with vorticity couplet could result from the complex interactions between diurnal heating and cold-pool dynamics, where the cold-pool-induced horizontal buoyancy gradients generated horizontal vorticity which was further tilted by differential solar heating and stretched by low-level updrafts into vertical vorticity couplets (Liu et al. 2026). Although the diurnal heating was very predictable in some IOP cases, it was also irregular in other cases which resulted in miss-forecasts in the SOPs. For example, a low-level mesoscale vortex (offshore of western central Taiwan) produced by differential heating over the Taiwan Strait and central Taiwan, was not forecasted by operational models during IOP3. After the assimilation of radial velocity data from the operational radars at Chigu (RCCG) and Wufenshan (RCWF), this mesoscale vortex and convergence zone were successfully reproduced and the resulting heavy rainfall was better forecasted (Yang et al. 2024). More detailed studies and analyses are required to fully understand the complex interactions between the synoptic, mesoscale, convective processes, and even microphysical processes.

Finally, over 1,341 soundings were released during the TAHOPE/PRECIP/T-PARCII field campaign and more than 200,000 radar RHIs were already quality-controlled and composited into comprehensive profiles of polarimetric radar information. The TAHOPE dataset are now archived in an official databank in Taiwan, and are available for everyone to use upon request, including the domestic and international severe weather and climate community. More research outcomes and scientific results from the TAHOPE dataset will be reported in Master and PhD theses and journal articles in the future.

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Author contributions MJY provided the research founding and experimental design; MDC, KCL, PLC, TSH, JPH provided the operational observation data; YCL, MMB, KT , KSC, and WYC provided the radar data; PLL, PHL, CHL, SHS provided the sounding data; MJY, PLL, CYH, SCY, and CCW provided the model data; all authors reviewed the manuscript.

Data availability The TAHOPE data have been archived in the Atmospheric Science Research and Application Databank (ASRAD; https://www.asrad.pccu.edu.tw/dbar), which is supported by the National Science and Technology Council (NSTC) in Taiwan. Data access complies with the ASRAD's data release regulations.

Declarations

Competing interests The authors declare no competing interests.

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