

**The Role of Moist Absolutely Unstable Layer (MAUL) in Orographic Precipitation:
A Case Study from TAHOPE IOP 2**

**Ming-Jen Yang¹楊明仁, Jyong-En Miao¹繆炯恩,
Kristen Rasmussen², and Michael Bell²**

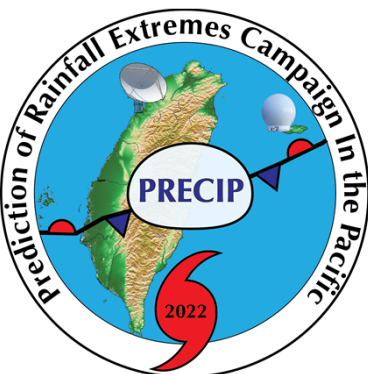
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114年第三十九屆天氣分析與預報研討會

台北市

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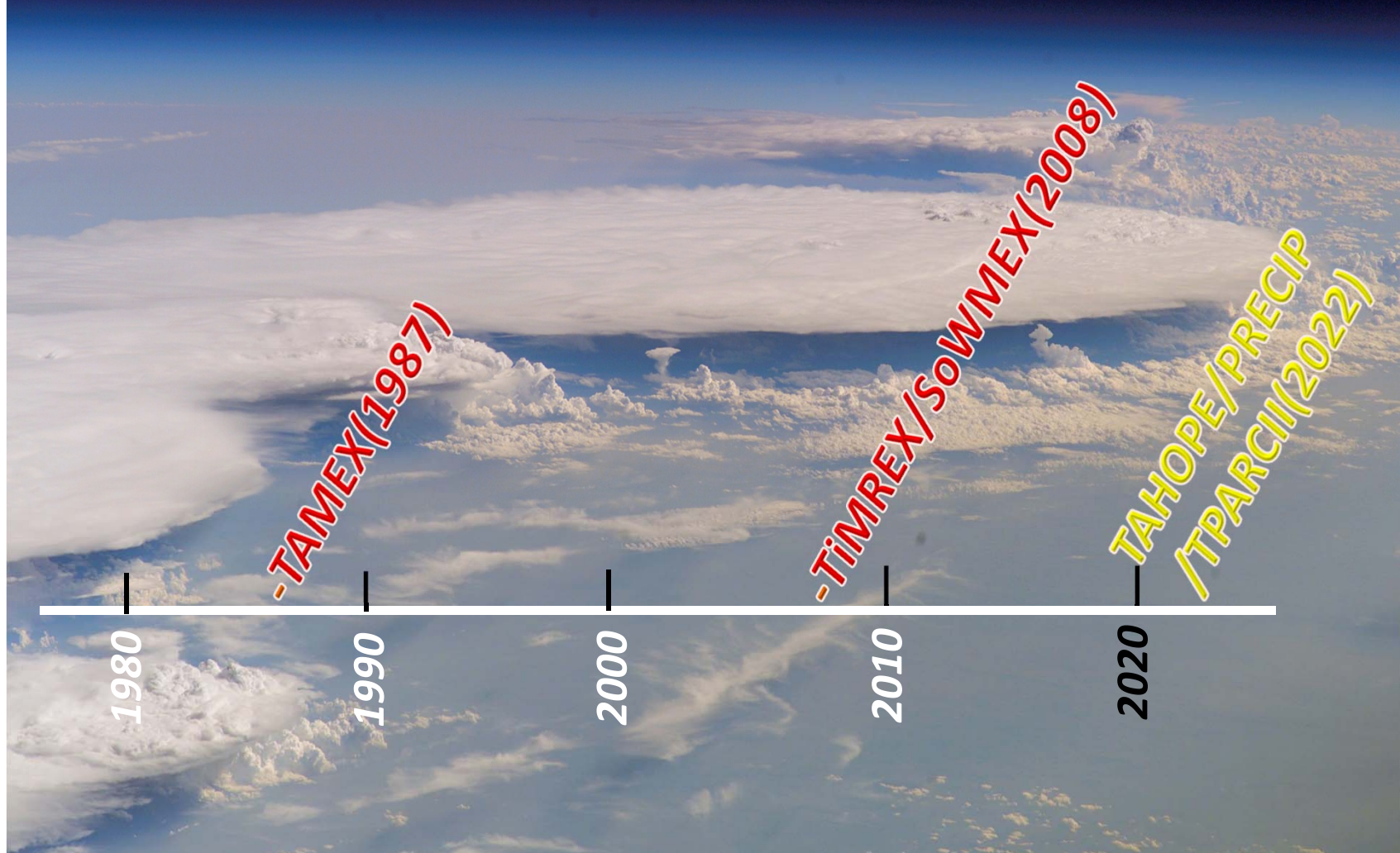
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NAR Labs
國家實驗研究院
National Applied Research Laboratories



NSTC 國家科學及技術委員會
National Science and Technology Council

International Field Campaigns on Taiwan Investigating Extreme Rainfall





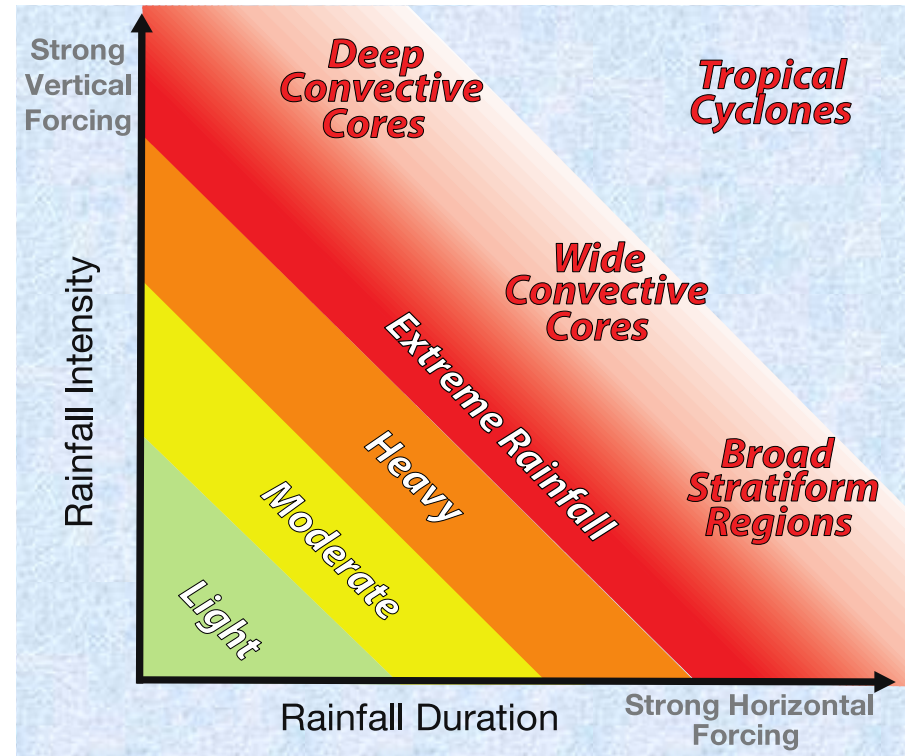
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- **Primary objective** is to simplify complexity of multi-scale interactions by identifying key ingredients and processes in the two limiting cases of high intensity and long duration events in a **moisture-rich environment**

NCAR S-Pol



NCU TEAM-R

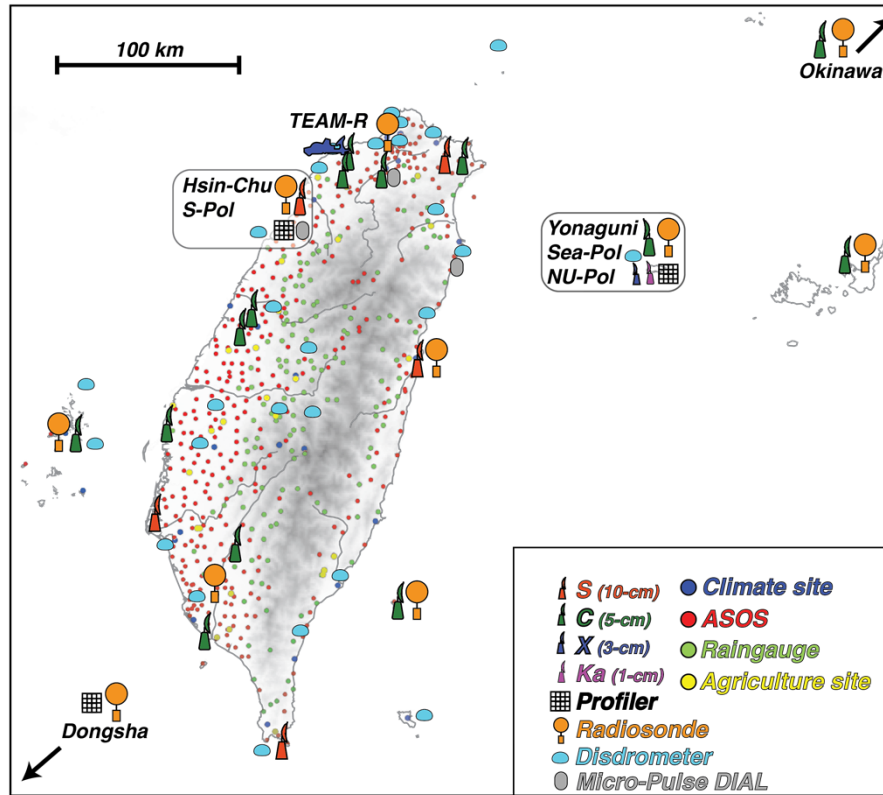


NCAR MPD



**TAHPOPE/
PRECIP/
T-PARCII
~~2020~~ 2022**

--Endorsed by WMO



CSU Sea-Pol

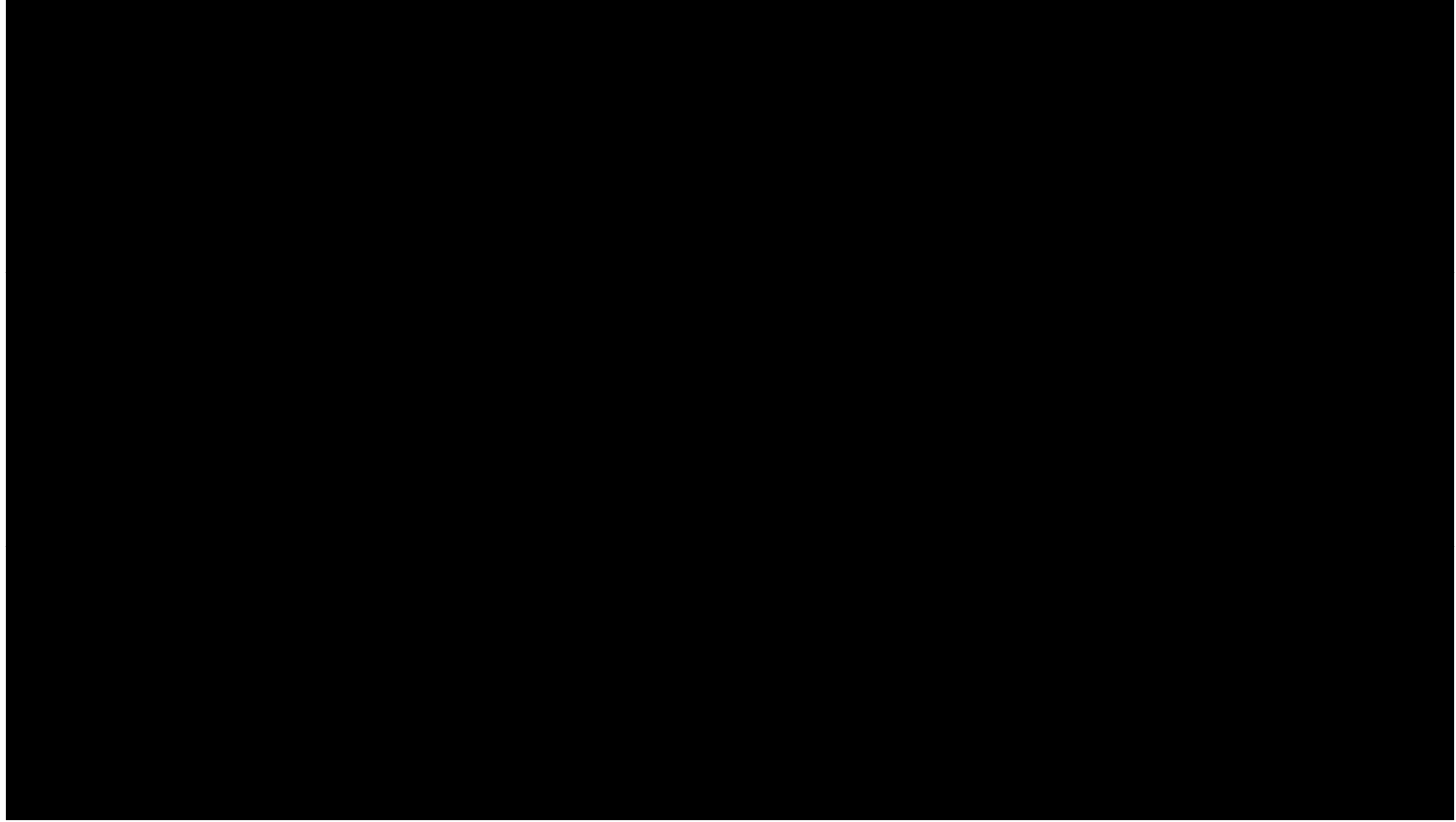


NAGOYA NU-POL



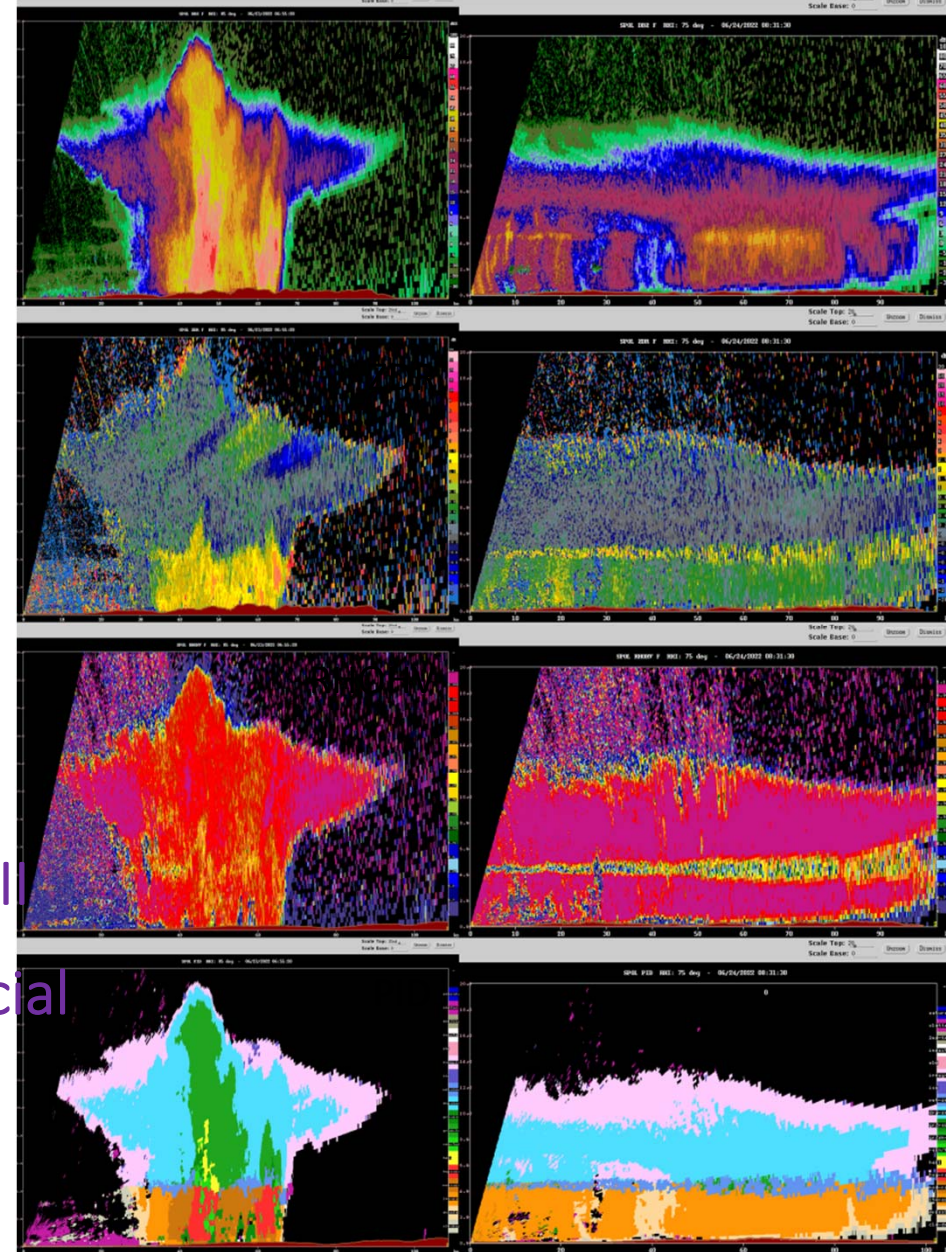
TAHOPE/PRECIP 2022

Radar Setup, Sounding Release, Weather Briefing, Closing Ceremony



Over 286,000 RHI scans in 2022

- S-Pol operated from 5/25 – 8/10 (78 days)
 - Over 176,000 RHIs
- SEA-POL operated from 6/10 – 8/22 (74 days)
 - Over 100,000 RHIs
- TEAM-R operated from 5/15 – 7/31 (78 days)
- 3 MPDs operated from 5/28 – 8/10 (75 days)
- 1,341 soundings from TAHOPE/PRECIP/T-PARCI
- 11 Intensive Observing Periods (IOPs) & 8 Special Observation Periods (SOPs)



List of IOPs & SOPs during TAHOPE 2022 (5/25 to 8/10 : 11 IOPs & 8 SOPs)

	Period	Description
SOP1	5/25 00Z – 5/26 00Z	Mei-Yu front and MCS
IOP1	5/26 00Z – 5/28 00Z	Mei-Yu front and MCS (Backbuilding MCS on 5/26)
IOP2	5/31 00Z – 5/31 12Z	Afternoon thunderstorm (Thunderstorms with seep echo top of 16-km over Yilan)
IOP3	6/06 06Z – 6/12 12Z	Quasi-stationary Mei-Yu front on Taiwan (Backbuilding MCS over Miaoli; a squall line approaching northern Taiwan on 6/10)
IOP4	6/15 00Z – 6/16 00Z	Prefrontal southwesterly in a weakening Mei-Yu front (Dry air intrusion at low level over northern Taiwan)
SOP2	6/23 00Z – 6/24 00Z	Afternoon thunderstorm
SOP3	6/24 00Z – 6/25 00Z	Afternoon thunderstorm (Hail case at Taipei Basin)
IOP5	6/25 00Z – 6/25 15Z	Afternoon thunderstorm (Intense thunderstorms over Taipei, Taoyuan, and Miaoli)
SOP4	6/29 00Z – 6/30 00Z	Afternoon thunderstorm
IOP6	7/01 00Z – 7/04 00Z	Rainfall associated with TC Chaba and TC Aere (Heavy rainfall on eastern and southern Taiwan)

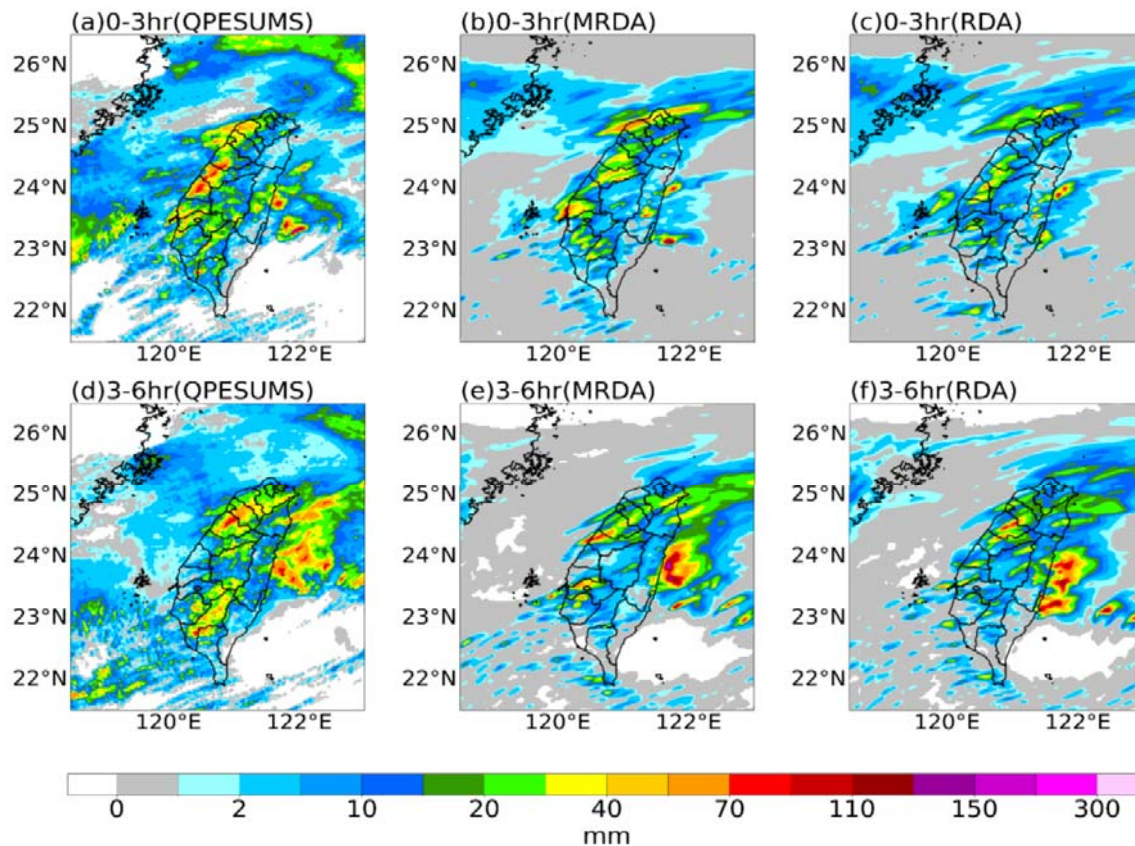
List of IOPs & SOPs during TAHOPE 2022 (5/25 to 8/10 in Year 2022: 11 IOPs & 8 SOPs)

IOP7	7/05 00Z – 7/05 04Z	Typhoon Aere approaching Kyushu with dropsondes observation (Heavy rainfall over Kyushu and Honshu)
SOP5	7/05 00Z – 7/06 00Z	Afternoon thunderstorm at Taipei Basin
SOP6	7/06 00Z – 7/07 00Z	Afternoon thunderstorm at Taipei Basin
IOP8	7/13 06Z – 7/16 06Z	Rainfall associated with TD 90W (Heavy rainfall on eastern and southern Taiwan)
SOP7	7/19 00Z – 7/20 00Z	Afternoon thunderstorm at Taipei Basin
SOP8	7/20 00Z – 7/21 00Z	Afternoon thunderstorm at Taipei Basin
IOP9	7/29 00Z – 7/29 12Z	Moisture transport by low pressure and afternoon thunderstorm (Heavy rainfall in the evening; thunderstorms and lightning over northern Taiwan)
IOP10	8/01 00Z – 8/03 18Z	Moisture transport by low pressure (Heavy rainfall in Taipei Basin, central and southern Taiwan)
IOP11	8/04 00Z – 8/04 12Z	Afternoon thunderstorm (Thunderstorms in Taipei Basin)

備註：

IOP (intensive observation periods) 為有劇烈降水天氣且有額外密集觀測之個案。

SOP (special observation periods) 為有劇烈降水天氣，但沒有額外密集觀測之個案(無探空加放)。



Source:
 Prof. Shu-Chih Yang (NCU) &
 Prof. Shu-Hua Chen (UC Davis)

**Assimilating the S-Pol radar
 data improves the QPF skill!**

Fig. 7. Three-hourly accumulated rainfall from (top) 0300 to 0600 UTC and (bottom) 0600 to 0900 UTC on 7 June from (a, d) QPESUMS and model forecasts from (b, e) MRDA and (c, f) RDA initialized by the ensemble analysis mean at 0300 UTC on 7 June.

Yang, S.-C., S.-H. Chen, L. J.-Y. Liu, H.-L. Yeh, W.-Y. Chang, K.-S. Chung, P.-L. Chang, and W.-C. Lee, 2024: Investigating the mechanisms of an intense coastal rainfall event during TAHOPE/PRECIP-IOP3 using a multiscale radar ensemble data assimilation system. *Mon. Wea. Rev.*, 152, 2545-2567.



RESEARCH ARTICLE

10.1029/2024JD042375

Key Points:

- Multiple convective cell mergers favored by terrain-induced circulation led to intense updrafts and extreme rainfall over Taipei Basin
- Merged convective cells showed stronger updrafts, more graupel, and broader enhanced ZDR regions (>1 dB) than isolated cells
- A wide (>8 km) enhanced ZDR region at 5.5 km altitude formed during cell merger and was followed by intense updrafts and rainfall

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Miao, J.-E., Yang, M.-J., Rasmussen, K.

Microphysical and Kinematical Characteristics of Merged and Isolated Convective Cells Over the Complex Terrain of the Taipei Basin

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Abstract This study investigates the microphysical and kinematic characteristics in extreme afternoon thunderstorm rainfall during Taiwan-Area Heavy rain Observation and Prediction Experiment/Prediction of Rainfall Extremes Campaign In the Pacific IOP 2. The high-quality S-Pol radar observations and multi-Doppler winds provided valuable information about the convective organization over complex terrain. There were two episodes of heavy rainfall in this event. Episode 1 (1200–1400 LST, Local Standard Time) featured multiple cell merger (MCM) favored by terrain-induced circulation. Around the time of MCM, the enhanced ZDR region (>1 dB) broadened horizontally to ~8 km in width at 5.5 km above mean sea level (AMSL). Afterward, maximum vertical velocity increased dramatically to ~20 m s⁻¹ and graupel reached up to 12 km AMSL. In contrast, Episode 2 (1500–1700 LST) exhibited isolated cells with weak updrafts (<10 m s⁻¹) and more snow aloft. The merged ZDR columns coincided with MCM occurrence, preceding peaks in both vertical velocity and rainfall intensity. Building on emerging research investigating the relationship between ZDR column size and severe weather in the US, this study suggests that wide merged ZDR columns may be relevant to severe storms over complex terrain in Taiwan, highlighting their potential utility as indicators of storm intensification.

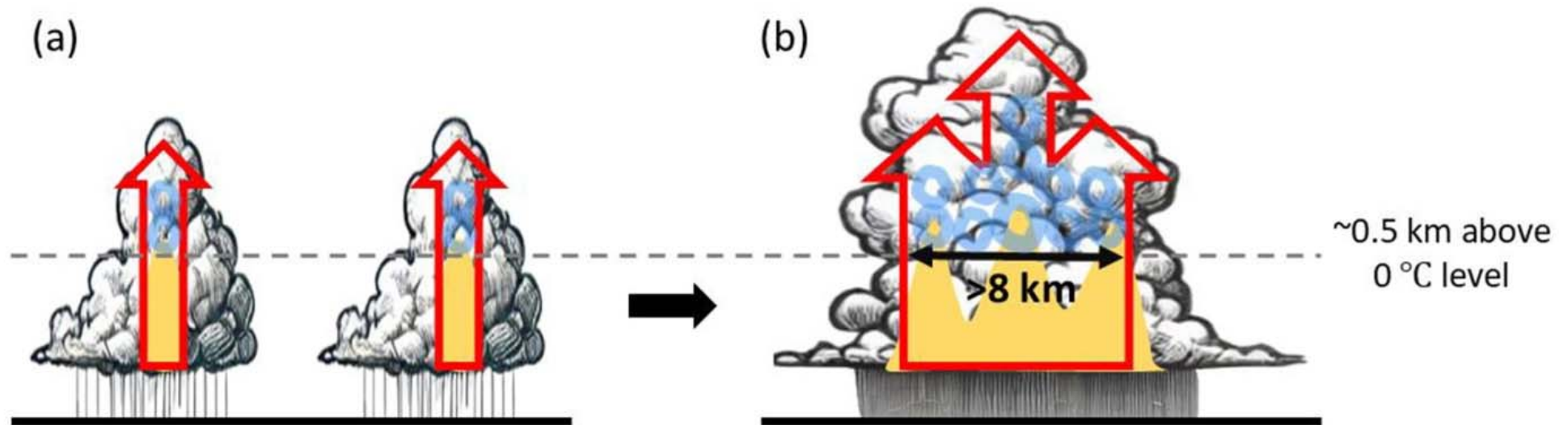
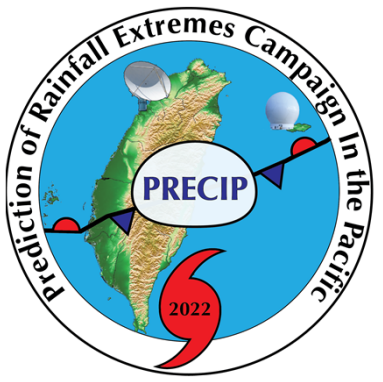


Figure 18. Conceptual diagram illustrating changes in ZDR column structure associated with multiple cell mergers. (a) Before the merger, individual convective cells contain distinct ZDR columns (yellow shading), each associated with localized updrafts (red arrows). (b) After multiple cell mergers, the 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 environmental 0°C level). This structure indicates a larger, more organized updraft region with enhanced mixed-phased microphysical processes, including the lofting of graupel (blue circles) above the 0°C level.

Miao, J. E., **M-J. Yang***, K. L. Rasmussen, M. M. Bell, H.-C. Kuo, and T.-Y. Cha, 2025: Microphysical and kinematical characteristics of merged and isolated convective cells over the complex terrain of the Taipei Basin, *J. Geophys. Res. Atmos.*, 130, e2024JD042375. <https://doi.org/10.1029/2024JD042375>.

2023年TAHOPE研討會



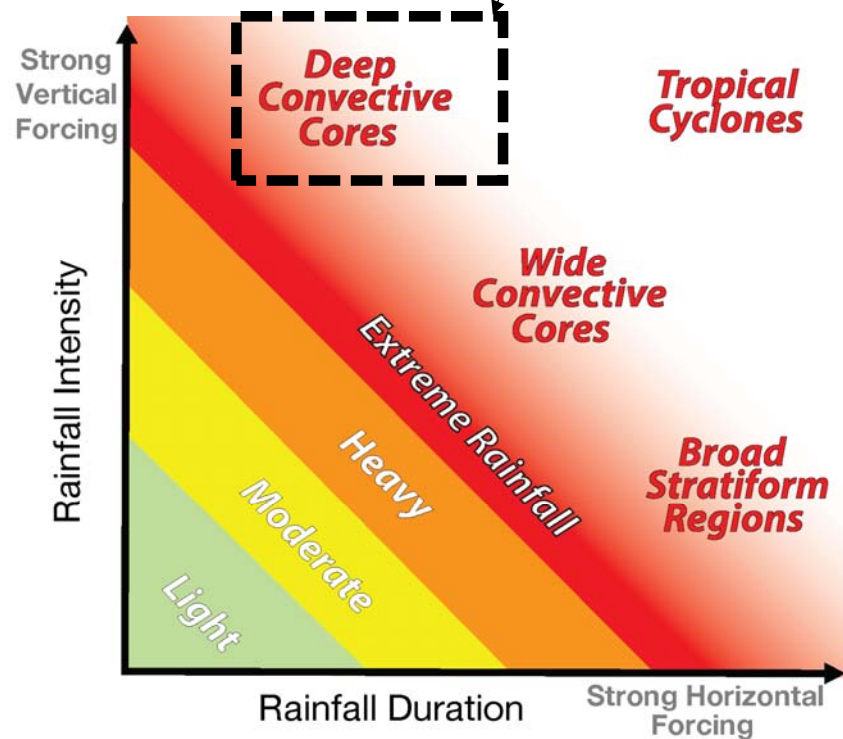
Achievements

- TAHOPE/PRECIP/T-PARCII 2022 field experiment were conducted successfully despite 2-year delay and ongoing COVID-19 pandemic
 - 1st deployment of NCAR MicroPulse DIAL (MPD) on Taiwan
 - 1st land-based deployment of CSU SEA-POL on Yonaguni, Japan
 - 1st international field campaign on Mei-Yu fronts, MCSs, thunderstorms, and typhoons
- Boundary-layer lifting in moisture-rich environment surrounding Taiwan is a critical factor
 - Strength and position of frontal forcing are essential
 - Diurnal heating over complex terrain on Taiwan – very predictable in some cases, but unpredictable in other cases
- Over 200,000 radar RHIs are composited into comprehensive profiles of polarimetric radar information, and the TAHOPE/PRECIP/T-PARCII data are now open for everyone to use.
- **Call for paper!**: Special Issue of TAHOPE and severe weather papers in TAO (Due: 31 Jan. 2026; <https://link.springer.com/collections/fdhidechfc>)



- TAHOPE/PRECIP 2022
- Intensity-duration framework
- Moisture-rich environment
- Key ingredients and processes

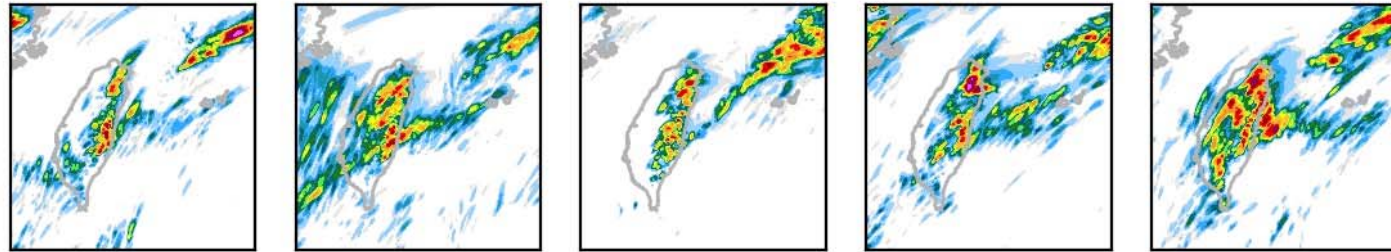
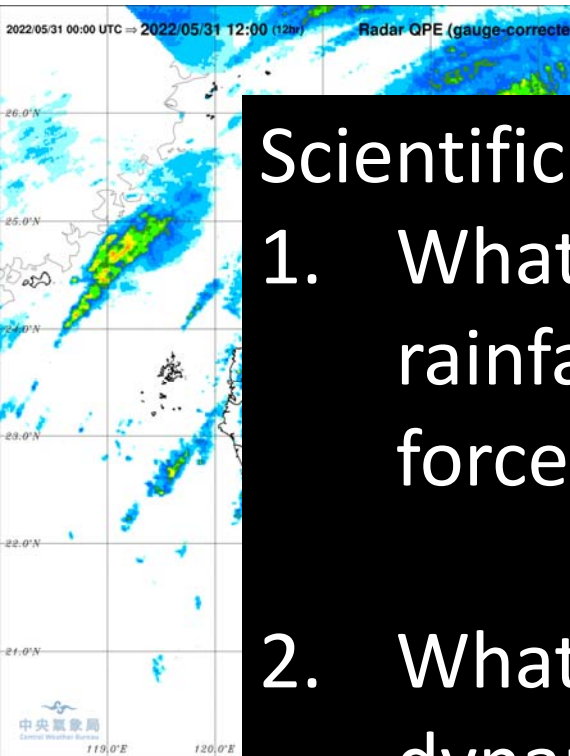
Afternoon Thunderstorms (ATS)
IOP 2



2022/05/31 08–20 LST
QPE

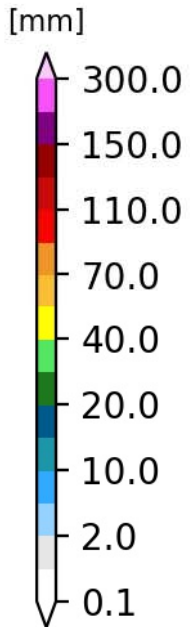
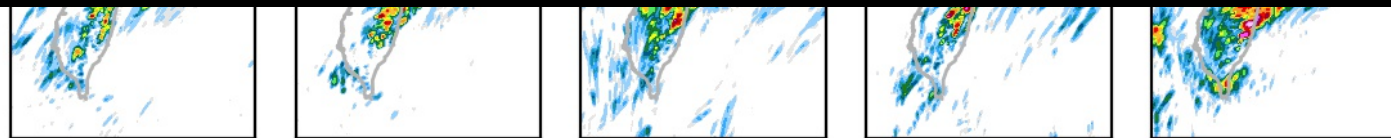
PSU WRF-EnKF
12-h 20-member Rain

init: 2022-05-30_12:00:00
valid: 2022-05-31_12:00:00
Taiwan LT: 2022-05-31_20:00:00



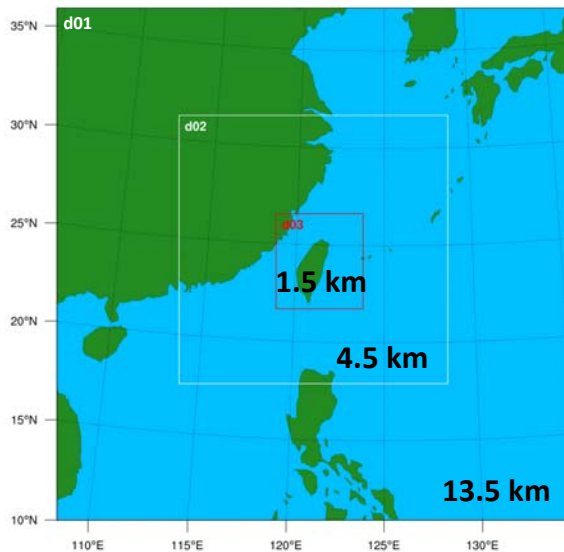
Scientific questions:

1. What are the key processes driving extreme rainfall over northern Taiwan in this strongly forced ATS case with low predictability?
2. What is the role of terrain in influencing the dynamic and thermodynamic processes?



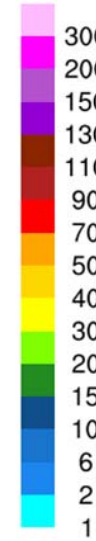
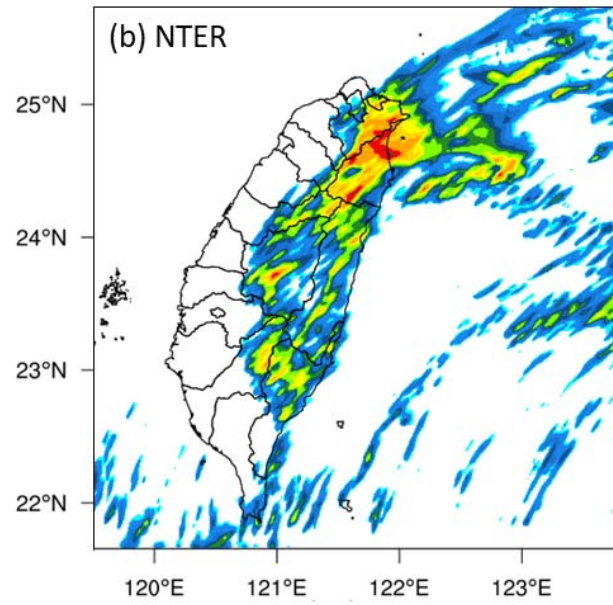
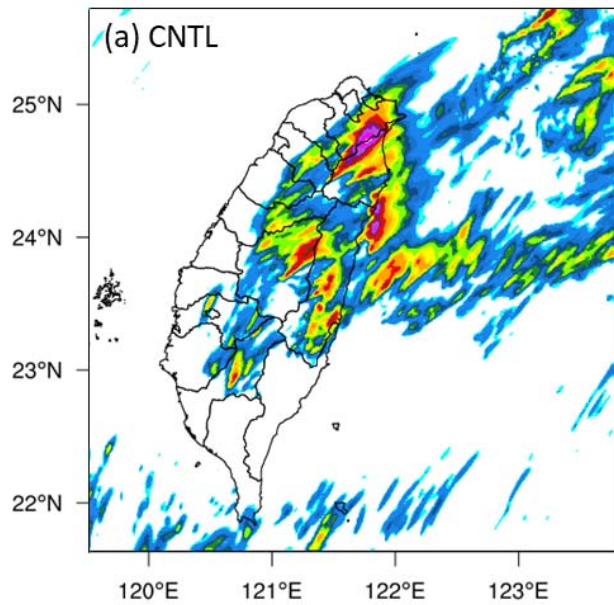
WRF Simulations: Terrain Modification

- Sensitivity tests on IC and microphysics
- ~30 WRF runs (NCAR Derecho supercomputer)
- Verification: synoptic and mesoscale environment, rainfall, reflectivity, wind

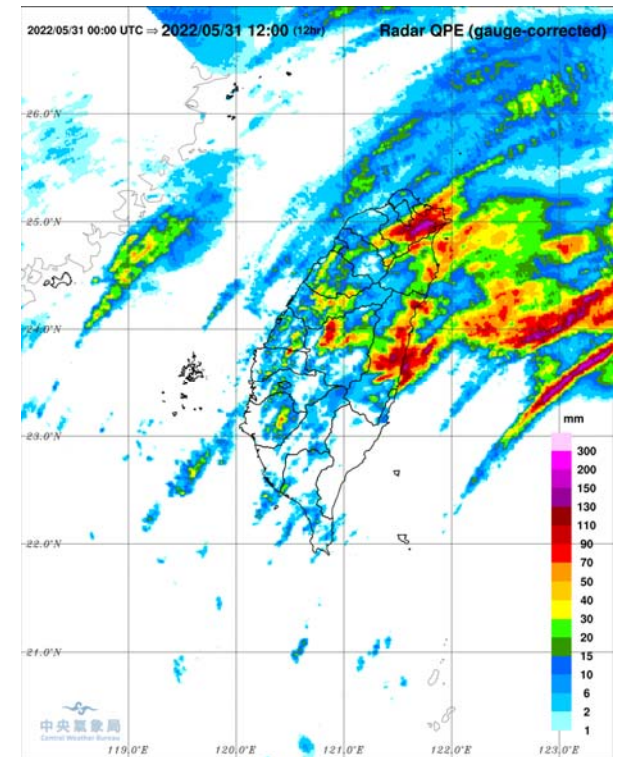


Exp.	microphysics	Initial & boundary condition	Grid spacing	Terrain
CNTL	WDM6	NCEP FNL	1.5 km (d3)	Full terrain
NTER	WDM6	NCEP FNL	1.5 km (d3)	No Taiwan terrain

08-20 LST accumulated rainfall



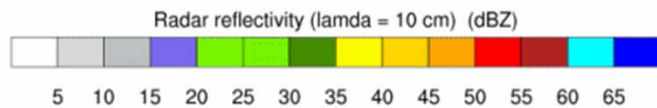
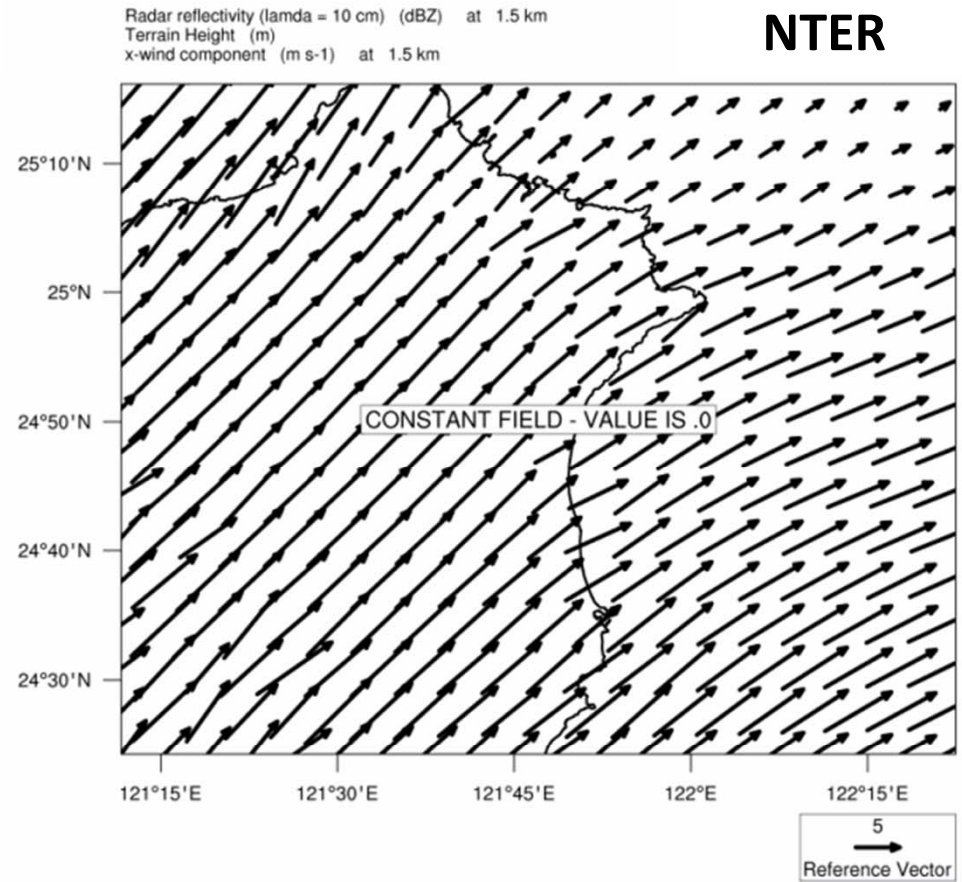
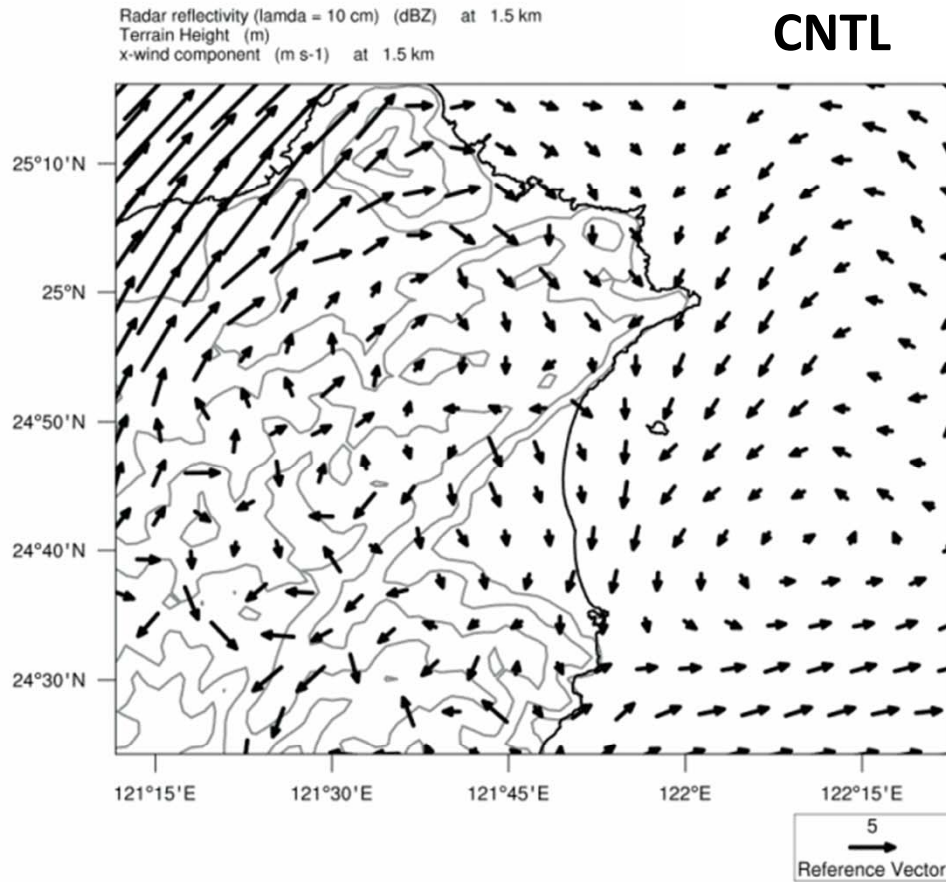
2022/05/31 08-20 LST QPE



Reflectivity and winds @1.5km MSL

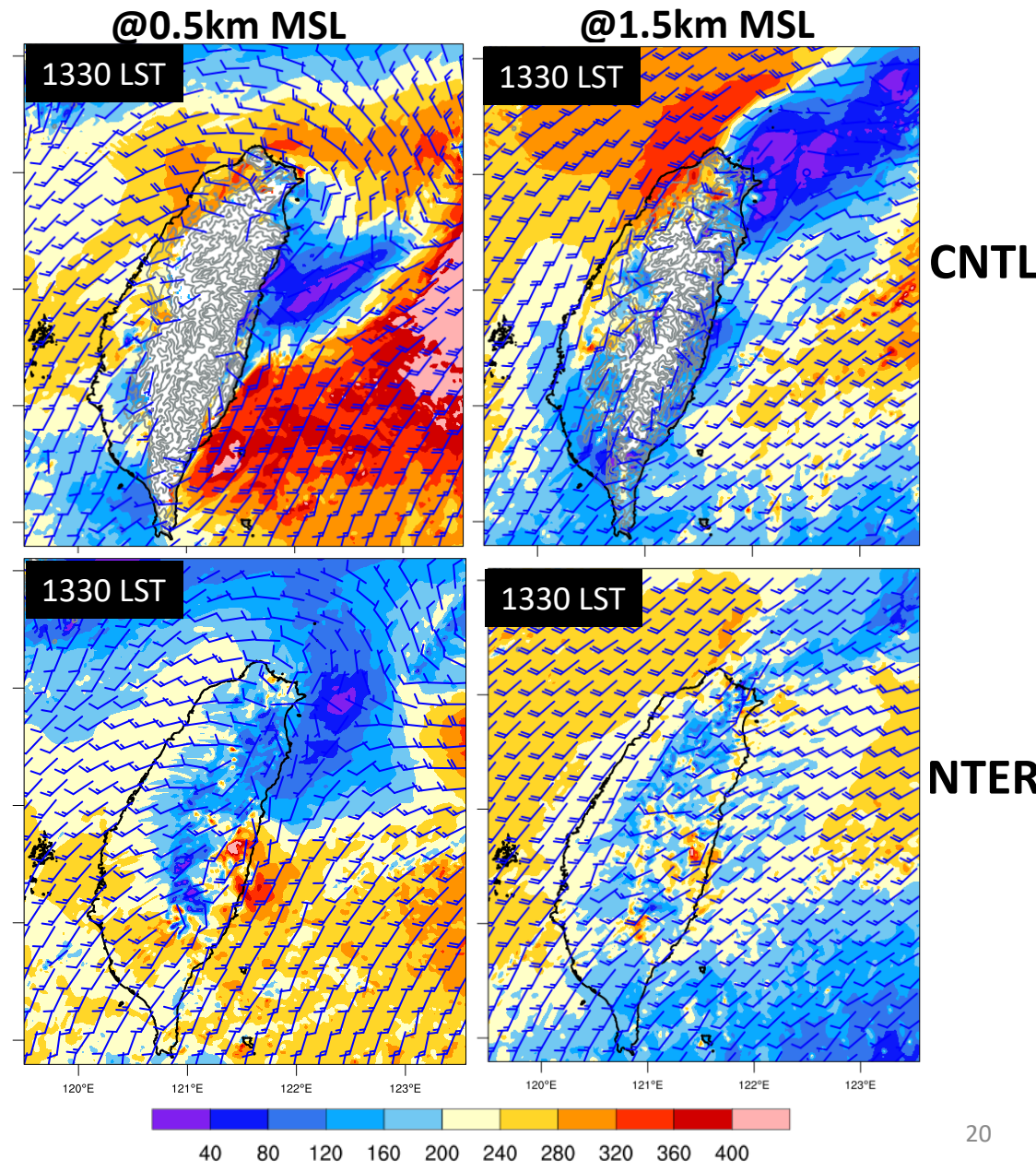
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Valid: 2022-05-31_02:00:00



- Higher moisture flux over northern Taiwan and eastern ocean in CNTL
- Terrain-blocked flow & sea breeze/upslope wind
- Enhanced low-level convergence over the eastern coast

Colors: moisture flux ($\text{g kg}^{-1} \text{ m s}^{-1}$)
 Wind barbs (kts) @0.5km MSL



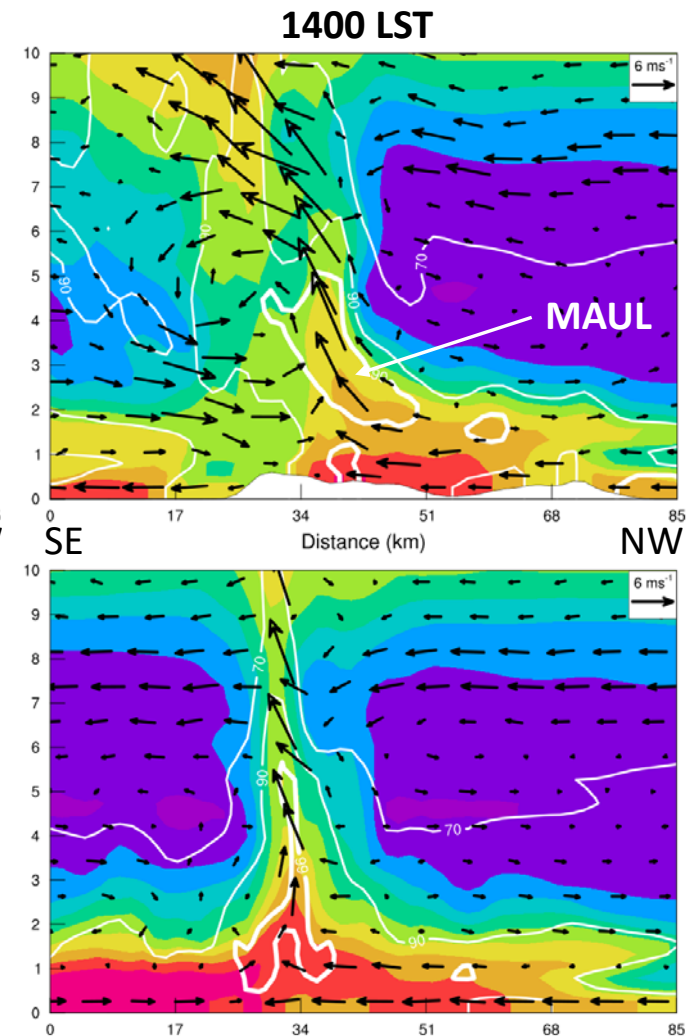
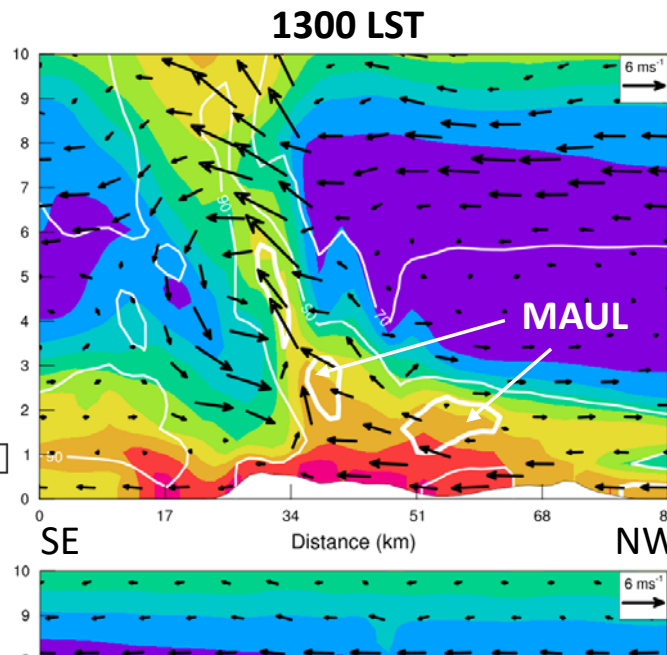
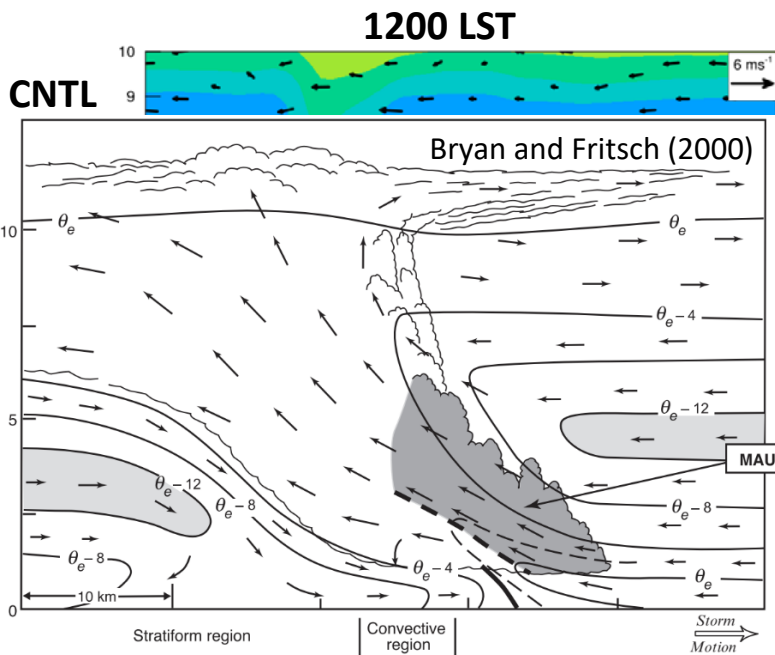
Time-averaged vertically (0-3 km MSL) integrated moisture flux convergence ($10^4 \text{ kg s}^{-1}\text{m}^{-2}$) in each simulation in the northern Taiwan region. All values are averaged from hours 12–24 of each simulation.

Exp.	MFC	MFC _{conv}	MFC _{adv}
CNTL	44.5	44.4	0.1
NTER	37.8	34.5	3.3

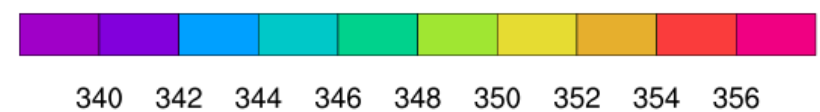
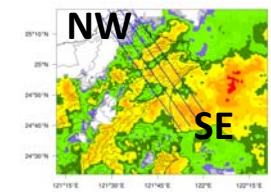
$$\text{MFC} = -\nabla \cdot (q\mathbf{V}_h) = -\mathbf{V}_h \cdot \nabla q - q\nabla \cdot \mathbf{V}_h,$$

$$\text{MFC} = \underbrace{-u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y}}_{\text{advection term}} - \underbrace{q \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)}_{\text{convergence term}}.$$

Banacos and Schultz 2005;
Rasmussen and Houze 2016



- Moist absolutely unstable layer (MAUL): a very humid layer with the temperature lapse rate > moist-adiabat nearby MCSs
- 1. moist environment; 2. mesoscale lifting; 3. layer lifting



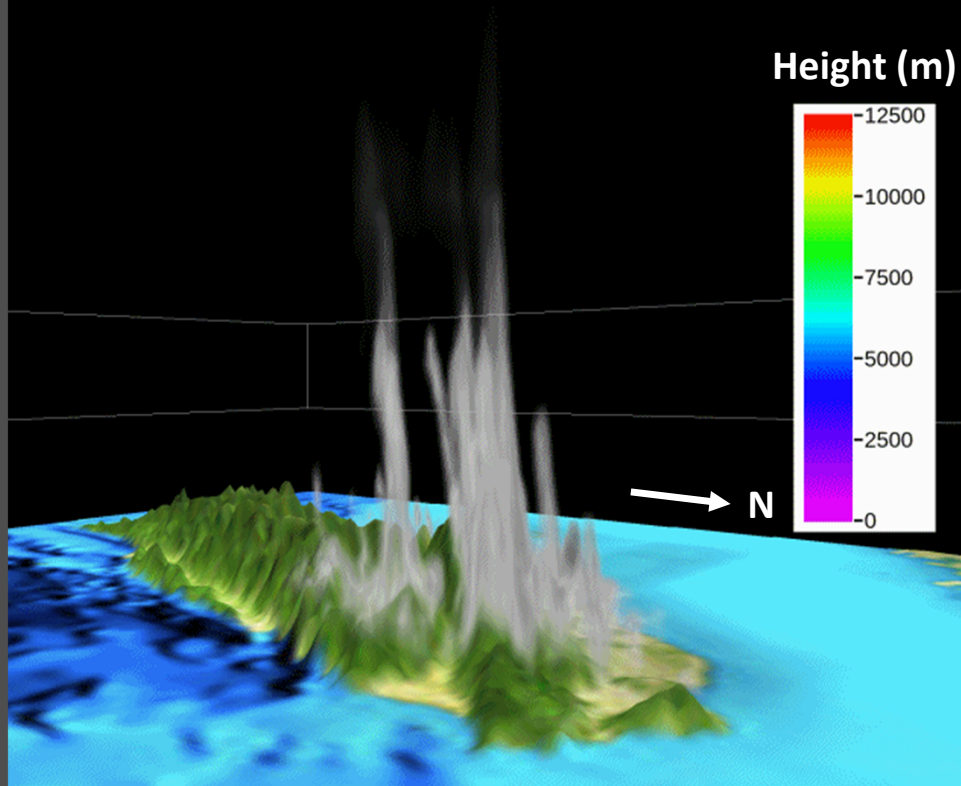
Colors: θ_e (K); Contours: relative humidity (70, 90, 99 %)
Arrows: winds

Table 4.1. Summary of documented MAUL-related events in previous studies.

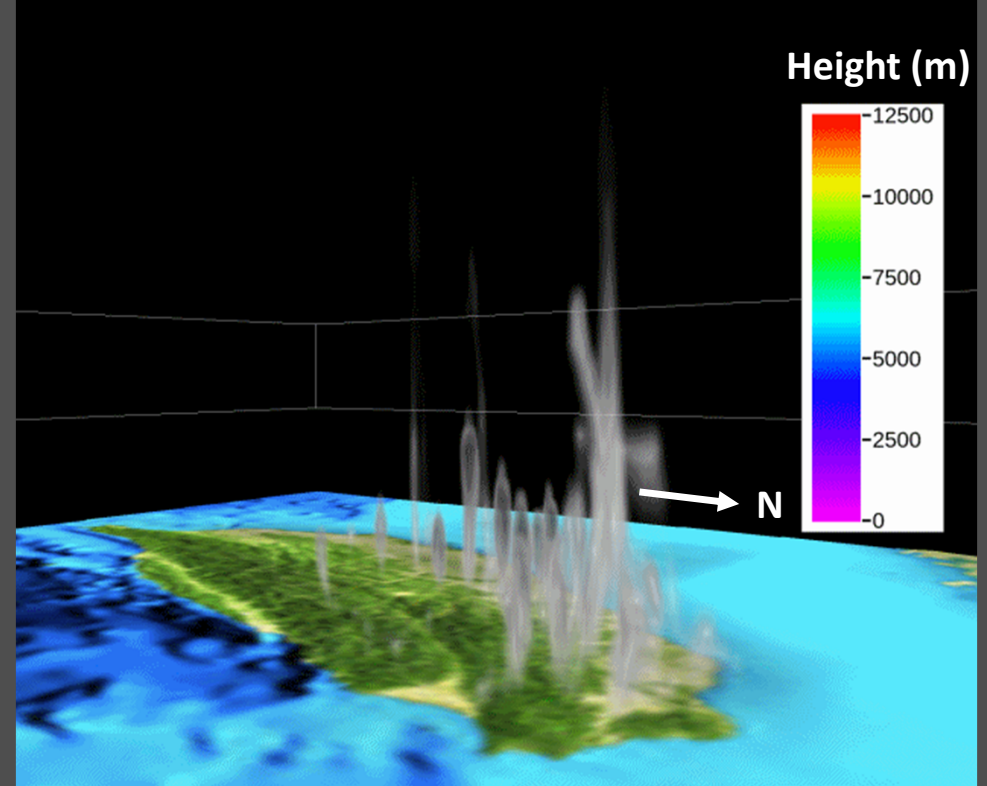
Reference	Storm type and region	MAUL horizontal/vertical scale	MAUL formation mechanism
Bryan and Fritsch (2000, BAMS)	Midlatitude MCSs over the United States	O(100 km) along MCS axis; O(10 km) across; ~100 mb deep	Mesoscale layer lifting by cold pool
Mechem et al. (2002, QJRM)	MCSs over western tropical Pacific warm pool	Similar to Bryan and Fritsch (2000)	Mesoscale layer lifting by cold pool
Schumacher and Johnson (2008, MWR)	MCS producing flash flooding over eastern Missouri	O(100 km); 1–2 km deep	Lifting by mesoscale convective vortex
Choi et al. (2011, APJAS)	Linear MCS in central Korean Peninsula	O(100 km) along MCS axis; O(10 km) across; ~200 mb deep	Strong vertical motion due to low-level jet
Takemi and Unuma (2020, SOLA)	Typhoon Hagibis (2019) over eastern Japan	O(100 km); >2 km deep	Moisture and circulation associated with typhoon
Hua et al. (2020, JGR)	Convective system in mountainous North China	O(10 km); <1 km deep	Weak (<1 m s ⁻¹) orographic gravity wave ascent
Tsuji (2021, GRL)	MCS in western Japan	O(10 km); 800–500 hPa	Not investigated
Zou et al. (2023, JGR)	Cold frontal rainband in California	O(10 km) wide; ~850–700 hPa	Large-scale convergence in frontal zone

CNTL showed a pronounced layer-lifting mode

CNTL

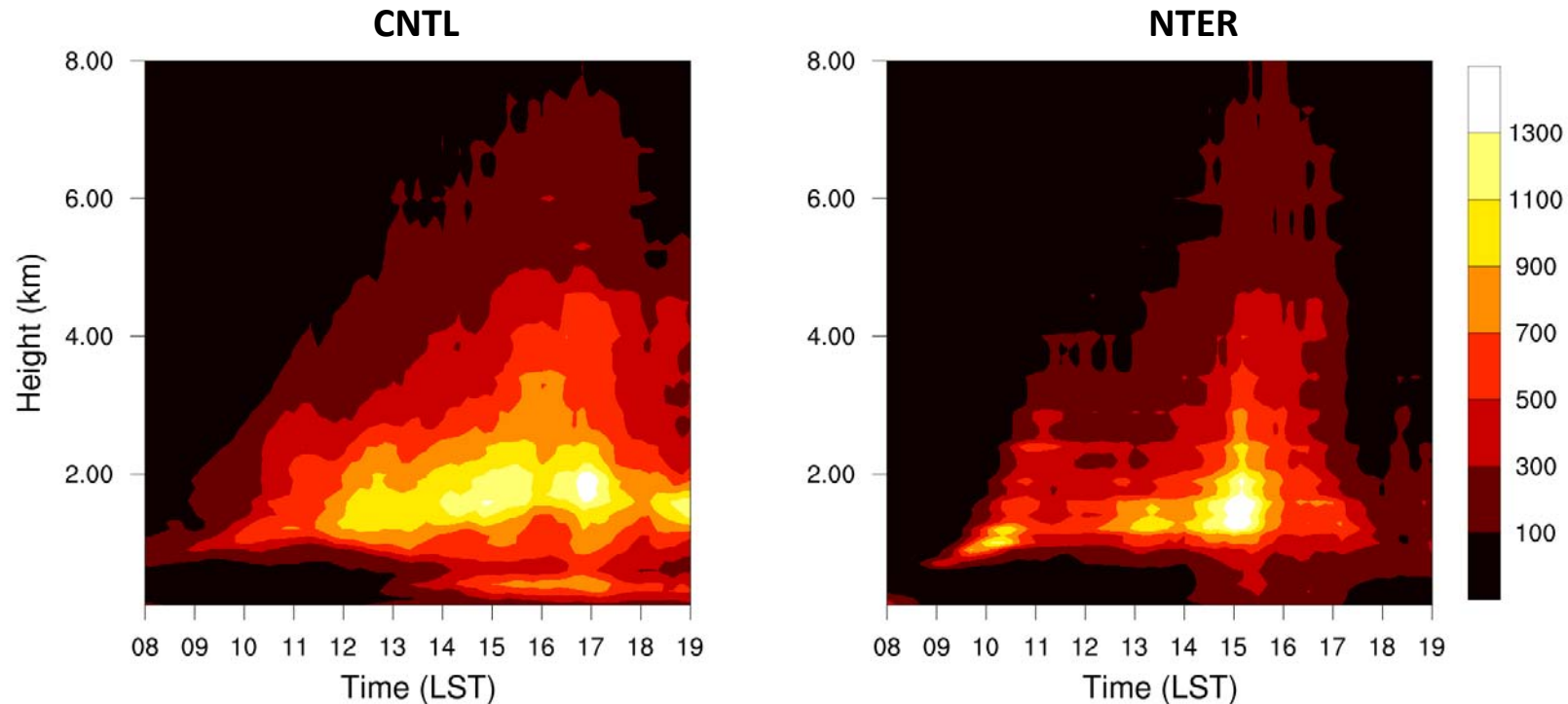


NTER

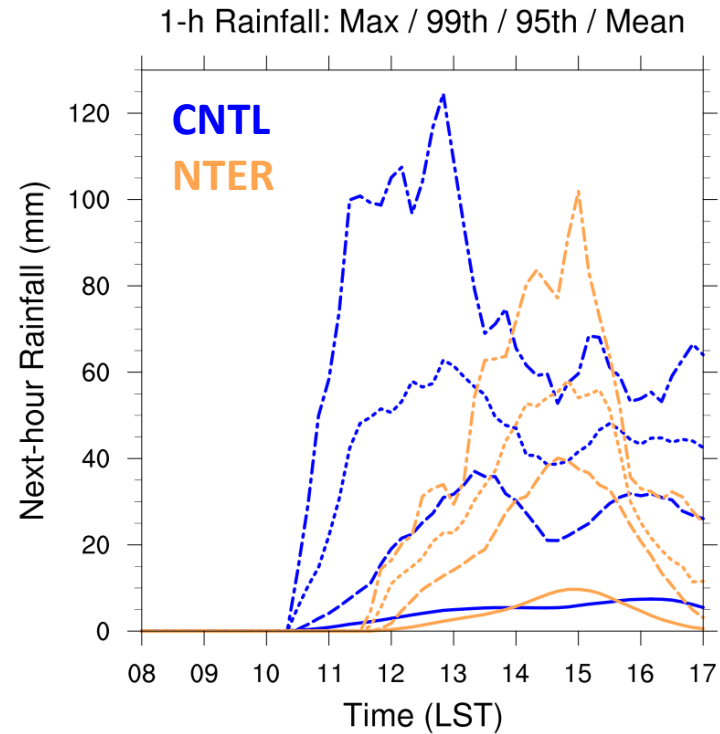
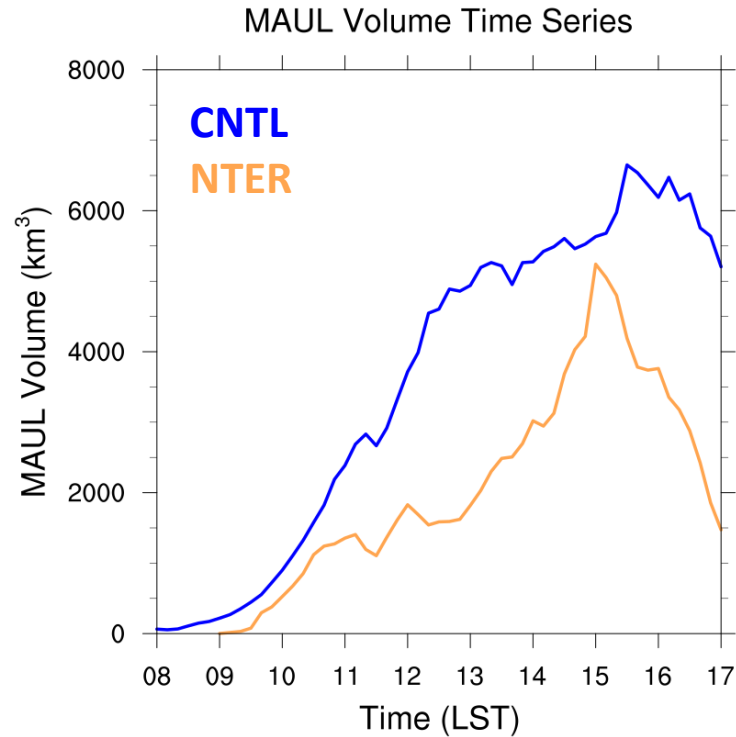


- Forward trajectories of 30 air parcels originating in the low levels

Time evolution of the average number of moist absolutely unstable layer (MAUL) grids

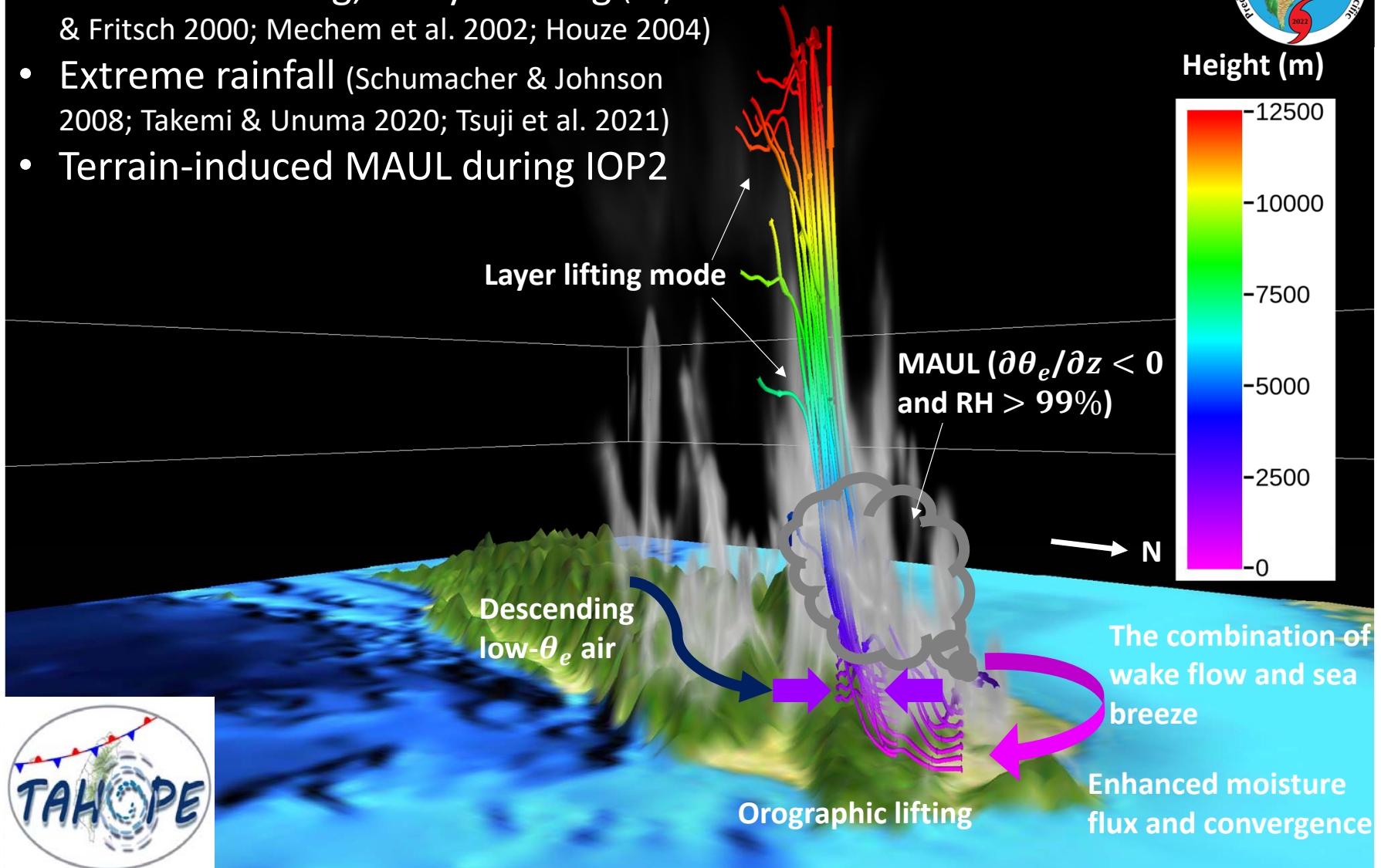
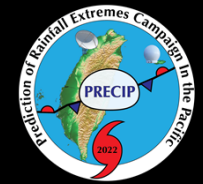


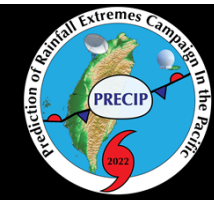
- MAUL condition: $\frac{\partial \theta_e}{\partial z} < 0$ and $RH > 99\%$, (Takemi and Unuma 2020)
- CNTL exhibited higher number of MAUL grids than NTER.
- Enhanced moisture convergence and orographic lifting



- MAUL volume is calculated by multiplying the MAUL depth (>500 m) by the horizontal grid area, summed over land points within the northern Taiwan domain.
- CNTL exhibits a more rapid and pronounced increase in MAUL volume compared to NTER.
- Extreme rainfall in CNTL occurs earlier and is more intense than in NTER.
- Terrain confines convection to mountainous region and enhances localized extreme precipitation.

- MAUL: 1. moist environment; 2. mesoscale lifting; 3. layer lifting (Bryan & Fritsch 2000; Mechem et al. 2002; Houze 2004)
- Extreme rainfall (Schumacher & Johnson 2008; Takemi & Unuma 2020; Tsuji et al. 2021)
- Terrain-induced MAUL during IOP2





- *The increased number of MAUL grids in CNTL was attributed to enhanced moisture convergence and orographic layer lifting.*
- *Terrain-induced MAUL throughout the low and mid levels characterize the environmental conditions for the development of extreme rainfall.*

