

DISSERTATION

A MULTI-SCALE INGREDIENTS-BASED FRAMEWORK FOR MEIYU-SEASON
EXTREME RAINFALL OVER TAIWAN

Submitted by

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ABSTRACT

A MULTI-SCALE INGREDIENTS-BASED FRAMEWORK FOR MEIYU-SEASON EXTREME RAINFALL OVER TAIWAN

Heavy rainfall during the Meiyu season is among the most high-impact weather hazards affecting East Asia, producing flash and river flooding and widespread impacts from late spring through early summer. Over Taiwan, the interaction of the Meiyu front with the steep topography of the Central Mountain Range (CMR) amplifies rainfall totals and challenges both operational forecasting and physical understanding. This dissertation develops a framework for diagnosing Meiyu-season extreme rainfall by applying a common set of storm-mode and ingredients-based diagnostics across satellite climatology, numerical modeling experiments, and convection-permitting ensemble contexts.

The first study (Chapter 2) develops a 15-year climatology of extreme convective storm modes over tropical and subtropical East Asia using the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar. Deep and Wide Convective Cores (DWCCs) and Broad Stratiform Regions (BSRs) dominate volumetric rainfall in the moisture-rich Meiyu environment, despite the higher instantaneous rain rates of the smaller Deep Convective Cores. The analysis shows that the broader systems are associated with larger in area and longer timescales of vertical moisture flux and low-level wind shear that support the development of the horizontally large, organized storms. DWCCs and BSRs are also associated with the strongest large-scale moisture convergence along the Meiyu frontal band.

The second study (Chapter 3) examines the 1–3 June 2017 extreme Meiyu rainfall event over Taiwan using a convection-permitting Weather Research and Forecasting (WRF) simulation, with a halved-terrain experiment to isolate the role of the CMR. Reducing the CMR height by 50% shifts DWCCs from over the mountains to locations offshore east of Taiwan, allows BSRs to expand

westward over the island displacing the DWCC-dominant regime, and reduces total rainfall over Taiwan by approximately 30%. Upward vertical velocity and vertically integrated moisture flux emerge as the key variables through which terrain modulates the storm-mode balance and the associated rainfall, with further modulations by changes in the low-level shear on the leeside of the CMR.

The third study (Chapter 4) extends the framework to ensemble forecasting through the analysis of a 20-member subset of the Penn State University Ensemble Kalman Filter WRF ensemble (PRECIP PSU-EnKF) of Intensive Observation Period 1 of the 2022 Prediction of Rainfall Extremes Campaign in the Pacific (PRECIP). The top quintile of members produces 1.6–1.9 times as much 48-hour total rainfall as the bottom quintile. Domain-integrated upward vertical velocity and upward moisture flux are strongly correlated with total rainfall. Domain mean total precipitable water (TPW) has low correlation with total rainfall, but TPW does show slight increases for all storm modes in the high-rainfall members. High-rainfall members produce more extensive BSR coverage along the Meiyu front and show elevated DWCC frequencies over western Taiwan and surrounding ocean regions, while low-rainfall members show lower DWCC and BSR frequencies. The ingredient separation between high- and low-rainfall members is established at the first model output time, suggesting that the rainfall spread originates from initial-condition differences rather than from evolution during the simulation.

The three studies in this dissertation consistently identify the same dominant storm modes and the same controlling atmospheric ingredients for Meiyu-season extreme rainfall over Taiwan. DWCCs and BSRs produce the majority of the rainfall across all three datasets, with large-scale upward moisture flux and low-level shear emerging as the key environmental ingredients. The variability in these DWCCs and BSRs is strongly influenced by the Taiwan CMR and the synoptic dynamical forcing, with less influence from variability in the available moisture. These results advance the process-based understanding of extreme rainfall in moisture-rich environments.

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Chapter 1

Introduction

1.1 Motivation

Heavy rainfall is one of the most consequential high-impact weather phenomena worldwide, with the capacity to trigger flash floods, debris flows, landslides, and urban inundation on short timescales. Understanding what produces heavy rainfall, and what distinguishes an ordinary precipitation event from an extreme one, is therefore a long-standing goal of operational meteorology and atmospheric science research. A foundational conceptual framework for this question follows the Doswell et al. (1996b) ingredients-based approach, which expressed the net rainfall (P) as the product of the rainfall intensity (I) and its duration (D):

$$P = I \times D \quad (1.1)$$

The intensity can be further decomposed into the product of the precipitation efficiency (E), the vertical velocity (w), and the water vapor mixing ratio (q):

$$I = Ewq \quad (1.2)$$

Within this ingredients-based framework, extreme rainfall arises when sufficient moisture, strong upward motion, and adequate precipitation efficiency coincide over a sufficiently long duration. The ingredients are not independent of the flow configuration in which they occur: they depend on the scale, organization, and terrain interactions of the parent weather system. Quantifying which ingredients contribute the most to the total rainfall is therefore essential to the understanding and prediction of extreme rainfall.

One of the most prolific producers of heavy rainfall in the global tropics and subtropics is the Meiyu front, a quasi-stationary frontal zone that develops over East Asia during the late-spring to

early-summer transition between the East Asian winter and summer monsoons. Along the Meiyu front, moist and convectively unstable air from the South China Sea and western Pacific converges with cooler and drier air from the Asian continent, establishing a shallow baroclinic zone that focuses organized convection over thousands of kilometers. The same frontal phenomenon is known as the Baiu in Japan and the Changma in Korea, and its associated rainy season produces much of the annual precipitation, as well as most of the most damaging rainfall hazards, across southern China, Taiwan, Korea, and Japan from May through July.

Taiwan occupies a particularly exposed position within the Meiyu rainband. The island lies at the southern end of the region where the Meiyu front establishes in mid-May, and it is directly downstream of the southwesterly monsoonal flow that supplies moisture from the Bay of Bengal and the South China Sea. As a result, the Meiyu season over Taiwan routinely produces multi-day rainfall totals exceeding 500 mm, and the most extreme events deliver over 1000 mm (Chen et al. 2007a; Henny et al. 2023). On 2 June 2017, for example, the Taipei Basin in northern Taiwan received more than 600 mm of rainfall in twelve hours, the largest Meiyu-front rainfall total recorded in the preceding 26 years. Such events cause substantial loss of life and property and place Meiyu rainfall among the most socially consequential weather hazards in East Asia.

The severity of Meiyu rainfall over Taiwan is amplified by the steep topography of the island. The Central Mountain Range (CMR) extends more than 310 km along the north–south axis of Taiwan and reaches nearly 4000 m in elevation across a land surface only 100–200 km wide, presenting an abrupt orographic barrier to the low-level southwesterly flow that supplies the frontal moisture. The interaction of the Meiyu front with the CMR enhances rainfall through direct orographic lifting on the windward slopes, through the formation of a barrier jet along the northwestern coast, and through the splitting of the approaching front into windward and leeward branches. These interactions can concentrate extreme rainfall accumulations over specific mountain slopes and populated basins, and they redistribute the location of the heaviest rainfall in ways that depend sensitively on the approach angle, the strength of the low-level flow, and the upstream moisture supply.

The combination of a moisture-rich large-scale environment, a quasi-stationary frontal boundary, embedded mesoscale convective systems, and a steep orographic barrier makes the forecasting of Meiyu rainfall over Taiwan an exceptionally difficult problem. Small differences in the synoptic-scale flow, the moisture supply, or the effective terrain blocking can shift the location of the heaviest rainfall by tens of kilometers and change the total accumulation by a factor of two or more. Convection-permitting numerical weather prediction models exhibit substantial run-to-run spread in the location, timing, and intensity of extreme rainfall, and operational forecasting increasingly relies on ensemble systems to quantify the associated uncertainty. However, the physical interpretation of the resulting ensemble spread, and in particular the identification of which atmospheric ingredients drive forecast divergence across members, remains an open question. Addressing this question requires a framework that connects the large-scale moisture supply, the mesoscale organization of convection, the orographic modulation of storm location, and the ensemble-scale uncertainty in a physically consistent way.

This dissertation develops such a framework through three complementary studies that apply a common set of storm-mode and ingredients-based diagnostics across climatological, deterministic, and ensemble contexts. Together, the three studies establish that a small number of extreme storm modes dominate Meiyu rainfall at every scale examined, and that their spatial organization and environments can be diagnosed consistently across satellite climatology, convection-permitting simulations, and ensemble forecasts. The framework thereby provides a unified physical basis to improve both understanding and prediction of Meiyu-season extreme rainfall over Taiwan.

1.2 Literature Review

The literature on Meiyu-season extreme rainfall over Taiwan spans several decades and several methodological traditions, including ingredients-based conceptual frameworks for heavy precipitation, synoptic and climatological analyses of the East Asian summer monsoon, observational and modeling studies of the Meiyu front over Taiwan, process-based investigations of terrain interac-

tions with the CMR, and recent advances in ensemble forecasting supported by the PRECIP 2022 field campaign.

1.2.1 Heavy rainfall and the ingredients-based framework

The ingredients-based framework articulated by Doswell et al. (1996b) provides the conceptual foundation for some modern approaches to heavy rainfall diagnosis. By decomposing the net rainfall into the product of intensity and duration, and the intensity into precipitation efficiency, vertical velocity, and moisture, the framework separates the thermodynamic and dynamic contributions to rainfall production and identifies the variables that can be examined directly in observations and model output. This decomposition has been applied across a wide range of heavy-rainfall settings, from flash-flood-producing mesoscale convective systems in the United States to orographically enhanced rainfall in complex terrain (Lin et al. 2001). In orographic settings, Lin et al. (2001) extended the framework by cataloguing the mesoscale ingredients that distinguish extreme orographic rainfall events, including a conditionally or potentially unstable air mass impinging on the mountain, a strong low-level jet, and a steep mountain slope. Jiang (2003) further showed that terrain influences rainfall through a combination of enhanced lifting on the windward side and reduced moisture supply in the lee, while Kirshbaum et al. (2018) and Nugent and Rios-Berrios (2018) demonstrated that terrain can also modify rainfall duration by either favoring rapid, intense convection or redirecting the flow through mechanical and thermal mechanisms.

In moisture-rich environments such as the Meiyu region, the first ingredient (available moisture) is often large and relatively uniform, so the variability in the remaining ingredients, particularly in the vertical velocity and the degree of convective organization, takes on a correspondingly greater role in determining rainfall outcomes (Panasawatwong et al. 2022). This asymmetry motivates an emphasis on dynamical and organizational diagnostics in the Meiyu context, rather than on column moisture alone.

1.2.2 The East Asian monsoon and the Meiyu front

At the continental scale, the Meiyu rainy season is a manifestation of the seasonal transition of the East Asian monsoon. As the winter northeasterly monsoon weakens and the summer southwesterly monsoon strengthens through May and June, a quasi-stationary frontal zone develops over East Asia along which the two air masses converge (Lau et al. 1988; Chen 1983, 1992; Ninomiya 1984; Tao and Chen 1987; Ding and Chan 2005a). Akiyama (1973a) first characterized the large-scale aspects of the Baiu front and identified steep gradients of specific humidity, equivalent potential temperature, and low-level wind shear as its defining features; low-level wind shear has subsequently been used as a proxy for the front's location in many diagnostic studies (Ninomiya and Shibagaki 2007a; Sampe and Xie 2010a; Panawatwong et al. 2022). The Meiyu front establishes over Taiwan and Okinawa in mid-May, marking the onset of the East Asian monsoon, and progresses northward to the Yangtze River Valley and mainland Japan from mid-June to mid-July (Akiyama 1973a; Ding and Chan 2005a; Sampe and Xie 2010a). The associated moisture transport is sustained by strong southwesterly flow from the Bay of Bengal and the South China Sea, which acts as a moisture conveyor toward Taiwan and the rest of East Asia (Chen 1994; Chang and Chen 1995).

Recent climatological analyses have placed the Meiyu front within the broader pattern of East Asian extreme precipitation trends. Using 41 years of gridded rainfall observations, Henny et al. (2023) showed that Meiyu-season extreme precipitation days over Taiwan associated with atmospheric-river-like moisture transport have become more frequent and more intense since 1979, with a small number of long-duration events contributing disproportionately to the positive season-total precipitation trend. These findings indicate that the Meiyu rainfall regime is not stationary, motivating continued process-based investigation of the mechanisms that translate available moisture into extreme rainfall in individual events.

1.2.3 The Meiyu front over Taiwan: synoptic and mesoscale processes

Over Taiwan, the Meiyu front interacts with a hierarchy of embedded disturbances, including low-level jets, southwest vortices, and mesoscale convective systems, that together determine the location and intensity of the heaviest rainfall. Chen and Yu (1988) documented the role of the low-level jet in supplying moisture to the frontal zone and triggering heavy rainfall over northern Taiwan, and Chen et al. (2005) analyzed the characteristics of low-level jets during the Meiyu season and their relationship to heavy rain events. Chen et al. (2022) provided a comprehensive overview of low-level jets and their roles in heavy rainfall over the Taiwan area during the early summer rainy season. Chen and Tu (2024) synthesized the current understanding of the Meiyu season over Taiwan, including the synoptic configurations, mesoscale structure, and diurnal cycle of heavy rainfall. Chen et al. (2007a) compiled statistics of heavy rainfall occurrences in Taiwan, establishing a climatological baseline for the frequency and intensity of Meiyu-season extreme events.

The quasi-stationary nature of the Meiyu front, combined with the presence of mesoscale disturbances, can produce persistent rainbands whose interaction with Taiwan's terrain generates some of the most extreme rainfall accumulations on record. Arakane et al. (2019) documented the remote influence of Tropical Cyclone Mora in the Bay of Bengal on the enhanced moisture transport that contributed to the record-breaking 2 June 2017 event over Taipei. Chien and Chiu (2023) analyzed the record-breaking early-2020 Meiyu event in southern Taiwan and traced it to an intensified Pacific subtropical high, an anomalously strong southwesterly monsoonal flow, and an eastward-propagating southwest vortex that acted as a moisture conveyor toward the Taiwan Strait. Together, these studies indicate that extreme Meiyu events over Taiwan are produced by specific synoptic configurations that align the available moisture with the frontal convergence zone.

At the mesoscale, the heavy rainfall along the Meiyu front is produced by organized convective systems whose structure and rainfall contribution can be characterized using storm-mode classification schemes derived from spaceborne radar observations. Houze et al. (2007a) introduced a classification based on the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar

that identifies Deep Convective Cores (DCCs), Wide Convective Cores (WCCs), Deep and Wide Convective Cores (DWCCs), and Broad Stratiform Regions (BSRs) as four extreme storm modes distinguishable by their reflectivity structure. Houze et al. (2015a) extended the framework to the global tropics and subtropics using the full TRMM record. Panasawatwong et al. (2022), which forms the basis of Chapter 2 of this dissertation, applied the framework specifically to tropical and subtropical East Asia and established that DWCCs and BSRs are the dominant volumetric contributors to heavy rainfall in the moisture-rich Meiyu environment, despite the higher instantaneous rain rates of the smaller DCCs. Rasmussen and Houze (2011a) and Rasmussen et al. (2016) applied the same classification framework to the South American monsoon region and documented the role of wide and deep convective systems in producing a majority of the rainfall, providing a methodological precedent for the East Asian analysis. Miao et al. (2025) examined the microphysical and kinematic characteristics of merged and isolated convective cells over the complex terrain of the Taipei Basin, providing observational context for the convection-permitting analyses presented in later chapters. Most recently, DeHart and Bell (2025) used radar observations collected during the 2022 PRECIP field campaign to quantify the relationship between convective dynamics and rainfall intensity along oceanic Meiyu fronts and found that the highest rain totals preferentially occur in moderately strong rotating convection rather than in the most intense cells. This result, from a radar-observational perspective, is consistent with the climatological finding that the bulk of Meiyu rainfall comes from widespread, moderately organized convection rather than from the most intense convective cores.

1.2.4 Terrain interactions with the Central Mountain Range

Taiwan's Central Mountain Range modulates Meiyu rainfall through a combination of orographic lifting, frontal blocking, and barrier jet formation. Field campaigns including the Taiwan Area Mesoscale Experiment (TAMEX) in 1987 (Kuo and Chen 1990), the combined Terrain-influenced Monsoon Rainfall Experiment and Southwest Monsoon Experiment (TiMREX/SoWMEX) in 2008 (Jou et al. 2011), and most recently the joint Prediction of Rainfall Extremes Campaign

in the Pacific (PRECIP) and Taiwan-Area Heavy rain Observation and Prediction Experiment (TAHOPE) in 2022 have progressively characterized the mesoscale flow regimes that develop when the Meiyu front interacts with the CMR. Among the most important of these is the barrier jet, a low-level, terrain-parallel jet that forms along the northwestern coast of Taiwan when the incoming southwesterly flow is partially blocked by the CMR (Chen et al. 2022). The Meiyu front itself can split into windward and leeward branches as it encounters the CMR, with the windward branch typically associated with the most extreme rainfall (Chen 1992; Wang et al. 2012). The position of the front relative to the terrain is therefore a key control on the location and intensity of the heaviest rainfall.

The mountain-flow regime that develops for a given event depends sensitively on the effective Froude number, which measures the ratio of the incoming flow speed to a characteristic mountain-crossing speed and discriminates between flow-around and flow-over regimes. Cornejo et al. (2024) used convection-permitting simulations of the 1–3 June 2017 extreme Meiyu event over Taiwan to show that reducing the CMR height by 50% weakens the orographic barrier jet, accelerates Meiyu-front propagation, and shortens rainfall duration in northern Taiwan and over the CMR. Panawatwong et al. (2026), which forms the basis of Chapter 3 of this dissertation, performed a parallel halved-terrain experiment on the same event and showed that the terrain modulation extends beyond the bulk rainfall amount to the storm-mode composition itself: DWCCs shift from over the CMR to locations offshore east of Taiwan, BSRs expand westward over the island, and the total rainfall over Taiwan decreases by approximately 30%. These complementary studies establish that the CMR controls not only the rainfall amount but also the spatial organization of the convective systems responsible for producing it, and that the controlling variables are the upward vertical velocity and the vertically integrated moisture flux.

1.2.5 Ensemble analysis of ingredients supporting heavy rainfall

Despite the progress in characterizing the climatology and the mechanisms of Meiyu extreme rainfall, accurate deterministic prediction of individual events remains difficult. Convection-

permitting numerical weather prediction models exhibit substantial run-to-run spread in the location, timing, and intensity of heavy rainfall, reflecting a combination of initial-condition uncertainty, model physics uncertainty, and the intrinsic sensitivity of mesoscale convection to small perturbations. Operational forecasting of Meiyu events increasingly relies on ensemble systems that sample these uncertainties, and a substantial body of literature has documented the use of stochastic parameterization and ensemble data assimilation to quantify and reduce forecast error (Berner et al. 2017). However, the physical interpretation of ensemble spread, and in particular the identification of which atmospheric ingredients drive rainfall divergence across members and how that spread evolves with time, remains an open question for Meiyu-season convection.

The 2022 PRECIP and TAHOPE joint field campaigns provide a unique foundation for addressing this question. The campaigns produced a comprehensive set of radar, radiosonde, and surface observations of Meiyu-season convection over Taiwan and the surrounding ocean, supporting both direct analysis of the observed storm structures (DeHart and Bell 2025) and controlled ensemble modeling studies initialized against the campaign observations. In particular, the Penn State University ensemble Kalman filter simulations (hereafter PRECIP PSU-EnKF) produced a 40-member convection-permitting WRF ensemble for each Intensive Observation Period, sampling the initial-condition uncertainty while keeping the model configuration fixed (Zhang et al. 2023). The first Intensive Observation Period (IOP 1), on 26–28 May 2022, captured a two-day extreme rainfall event associated with a persistent Meiyu front over northern Taiwan, and is the subject of Chapter 4 of this dissertation. Applying the storm-mode and ingredients-based frameworks developed in the preceding chapters to this ensemble provides an opportunity to test whether the physical drivers of ensemble spread can be diagnosed using the same variables that organize the climatology and the deterministic terrain experiments shown in Chapters 2 and 3, respectively.

1.3 Dissertation Objectives and Outline

The objective of this dissertation is to develop a coherent physical framework for the understanding and prediction of Meiyu-season extreme rainfall over Taiwan by applying a common set

of storm-mode and ingredients-based diagnostics across three complementary studies. The three studies progress from climatological context to physical mechanism to ensemble predictability, and the common framework is designed to make the connections among them explicit.

Chapter 2 presents a climatology of extreme convective storm modes across tropical and subtropical East Asia based on 15 years of TRMM Precipitation Radar observations. The climatology establishes which storm modes contribute the most volumetric rainfall over Taiwan and identifies the ingredient composites, in terms of vertical moisture flux, moisture divergence, and low-level shear, that characterize the environments in which each mode occurs. The results identify Deep and Wide Convective Cores and Broad Stratiform Regions as the dominant rainfall contributors in the moisture-rich Meiyu environment and motivate the process-based studies of these modes that follow.

Chapter 3 presents a terrain-sensitivity study of the 1–3 June 2017 extreme Meiyu event over Taiwan, using a convection-permitting WRF simulation with a halved-terrain experiment to isolate the role of the CMR. The study compares storm-mode frequency, spatial distribution, and ingredient composites between a control simulation and a simulation with the CMR height reduced by 50%, identifying the physical mechanisms by which terrain height reshapes the storm-mode balance. Upward vertical velocity and vertically integrated moisture flux emerge as the key variables linking terrain modification to storm-mode reorganization and rainfall change, setting up the ingredients-based framework that carries forward into the ensemble analysis.

Chapter 4 presents an ensemble analysis of the PRECIP 2022 IOP 1 event, using a 20-member subset of the PRECIP PSU-EnKF WRF ensemble with full 48-hour output. An algorithm called ISLAND (Ingredients-based Storm aLgorithm Applied to the eNsemble Data) is developed to calculate a wide range of ingredients associated with each storm mode identified in the ensemble simulations. The study examines the ensemble spread in 48-hour total rainfall, identifies which atmospheric ingredients distinguish high-rainfall from low-rainfall members, and diagnoses how the storm-mode organization differs between the two groups. A key finding is that ensemble rainfall spread is governed by domain-integrated upward moisture transport rather than by column mois-

ture content, and that the separation between high- and low-rainfall members is established at the first model output time and persists through the active phase of the event. This result indicates that the rainfall spread originates from initial-condition differences rather than from error growth during the simulation and has direct implications for the operational forecasting of Meiyu rainfall.

Chapter 5 synthesizes the findings from the three studies that when combined, provide important implications for the understanding and prediction of heavy rainfall in Taiwan and the surrounding areas.

Chapter 2

A climatology of extreme convective storms in tropical and subtropical East Asia and their ingredients for heavy rainfall as seen by TRMM¹

2.1 Introduction

Heavy rainfall is a high-impact weather phenomenon that disrupts the economy and impacts human life around the world every year. In the US, flooding is the second most deadly weather-related natural disaster (Ashley and Ashley 2008). The contiguous US also broke the 12-month record of highest precipitation in July 2018–June 2019, and the top six of the wettest 12-month periods have been in the past ten years (Leslie 2019). The US has also recently seen multiple state rainfall records broken due to tropical cyclones (TCs) such as Hurricane Harvey (Brauer et al. 2020; DeHart and Bell 2020) and Hurricane Lane (Nugent et al. 2020). Rainfall systems that produce heavy rainfall vary in their intensity and duration across a wide spectrum of storm types, such that an extreme rainfall event needs to have high intensity, long duration, or both. Given the wide variety of rainfall systems that can produce heavy rainfall, it is very challenging to predict these events using numerical weather prediction (NWP) models (Sukovich et al. 2014).

In addition to having a large impact in the current climate, heavy rainfall is expected to increase in a future warmer climate given that the increasing global-mean temperature will increase the amount of water vapor in the atmosphere by 7% per degree Celsius according to the Clausius–Clapeyron relation. Climate change may lead to an increase in precipitation and probability for

¹The results outlined in Chapter 2 have been published in the *Journal of Geophysical Research: Atmospheres*: Panawatwong, W., K. L. Rasmussen, and M. M. Bell, 2022: A climatology of extreme convective storms in tropical and subtropical East Asia and their ingredients for heavy rainfall as seen by TRMM. *J. Geophys. Res.: Atmos.*, **127**, e2022JD036 863, doi: 10.1029/2022JD036863. ©American Geophysical Union. Used and adapted with permission.

floods with extreme rain characteristics (Dougherty and Rasmussen 2020, 2021). For example, the precipitation from the intense convective storms and the chance for flash floods over the Mississippi river basin is expected to increase in the warming future (Dougherty and Rasmussen 2021). In addition, an overall increase in rainfall and flooding associated with TCs is expected to increase (Knutson et al. 2020; Gutmann et al. 2018). In the US, the total damage may increase in the future due to the growing population in coastal cities impacted by TCs (Klotzbach et al. 2018).

To investigate the common factors of different extreme rainfall events, Doswell et al. (1996a) proposed the ingredients-based framework for understanding rainfall intensity (I) and duration (D) separately, such that

$$P = I \times D, \quad (2.1)$$

where P is the net accumulated precipitation. The intensity can be represented as

$$I = Ewq, \quad (2.2)$$

where E is precipitation efficiency, w is vertical velocity, and q is the water vapor mixing ratio. The duration is the amount of time that a storm is present over an observing point,

$$D = L/C \quad (2.3)$$

where L is the length scale of the storm, and C is the horizontal velocity of the storm along that length scale. This framework can be used to evaluate the spectrum of storms producing heavy precipitation from NWP models as well as from observations, making it a useful framework to improve our understanding of heavy rainfall.

A key ingredient for heavy rainfall production is moisture, as represented by the water vapor mixing ratio in Doswell's framework ((2.2)). In many arid or continental regions, floods are often the result of an unusually high moisture air mass being advected into the area. These anomalous high moisture environments may lead to an under-prediction of heavy rainfall from NWP models.

For example, the 2013 Front Range flood in Colorado was not well forecasted because of the underestimated high moisture air with a tropical characteristic located east of the Rocky Mountains for an extended period of time, leading to a significant underestimate of rainfall from both NWP models and radar-estimated rainfall (Gochis et al. 2015). The 2010 Leh India and Pakistan floods (Houze et al. 2011; Rasmussen and Houze 2012) and other extreme floods in Pakistan (Rasmussen et al. 2015) were also the result of the combination of anomalous high moisture air masses that were orographically lifted along the foothills of the Himalayas.

In contrast to arid environments, tropical oceanic regions frequently have abundant moisture available for rainfall production. The presence of ample water vapor is only one necessary but insufficient condition for heavy rain. For example, in Tropical and Subtropical East Asia (TSEA) during the spring and summer months, the southwest monsoonal flow provides an ample supply of water vapor from the deep tropics into the subtropics. In these moisture-rich environments, the variability in the other ingredients in Doswell's framework take on a greater role. In the TSEA region, the Meiyu front associated with the East Asian monsoon often provides a focal point for vertical motion over a large area and long duration, leading to frequent extreme rainfall and extreme storms to the region from May to July (Akiyama 1973b; Ding and Chan 2005b; Sampe and Xie 2010b). In addition, TCs frequently pass through this region in July–August, bringing additional extreme rainfall events into the region (Chen et al. 2007b; Wu et al. 2017).

A campaign called the Prediction of Rainfall Extremes Campaign in the Pacific (PRECIP) will study the processes producing heavy rainfall in the moisture-rich environment of TSEA. The PRECIP study region is focused on Taiwan and southern Japan where heavy rain events are common due to the abundant monsoon moisture and presence of the Meiyu front, tropical cyclones, land–sea contrasts, and complex terrain. In preparation for the PRECIP field campaign, it is important to have a broader understanding of the nature of precipitating systems with extreme characteristics in the TSEA. In this study, we utilize observations from the Tropical Rainfall Measuring Mission (TRMM) satellite's Precipitation Radar (PR) that allows us to observe a wide spectrum of storms over the entire TSEA region over a multi-year record from 1998–2013. TRMM PR ob-

servations have provided unprecedented information to study the nature of precipitating systems globally (Houze et al. 2015b; Zipser et al. 2006), including rainfall associated with the Indian summer monsoon (Houze et al. 2007b; Romatschke et al. 2010), floods in India and Pakistan (Houze et al. 2011; Rasmussen et al. 2015; Rasmussen and Houze 2012), and deep convection east of the Andes in subtropical South America (Rasmussen et al. 2014; Rasmussen and Houze 2011b, 2016). The TRMM PR dataset is used herein to analyze the seasonal and regional variability of several different types of extreme storms.

In the first part of this study, the variability of extreme storms and their rainfall characteristics is investigated over the TSEA region (Figure 2.1, Section 2.3). The second part of the study looks specifically at Taiwan and the ingredients supporting extreme storms observed by TRMM in this region (Section 2.4). Overall, this study uses Taiwan and TSEA as a natural moisture-rich laboratory to study the spectrum of precipitating systems producing heavy rainfall and the ingredients that support such systems, with the goal to improve the prediction of heavy rainfall in the current climate and also understand how climate change may impact future heavy rainfall events.

2.2 Methodology

This study focuses on understanding the nature of convection in the TSEA region shown in Figure 2.1. For the purposes of this study, TSEA is divided into nine subregions each with a predominant land or sea type description in Table 2.1. As the size of the subregions varies, the number of storms in each subregion is a reflection of both the size of the subregions and the climatological frequency of different storm types.

This study identifies the extreme storm events and analyzes the rain echoes from 1998–2013 using TRMM PR version 7 rain characteristics (2A23; Awaka et al. 1997) and rainfall rate and profile (2A35; Iguchi et al. 2000b,a) products. The TRMM PR orbital data are remapped into Cartesian coordinates of 250 m vertical resolution and ~ 5 km horizontal resolution following the methodology from Houze et al. (2007b). The data was geolocated and remapped to accommodate



Figure 2.1: Geographical location of Tropical and Subtropical East Asia and its subregions during May–September. Blue boxes mark sea-only subregions. Black boxes mark land-only subregions and the land-and-sea subregion (namely Taiwan).

Table 2.1: Number of TC-related and not TC-related storms, respectively, by each extreme storm type and subregion from 1998–2013 for every month.

Storm type	Subregions (land–sea type)						
	N Pacific (Sea)	SE China (Land)	Taiwan (Land&Sea)	Philippines Sea (Sea)	Philippines (Land)	South China Sea (Sea)	Indochina (Land)
DCCs	1267: 4268	1542: 7963	136: 337	176: 1534	394: 2583	642: 3530	248: 1595
DWCCs	622: 2451	501: 3198	68: 150	129: 726	102: 638	309: 1222	79: 386
WCCs	899: 6205	144: 1566	80: 205	130: 654	94: 252	327: 1081	81: 164
BSRs	591: 3838	145: 1583	34: 47	45: 128	32: 63	138: 242	26: 41

for the beam width and scan width angle geometry into the correct Cartesian grid points in three dimensions. Raining pixels from each storm are categorized into convective or stratiform components from the 2A23 product. Three-dimensional radar reflectivity data are separated into extreme storm types that represent different phases of convective development and organization. We use the definition of four extreme storm types following the ‘moderate’ criteria used in Houze et al. (2015b) to account for the predominantly maritime environment of TSEA. The storm categories are defined as: (1) Deep Convective Cores (DCCs) with ≥ 30 dBZ echo volumes ≥ 8 km in altitude; (2) Wide Convective Cores (WCCs) with ≥ 30 dBZ echo volume ≥ 800 km² in horizontal area; (3) Deep and Wide Convective Cores (DWCCs) are storms that satisfy both the DCC and WCC criteria; and (4) Broad Stratiform Regions (BSRs) with a contiguous stratiform rain area $\geq 40,000$ km² in area.

Although TCs frequently influence the TSEA region, this study only considers extreme storms that do not have a nearby TC influence to simplify the interpretation of the results. We filtered out TC-related storms because the environment and ingredients supporting such storms are likely different from those not affected by TCs due to possible influences on the background wind, moisture, and other rainfall ingredients. As such, the TRMM-identified storms are removed from the database if a TC was within 750 km of the storm location. The TC identification is performed following Brown et al. (2016) which had matched TRMM TMI swaths with TC best track data. The TC filtering results in a 10–45% reduction in the number of TRMM-identified storms, depending on the region (Table 2.1).

For each subregion, the land–sea mask is then applied to the storm core location, considering only storms with center points over only land or sea (Table 2.1). Taiwan is the only subregion where we consider storm cores that occur both over land and sea, particularly to understand the storm climatology over the region that is relevant for the PRECIP 2022 field campaign.

To focus on the peak rainfall season of the TSEA region, the analysis focus on the monsoonal months of May–September. Only the monthly distribution analysis and the storm number distribution for each subregion are computed over the entire twelve months.

The monthly distribution of each extreme storm type in each subregion is computed over the annual cycle. The number of storms is normalized by the total number of each storm type in each subregion shown in Table 2.1, because the cumulative number of storms that occur in each subregion is variable and this allows for comparisons across the annual cycle. It is worth noting that the number of BSRs can be significantly lower than other types for some subregions (Table 2.1). For example, the number of BSRs in Indochina and Taiwan is smaller than the other regions, but their number is still large enough for the monthly distribution analysis.

Rain characteristics are calculated to examine the distribution of the rain intensity (mm/hr) and volumetric rain rate (kg/s) during the extended warm season (May–September). They are computed using the Z–R method for determining surface rainfall from Romatschke and Houze (2011) and Rasmussen and Houze (2016) to correct the bias of the TRMM PR of underestimating the rain intensity over land (Rasmussen et al. 2013) and from storms with higher echo-top heights (Gingrey et al. 2018).

Contoured Frequency by Altitude Diagrams (CFADs) are calculated for storms that fall within the boundaries of the subregions (Figure 2.1) during the extended warm season. Thus, a storm may be counted toward more than one subregion if they fall across region boundaries. This method is meant to take into consideration the horizontally larger storms (i.e., WCCs and BSRs). To create the CFADs, we sum the full-storm 3D reflectivity of each extreme storm for each subregion by their height and take the histogram of each height level by their reflectivity. The distribution of each level is then normalized by dividing by the maximum number of pixels at that specific height level.

ERA5 reanalysis (Copernicus Climate Change Service (C3S) 2017) is used to calculate the ingredients-based composites of the mesoscale environments supporting extreme storms between 5–35°N and 97–150°E during the extended warm season. We select 850 hPa vertical moisture flux and vertically integrated moisture divergence to represent the intensity factors from Doswell’s ingredients-based framework ((2.1)) and the 700–900 hPa low-level shear (LLS) to represent the influence of the Meiyu front (Akiyama 1973b; Sampe and Xie 2010b). To make the daily-mean

composite maps of these ingredients, we choose the date from the TRMM overpass timestamp of each storm type over Taiwan. The all hourly data from that date from ERA5 is then averaged together to create a daily average composite map of each ingredient during extreme storms over Taiwan. This process is repeated for each storm type in each subregion. The time-lag of these ingredients is computed from area-averaged hourly-averaged ERA5 data for each subregion from seven days before to seven days after the time each echo was observed by TRMM PR.

2.3 Climatology of storms containing deep convective cores, wide convective cores, and broad stratiform regions in tropical East Asia

2.3.1 Seasonal and regional variabilities of extreme radar echo structures

To understand the seasonal and regional variability of the spectrum of storms seen by TRMM, we analyzed the monthly distribution of storms with extreme characteristics in each subregion across TSEA. Figure 2.2 shows the geographical distribution of the probability of finding each extreme echo type (i.e., DCCs, WCCs, and BSRs) from May to September of 1998–2013 using TRMM PR data. The probability is scaled according to the TRMM overpass frequency over each pixel to take into account the differential sampling across latitudes as has been done in previous studies (Houze et al. 2007b, 2015b; Romatschke et al. 2010).

Figure 2.2a shows that DCCs are found throughout the TSEA region, with a notable minimum over the central Pacific Ocean. DCCs tend to cluster along the coastlines and the mountain ranges, suggesting that coastal effects and orographic lifting may influence their development. The distribution of DWCCs (Figure 2.2b) is similar to DCCs. They cluster even stronger along some coastal and mountain range locations, suggesting that there might be some local effect at play on top of the coastal effects and orographic lifting. It is well established from prior research using the TRMM satellite’s Precipitation Radar that the deepest convective storms on Earth occur over land regions (Zipser et al. 2006; Houze et al. 2015b). The primary reason for this preference is the connection

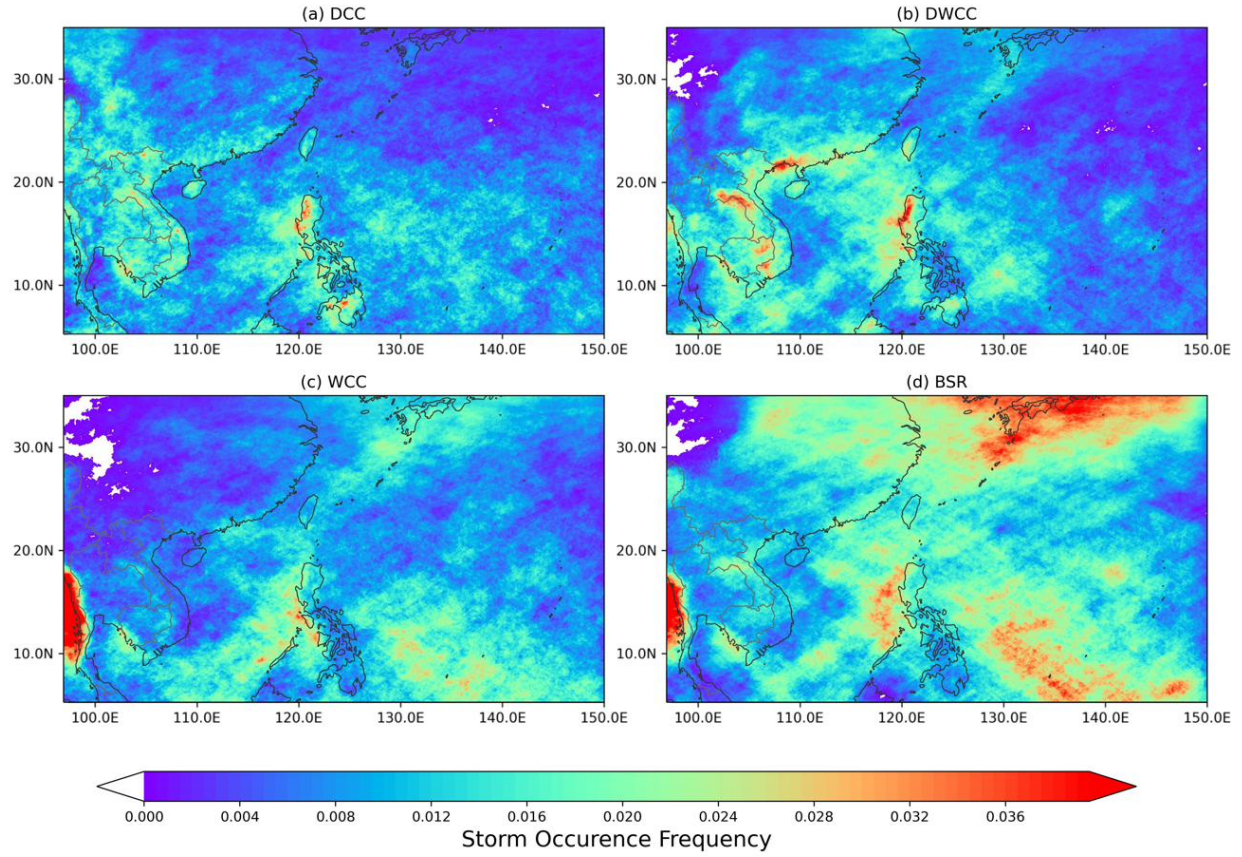


Figure 2.2: Geographical distribution of the probability of finding (a) DCCs, (b) DWCCs, (c) WCCs, and (d) BSRs over Tropical and Subtropical East Asia during May–September.

to the significant diurnal heating effects over land that are necessary for the generation of vigorous updrafts with strong buoyancy in general (Yu et al. 2021, and many others).

On the other hand, WCCs and BSRs are found over the oceanic regions (Figure 2.2c, d), suggesting that WCCs share similar environmental ingredients with BSRs despite of WCCs being of convective type. The BSRs are more likely to occur over ocean regions as they often need enhanced moisture on a broader scale, both in time and space perspectives. Thus, oceanic and moist regions around the world tend to have enhanced stratiform activity (e.g., Houze et al. 2015b). Over the North Pacific subregion, BSRs concentrate over the northern border of TSEA. Extreme rainfall in this region is associated with both mid-latitude weather systems influencing the subtropics and the Meiyu front. Over the southern subregions, BSRs concentrate over the South China Sea off the west coast of the Philippines and spread out over the Philippine Sea. These latter high probability locations may be associated with the west Pacific warm pool region, as large areas of stratiform precipitation were documented by the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE). The region has large regions of stratiform precipitation that developed along the zonal wind shear as influenced by the westerly wind burst from the Kelvin–Rossby wave (e.g., Chen et al. 1996; Houze et al. 2000). Thus, the probability of BSRs in TSEA is the highest among the extreme echo categories based on their high detection in the TRMM record. However, as Table 2.1 shows the number of each extreme echo type over each subregion, the absolute number of BSRs are lowest among all types even for the oceanic subregions. Their high probability of detection is a result of their larger horizontal area and tendency to last longer than the other extreme echo types.

Analysis of the normalized monthly occurrence of the extreme storm types in each subregion is shown in Figure 2.3. The subregions on the x-axis are grouped into the northern subregions on the left (i.e., North Pacific, Southeast China, and Taiwan) and the southern subregions on the right (i.e., Philippine Sea, Philippines, South China Sea, and Indochina). In general, DCCs and DWCCs show similarities in the monthly storm occurrence variability across the subregions (Figure 2.3a, b) with the exception of North Pacific and Taiwan. In contrast, the monthly distribution of WCCs

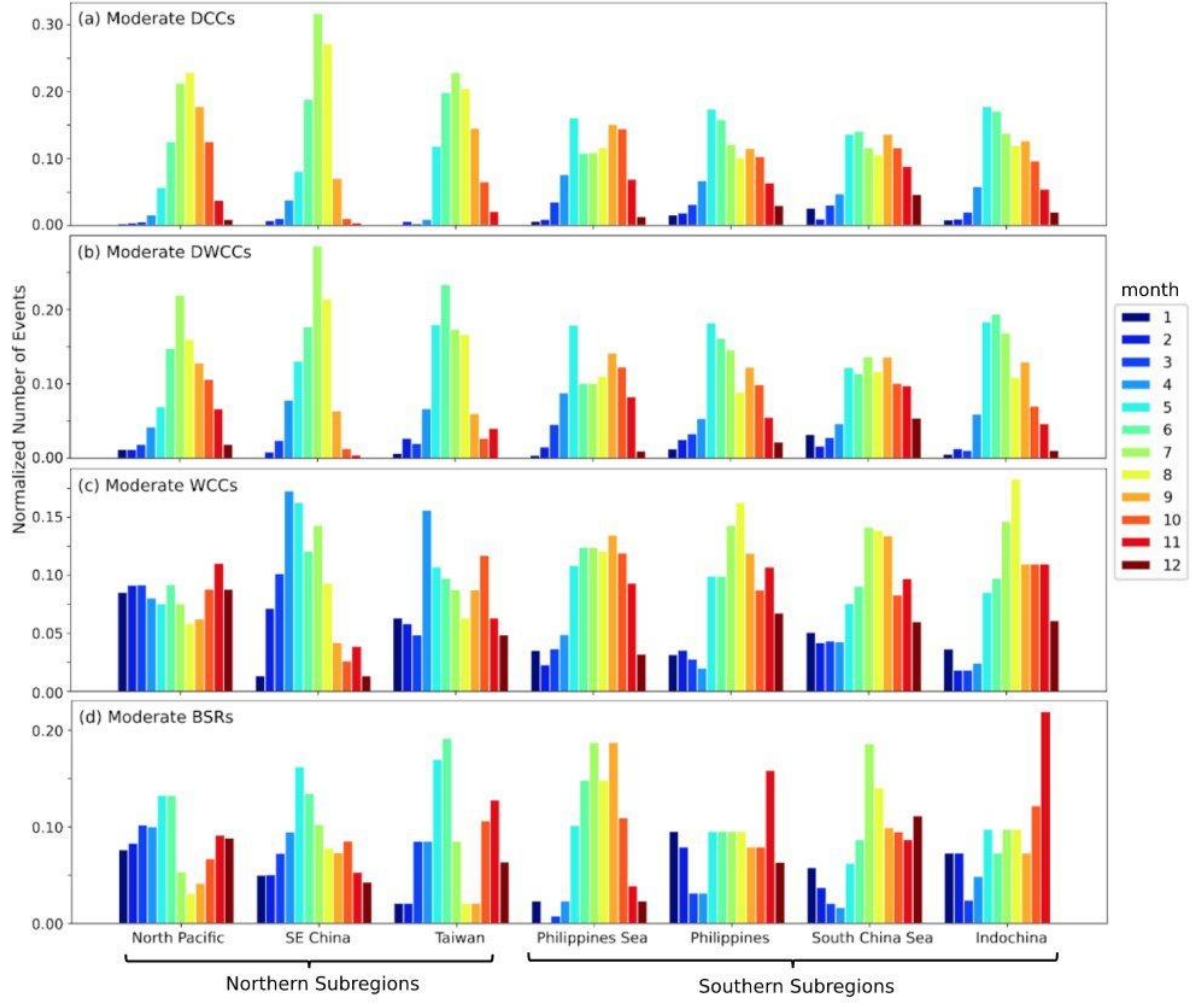


Figure 2.3: Normalized monthly occurrence distribution of (a) DCCs, (b) DWCCs, (c) WCCs, and (d) BSRs in each subregion as observed by TRMM PR from 1998–2013. Colors denote each month of the year.

differs from DWCCs (WCCs with deep components), particularly those in northern subregions (Figure 2.3c). The distribution of BSRs is different from the convective categories, suggesting that the environment supporting BSRs varies from those supporting convective categories. The northern and the southern subregions also show similarities in monthly storm occurrence for DCCs and DWCCs storm types.

In the northern subregions, DCCs and DWCCs show a higher probability of occurrence in the summer. Southeast China DCC and DWCC storms peak in July and have a similar monthly frequency pattern, with a slightly earlier occurrence of DWCCs from April compared to DCCs (Figure 2.3a, b), implying that the subregion has sufficient ingredients for both DCCs and DWCCs at the same time. DCCs in the Taiwan and North Pacific regions have a similar shape in the seasonal distribution, possibly suggesting similar seasonal shift of environment, such as large scale upward motion, during the peak of the East Asian summer monsoon season (Trenberth et al. 2000; Ding and Chan 2005b). While DCCs in Taiwan peak in July, those in the North Pacific region peak in August (Figure 2.3a). Their DWCC counterparts peak a month earlier than their DCCs, in June for Taiwan and July for North Pacific (Figure 2.3b), suggesting that there is some difference in the environment that support the congregation of convective cores from DCCs into the larger DWCCs in the earlier months. The Taiwan and North Pacific DWCCs occurrence frequency patterns also differ more from each other. While Taiwan shows a May–September occurrence, the North Pacific frequency skews toward the second half of the year.

The southern subregions have a broader spread in occurrence with double peaks in the spring and fall seasons for DCCs and DWCCs (Figure 2.3a, b), a characteristics of precipitation observed in the region (Lau and Yang 1997). To illustrate, Indochina and the Philippines are both ‘land-only’ regions and have a similar distribution. The distribution of DCCs in these regions each has a peak in late spring (i.e., May) and a lower peak in September. DWCCs in Indochina and the Philippines also have a similar distribution compared to DCCs (Figure 2.3a, b), but with an even higher probability of occurrence in spring and summer, peaking from May to July with higher

relative frequency in September, highlighting that the environment during the spring and summer season is favorable for both DCCs and even more for DWCCs in Indochina and the Philippines.

On the other hand, the Philippine sea DCCs occur primarily in fall and winter, peaking in September and October, but also have a secondary peak in May earlier in the year. Philippine sea DWCCs also show a similar frequency pattern, peaking higher in May and September. The South China Sea DCCs shows an almost equal probability for spring-to-summer and fall-to-winter occurrences, with a DCC maxima in May and June before increasing again in September. The South China Sea DWCC frequencies do not increase in spring or early fall like the other southern subregions, with a more uniform distribution while still having a similar seasonal distribution for summer-to-winter like South China Sea DCCs. The difference between the land and sea subregions suggests that there is the difference between their environment that may play a role in the southern subregions.

Even though DWCCs and WCCs share the same echo area criteria, WCC distributions differ from DWCC, especially in the northern subregions (Figure 2.3c). The biggest contrast is in North Pacific, where WCCs occurs more uniformly across the year compared to DWCCs. On the other hand, Southeast China's WCC distributions peak earlier in April–May in association with the regional spring rain (LinHo et al. 2008), while DWCCs maximize later in July. Taiwan WCCs show bimodal occurrence distributions, peaking in April also in association with the spring rain (Hung et al. 2004) with a secondary maximum occurring in October possibly due to early winter cold fronts which occur mostly to the northeast of Taiwan (Henny et al. 2021; Chen and Chen 2003). This frontal system should provide the shear for the storm to develop structure into larger storms. This Taiwan WCC distribution contrasts its DWCC distributions peaking in June.

In the southern subregions, WCCs show less of a bimodal distribution than DCCs and DWCCs. Southern WCC distributions essentially peak in between the two modes of DCCs and DWCCs over the summer months into September while maintaining the majority of occurrence between May–November. The Philippine Sea WCCs show broad occurrences from May to November, significantly higher than the other months. The Philippines and South China Sea WCCs have sharper

peaks from July to September and a lower peak in November. Indochina similarly shows a peak in July and August. These southern subregions' WCC distributions are related to the maritime-continent monsoon (Chang et al. 2005).

The distribution of BSRs is distinct from the convective categories. In the northern subregions, BSR distributions all peak in May–June. Southeast China's DCC and DWCC distributions tend to maximize earlier in the year, while the WCC and BSR distributions tend to maximize later in the year. One difference between WCCs and BSRs in Southeast China is that WCCs peak from April to July and are infrequent in the winter months, while the BSRs peak in May. However, the BSR frequency in the North Pacific is not as uniformly spread, but rather peaks in May and June and decreases quickly to the August minimum, which is when TC-related events were removed the most (Table 2.1). Taiwan BSRs also peak a month after WCCs in May and June and drop sharply in August and September, before picking up again over October and November (Figure 2.3d).

The variability of the maximum month of occurrence across the northern subregions for BSRs reflects the northward movement of the Meiyu front (Ding 1992; Ding and Chan 2005b). The front establishes over Taiwan and Okinawa, Japan, in mid-May from the confluence of mid-latitude eddies and southerly moist air, marking the onset of the East Asian Monsoon, and progress northward to the Yangtze River Valley in China and mainland Japan (out of our region of interest) from mid-June to mid-July (Akiyama 1973b; Ding and Chan 2005b; Sampe and Xie 2010b). The Meiyu front is a convective rainband that occurs along a stationary front with a steep gradient of specific humidity, equivalent potential temperature, and low-level wind shear (Akiyama 1973b; Ninomiya and Shibagaki 2007b). We will use low-level wind shear as a proxy to mark the location of the Meiyu front relative to the extreme storms later in this study.

In the southern subregions, BSRs peak in July for sea-only subregions and over the end of the year for the land-only subregions. The sea-only subregions also have similar occurrence distribution shape to their WCCs counterpart. The Philippine Sea BSRs peak in July but also in September, with a narrower distribution compared to WCCs. The South China Sea BSRs also hold a similar distribution shape to WCCs, but with smaller variability as well, peaking largely in July with a

smaller peak in December. On the other hand, the land-only BSRs do not have similar occurrence distribution shape to their WCCs counterpart. Philippines and Indochina BSR occurrence distribution is relatively flat with a peak later in the year, in November and December respectively.

Overall, DCCs and DWCCs are shown to have a similar monthly distribution within northern regions with one peak, and southern subregions with having two peaks. WCC distributions differ from DWCC, especially in the northern subregions, even though they share the same echo area criteria. The BSR distribution differs from the convective categories, suggesting that the environment supporting BSRs varies from others. In the northern subregions, BSRs are influenced by the East Asian summer monsoon and the accompanying Meiyu front.

2.3.2 Variability of rainfall characteristics for extreme storm categories

A key characteristic of the extreme storm climatology is rainfall intensity, from which important features of the extreme storm variability and hydrometeorological impact across the TSEA region can be assessed. To focus on the heavy rainfall season, the analysis will focus on the monsoonal months of May–September from this point onward. Figure 2.4 shows that storms containing extreme convective cores (i.e., DCCs, DWCCs, and WCCs) generally produce higher rain rates than storms containing large stratiform regions (i.e., BSRs). The convective events produce higher rain rates overall compared to stratiform rainfall, which is consistent with prior research on this topic (Ulbrich and Atlas 2002).

Among the convective core storms, DCCs and DWCCs produce a higher mean rain rate of about 5 mm/hr compared to 4 mm/hr associated with the WCCs (Table 2.2). Thus, deep convective storms with significant reflectivity values at higher altitudes compared to WCCs tend to produce higher rain rates. One interesting result from another study using TRMM radar observations is that the heaviest rainfall-producing storms are not necessarily the tallest storms due to the importance of warm-rain processes (Hamada et al. 2014). Although their study looked at different regions of the world, it is important to note the similarities and differences between our results. One important point is that the TRMM 2A25 rain rate product as used in Hamada et al. (2014) tends to

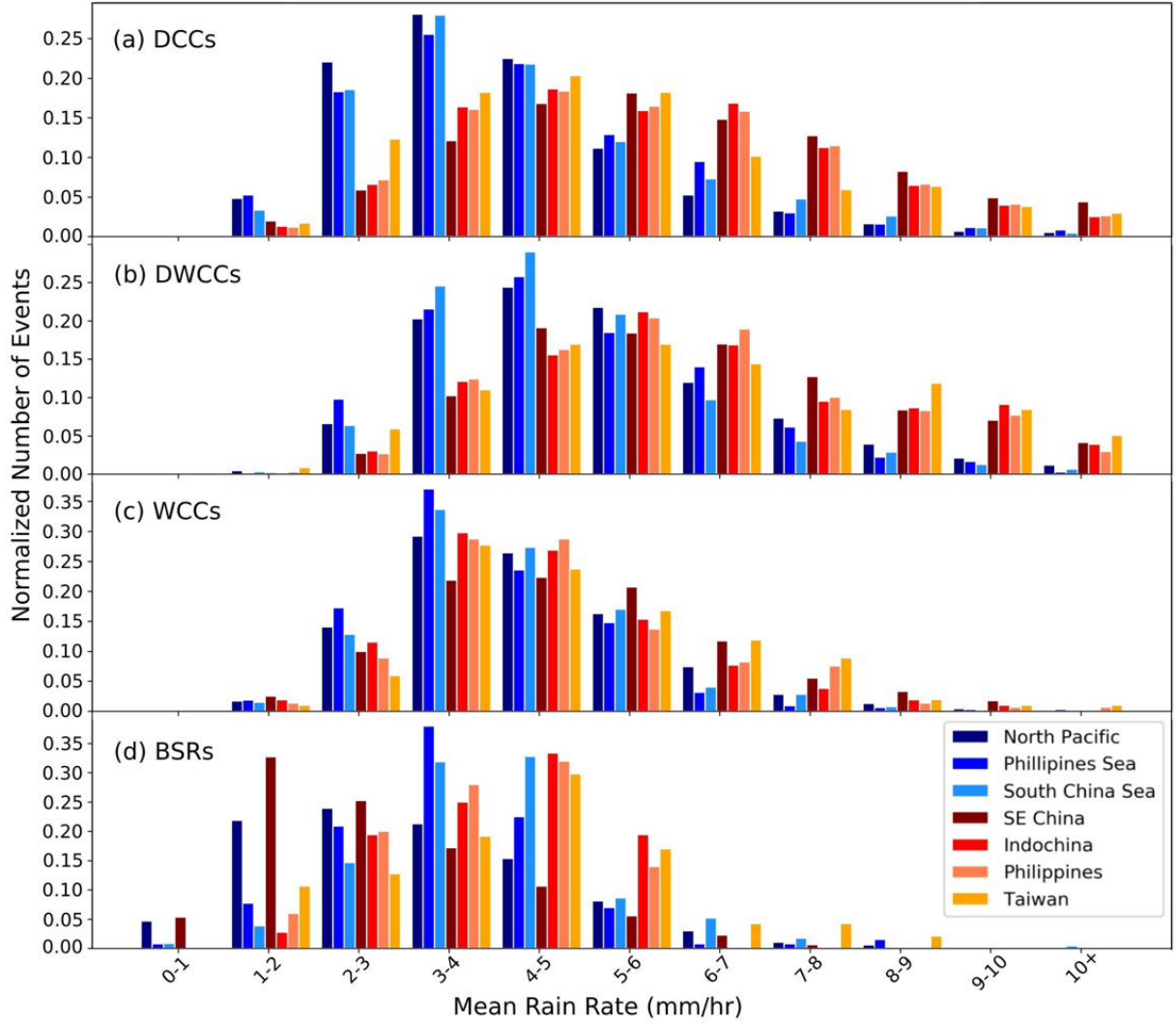


Figure 2.4: Normalized frequency of mean rain rate of (a) DCCs, (b) DWCCs, (c) WCCs, and (d) BSRs in each subregion during May–September. The blue bars represent the sea-only subregions. The orange bars represent the land-only subregions, and the yellow bar represents Taiwan.

Table 2.2: Mean and standard deviation of full storm mean rain rate and volumetric rain for each storm type during May–September.

Statistics	DCCs			DWCCs			WCCs			BSRs		
	land	sea	all	land	sea	all	land	sea	all	land	sea	all
Mean rain rate (mm/hr)	5.31	4.49	5.00	6.36	5.00	5.69	4.99	4.17	4.37	3.05	3.43	3.22
SD rain rate (mm/hr)	3.27	1.85	2.86	2.55	1.79	2.31	2.25	1.33	1.64	1.51	1.42	1.45
Mean vol. rain (kg/s)	5.85	12.80	8.48	16.89	5.00	5.69	19.56	24.27	23.19	71.61	84.66	80.99
SD vol. rain (kg/s)	14.65	27.84	20.94	26.27	39.28	2.31	31.59	37.39	36.20	48.22	51.67	51.06

underestimate rain rate in highly convective storms over land due to attenuation in TRMM Ku-band and non-uniform beam filling (Gingrey et al. 2018; Iguchi et al. 2009; Rasmussen et al. 2013). In response to this underestimation, the TRMM rain rate is computed with a Z–R relationship to avoid the low rain bias as was previously done in Rasmussen et al. (2013) and suggested in Gingrey et al. (2018). Thus, at least for the moisture-rich environment of TSEA, the heavier rainfall producing storms are associated with taller and more intense convective storms. Moreover, DWCCs that met both the height and area requirement produced a slightly higher mean rain rate than DCCs, as shown in Figure 2.4b. The larger storm area, mesoscale processes, and convective organization associated with DWCCs might help to increase rainfall through a reduction in dry air entrainment and other mesoscale dynamics that enhance vertical motion within organized convection (e.g., Rotunno et al. 1988). However, the difference between the DCCs and DWCCs mean rain rate distribution shape is sensitive to the selected interval. When increasing the interval to 2 mm/hr, the rain rate difference between the storm modes disappears.

The rain rate distribution in each subregion also highlights the differences between storms over land and sea. The warm colors indicate land-only regions and the cool colors indicate ocean-only regions, with the exception of Taiwan (yellow bars) that include both land and ocean regions. Rain rates over land subregions and Taiwan are higher than those over the sea subregions for almost all storm types. The difference is more obvious for the deeper storms than the wider storms. For DCCs (Figure 2.4a), the difference between the mean rain rates for ocean-only compared to land-only regions is evident across all subregions. This difference indicates that despite the variation in topography, land-surface type, and location across TSEA, all land-only regions have heavier convective rainfall compared to those over oceanic regions. The difference is less pronounced for DWCCs where the sea-only rain rates increase to $\sim 4\text{--}5$ mm/hr while the land-only rain rates stay the same (Figure 2.4b). Interestingly, the WCC rain rates for land- and sea-only show a much closer distribution, with the land-only rates being slightly higher overall (Figure 2.4c). This result suggests that storms with deep convection are more vigorous over land with higher rain rates, but storms with wide convective echoes have a similar rain rate distribution over both land and sea.

In contrast to the clear distribution in convective rain rates shown in Figure 2.4a–c, the rain rate distribution between land- and sea-only regions is more complex. As shown in Figure 2.4d, Southeast China is an outlier subregion with low mean rain rates of 1–2 mm/hr, while the other land-only subregions peak at 4–5 mm/hr. The sea-only subregions average around 3–4 mm/hr, which is lower than the land-only regions, except for Indochina. Higher rain rates over land can be explained by a more pronounced diurnal cycle than over the sea surface due to stronger daytime heating and nocturnal cooling over land regions (Yu et al. 2021). Orographic lifting could also help enhance the air motions and diurnal cycle.

Table 2.3: Mean and standard deviation of full storm area for each storm type during May–September.

Statistics of storm area	DCCs		DWCCs		WCCs		BSRs	
	land	sea	land	sea	land	sea	land	sea
Mean (km ²)	12,847	31,394	25,555	45,667	35,650	50,641	91,737	96,753
SD (km ²)	20,522	38,043	28,590	41,781	39,373	45,829	41,154	42,546

Another important rainfall metric beyond the mean intensity of the rain is the total rain volume produced by each extreme storm type shown in Figure 2.5. Volumetric rain can show the total rain accumulation the entire system can produce and more accurately represents the overall influence of the convective storm size and intensity relative to a mean rain rate estimate. In addition, volumetric rain is connected with the latent heat produced by the storm and is therefore important to examine in combination with the rain rate.

Despite producing the highest mean rain rates, DCCs produce the smallest amount of volumetric rain. DCC volumetric rain is smaller than DWCCs and WCCs by 10 times and BSRs by 20 times. This result is consistent with results from Rasmussen and Houze (2016) who showed that DCCs have the lowest percentage of rain contribution to the total rainfall compared to DWCCs, WCCs, and BSRs in subtropical South America. DCCs often represent the early phase of the convective lifecycle with vigorous, relatively short-lived and sometimes isolated convective cells that produce heavy rainfall locally, but do not tend to last for long periods of time (Houze et al. 2007b, 2015b). There is also no obvious volumetric rain distribution difference between the storms over

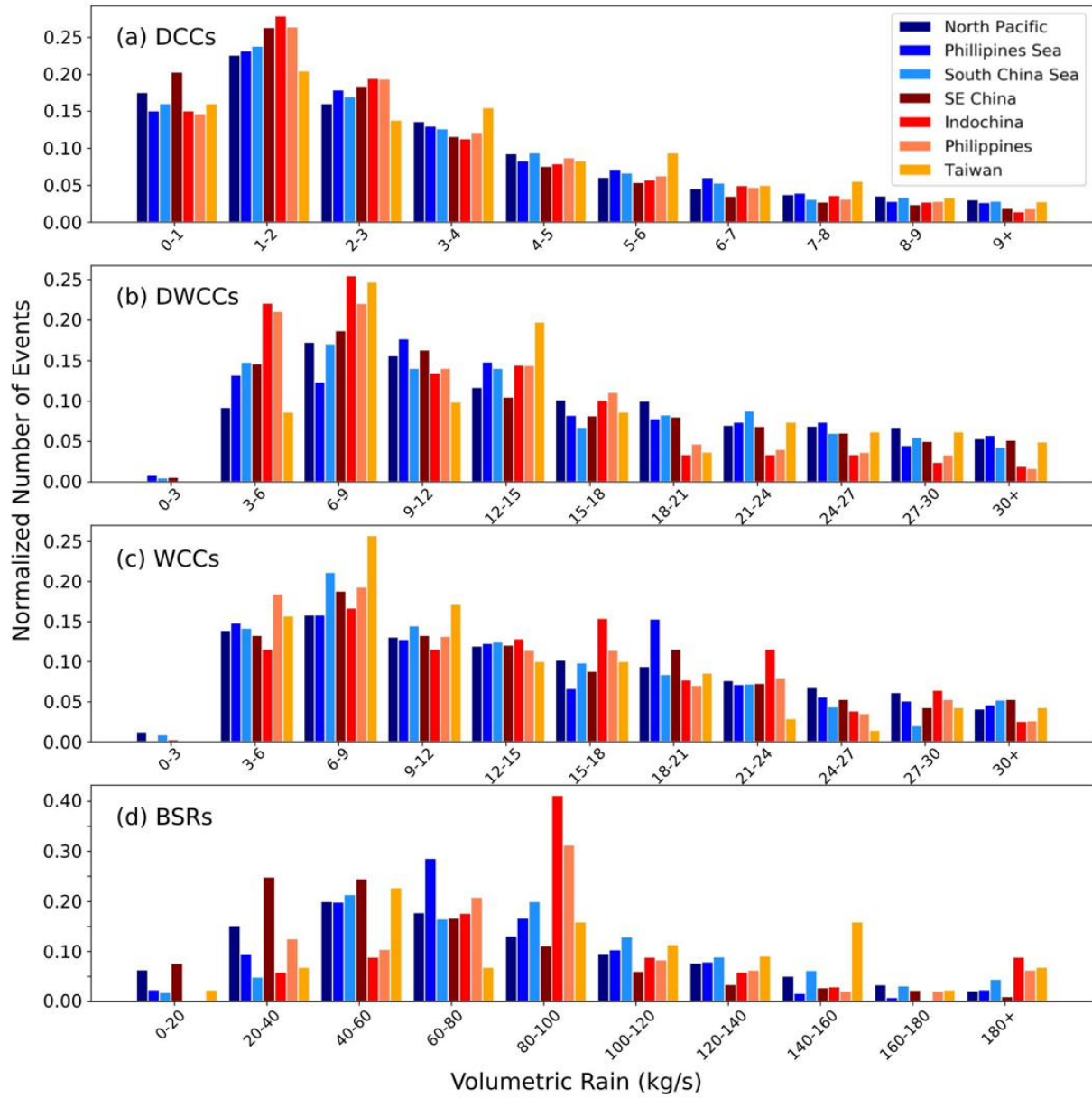


Figure 2.5: Same as Figure 2.4 but for volumetric rain.

land and sea (Figure 2.5a), contrasting with the distinct distributions of the mean rain rate distributions in Figure 2.4a. DWCCs also show the land-only regions skewed toward lower volumetric rain than the sea-only regions (Figure 2.5b). Given that the DWCC rain rates are also higher over the land than over the sea (Figure 2.4b), the DWCCs over land are generally smaller in size than those over the seas. In fact, DCCs and DWCCs over the sea have about double the mean horizontal area than those over land (Table 2.3). Overall, BSRs produced the most volumetric rain (Figure 2.5d), up to 20 times larger than DCCs due to the large horizontal area (Table 2.3).

Despite producing the lowest mean rain rates (Figure 2.4d), BSRs can produce the largest volume of rain. On the other hand, DCCs produced the least volumetric rain despite having the highest rain rates (Figure 2.5a), due in large part because the area is significantly smaller than DWCCs and WCCs (Table 2.3). Given that storm size is a factor in the rainfall duration of the ingredients-based approach ((2.1); Doswell et al. 1996a), understanding how both mean and volumetric rain rates vary across the storm modes provides important information on the hydrometeorological impact in the TSEA region.

2.3.3 Contoured Frequency by Altitude analysis

Contoured Frequency by Altitude Diagrams (CFADs; Yuter and Houze 1995) of the storm reflectivities from TRMM PR observations provide insights into the horizontal and vertical characteristics of the storms producing the rainfall described in the previous subsection. We normalized the frequency by the maximum frequency at a given altitude as is typical for CFAD analyses.

Figure 2.6 shows the normalized frequency of the reflectivity at a given height from all reflectivity observations captured by TRMM PR observations from May–September 1998–2013 in the TSEA region. The horizontal line at 5 km is marked as a reference for the approximate melting level, where the reflectivity is shifted to the right just below 5 km in Figure 2.6 due to the melting ice particle’s higher reflectivity or bright band. The vertical reference line at 30 dBZ marks where the low-level reflectivity frequently occurs from 20–30 dBZ, corresponding to the rain rate at the surface of up to 1–3 mm hr⁻¹. This estimated general rain rate is similar to that found during the

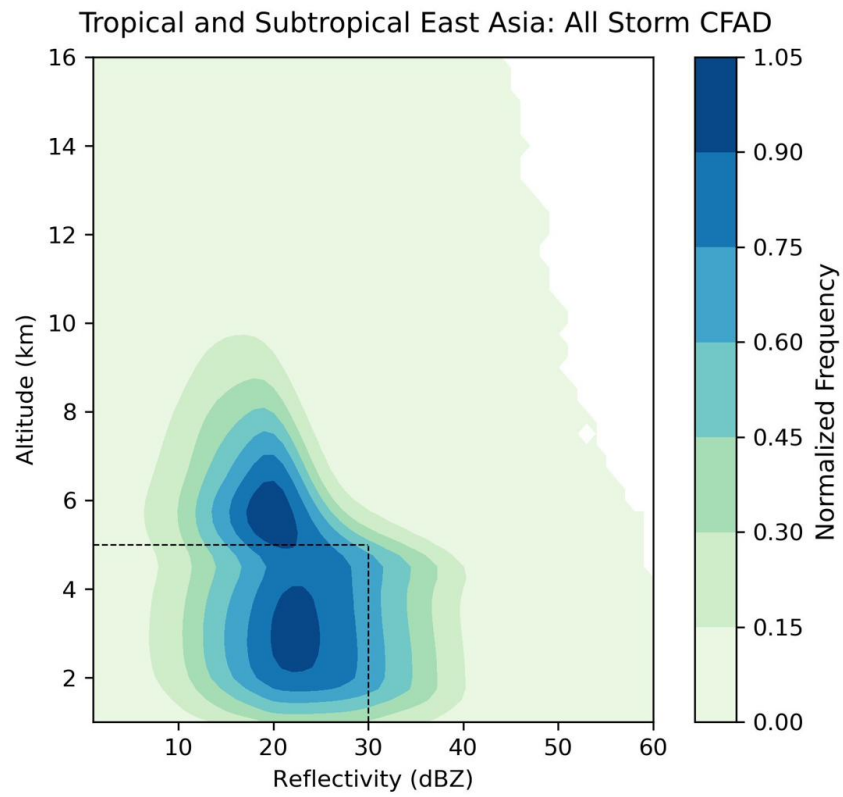


Figure 2.6: Contoured frequency by altitude diagram (CFAD) of all raining objects over TSEA during May–September.

Indian summer monsoon season in the Himalayan region of $1\text{--}2\text{ mm hr}^{-1}$ (Houze et al. 2007b). That region is located in the tropics and subtropics and is affected by the summer monsoon similar to the TSEA region, but is located outside of the West Pacific warm pool.

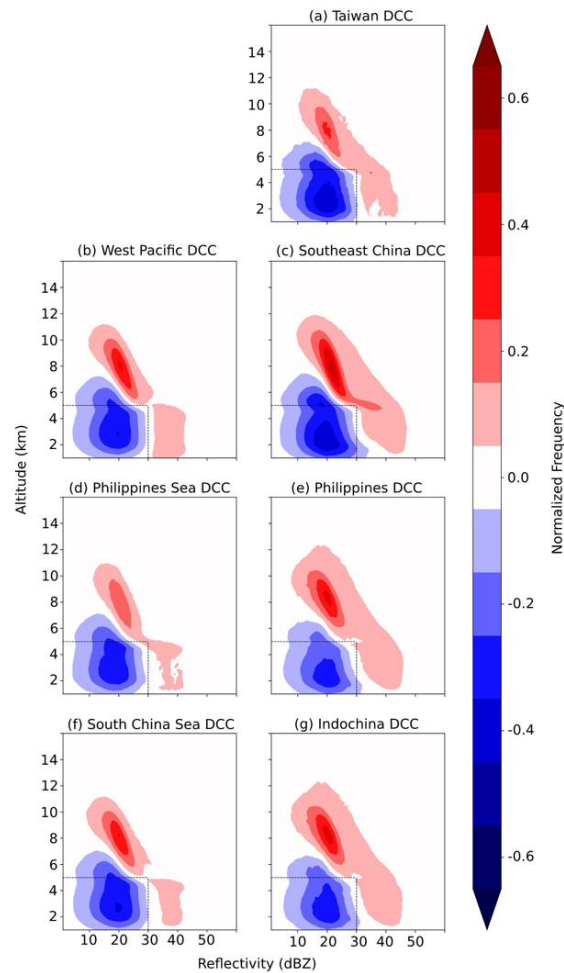


Figure 2.7: CFAD of DCCs for (a) Taiwan, (b) North Pacific, (c) Southeast China, (d) Philippines Sea, (e) Philippines, (f) South China Sea, and (g) Indochina during May–September. The left column represents sea-only subregions (b, d, f). The right column represents land-only subregions (c, e, g) and Taiwan.

To highlight the differences in the storm structures, the CFAD anomalies of each storm type and subregion are computed by subtracting the full TSEA CFAD (Figure 2.6) from each CFAD for

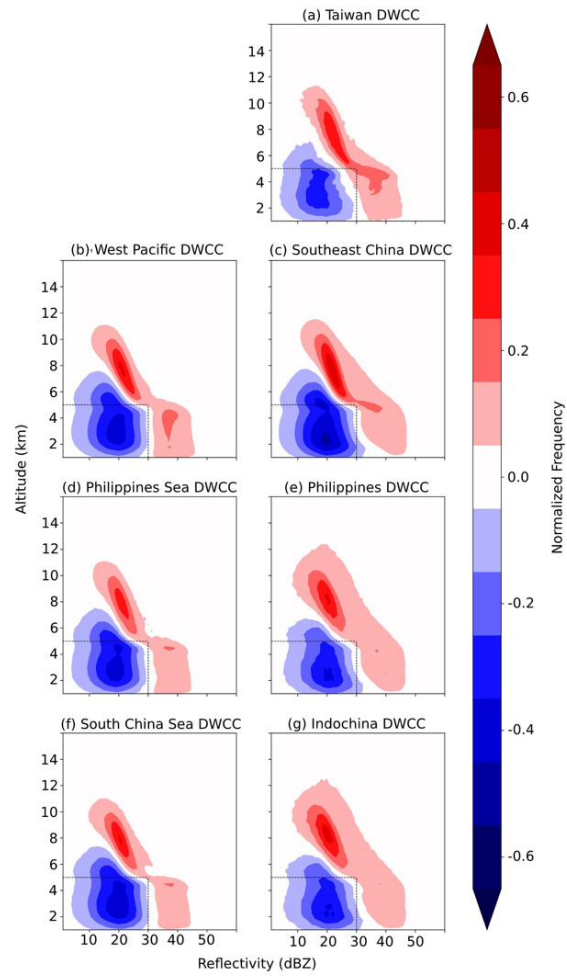


Figure 2.8: Same as Figure 2.7 but for DWCCs.

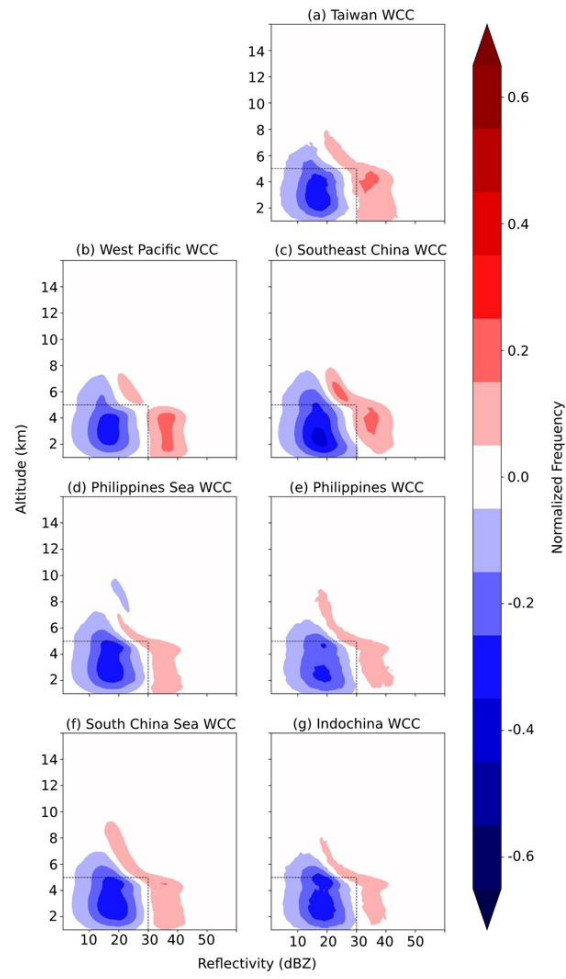


Figure 2.9: Same as Figure 2.7 but for WCCs.

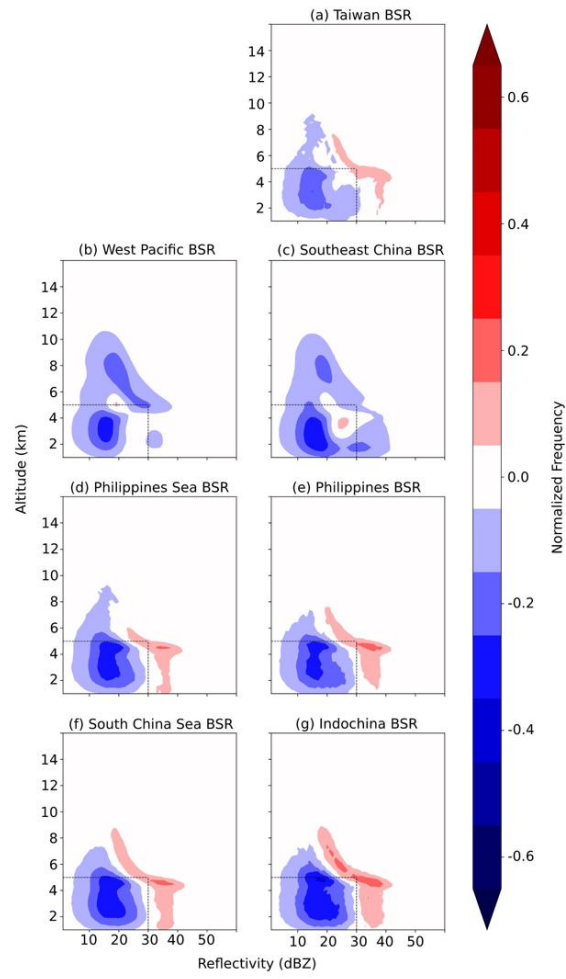


Figure 2.10: Same as Figure 2.7 but for BSRs.

DCCs, DWCCs, WCCs, and BSRs (Figure 2.7–2.10). The resulting CFAD anomalies of storms containing extreme convective cores (e.g., DCCs, DWCCs, and WCCs; Figure 2.7–2.9) show generally higher frequencies (positive anomalies) of reflectivity greater than 30 dBZ at low-levels and lower frequencies (negative anomalies) of reflectivity less than 30 dBZ from low-levels to slightly above the melting level. The higher reflectivity at low-levels for convective cores (Figure 2.7–2.9) compared to all of the raining data (Figure 2.6) is consistent with higher rain rate distributions compared to stratiform precipitation (Figure 2.4). The positive anomaly above the melting level demonstrates the strong convection characteristics by region in both height and vigor.

Among the three extreme convective core categories, DCCs and DWCCs share similar CFAD anomaly profiles (Figure 2.7 and 2.8), with strong reflectivity from the base to the cloud top, with a notable increase in reflectivity frequencies above the melting layer that reflects the convective core top height requirement. The land-only subregions (Southeast China, Philippines, and Indochina; Figure 2.7–2.8c,e,g) show that low-level reflectivity is also higher than the sea-only subregions by 5–10 dBZ, in agreement with the rain rate distributions in Figure 2.4a–b that the land-only rain rate mode is higher than the sea-only one. The land-only subregions also show a connected area of increased frequencies of reflectivity both above and below the bright band for both DCCs and DWCCs, indicating stronger convection overall. The Taiwan CFAD anomalies show the hybrid pattern of the land- and sea-only subregions. Even though Taiwan DCCs have a connected region of higher frequencies above and below the melting level like the land-only DCCs, Taiwan DWCCs have a stronger bright band like the sea-only DWCCs indicating the presence of larger stratiform precipitation regions over Taiwan associated with DWCCs compared to other regions.

Although WCCs have a higher frequency of high reflectivity values below the melting level (Figure 2.9) compared to the average TSEA rain CFAD (Figure 2.6), the magnitude is still lower than those associated with DCCs and DWCCs (Figure 2.7–2.8). The lower reflectivities also correspond with the lower rain rate distributions in Figure 2.4. Another distinct feature of WCCs from DCCs and DWCCs is that there is no obvious difference between the storms over land and ocean. However, WCCs in the northern subregions (West Pacific, Southeast China, and Taiwan;

Figure 2.9b,d,f) show a greater frequency of high reflectivity values at lower levels compared to those in the southern subregions (Philippines Sea, Philippines, South China Sea, and Indochina; Figure 2.9c,d,g). Interestingly, the West Pacific WCCs do not show a strong bright band signal.

The CFAD patterns for BSRs in TSEA (Figure 2.10) show similarities to WCCs (Figure 2.9). Although the CFADs do not show obvious differences in storms over land and sea, there is a difference in the northern and southern regions of TSEA. The most northern subregions, West Pacific and Southeast China, show BSRs with weak reflectivities overall. The four southern subregions show stronger bright bands, similar to their counterparts in WCC CFAD structures. Taiwan, in the middle of the two regions, shows a mix of both features with weak negative anomalies for low reflectivity values under the melting level with only a slight bright band enhancement. Robust stratiform regions with stronger brightband, such as those in the West Pacific warm pool, are usually connected with deep and intense convective echoes (Houze et al. 2015b). From the number of storms shown in Table 2.1, the ratio of the convective cores to BSRs in the southern subregions are higher than in the northern subregions. It is possible that a good number of these convective cores were embedded in the BSRs, and support the formation of these brightband and stronger reflectivity overall of the BSRs.

From the storm structure analysis in these subregions, Taiwan shows an interesting mix of factors influencing its extreme storms. The Taiwan subregion also combines the moisture-rich environment over the sea and the orographic lifting from the Central Mountain Range, mixing properties of both land and sea regions. Its location in the northern half of TSEA allows for the clear rain signal of the well-studied East Asian summer monsoon rain signal associated with the Meiyu front. Thus, the Taiwan subregion will be a focus for the remainder of this chapter.

2.4 Ingredients for heavy rainfall over Taiwan

The primary reason that Taiwan was selected is to provide context for the large international field campaign called PRECIP (Prediction of Rainfall Extremes Campaign in the Pacific) that took place in summer 2022 in the vicinity of Taiwan.

In addition to being the focal point for a recent field campaign, Taiwan is a unique subregion in TSEA. The rain intensity in that region is skewed toward higher rain rates and volumetric rain (Figure 2.4 and 2.5), even when compared with the other land-only subregions in TSEA. This characteristic implies that the unique topography of Taiwan and enhanced diurnal heating associated with thermal contrasts between the mountains and surrounding land amplifies the ‘land’ characteristics seen across all extreme storm types.

However, in terms of meso- and larger scale environment, it is a mix of both land and sea environments and is most similar to the other northern subregions, when they are influenced by the Meiyu front. Taiwan’s DCCs and DWCCs exhibit CFAD structures that are a mix of both land- and sea-only subregions. The monthly occurrence frequencies of Taiwan WCCs and BSRs are consistent with the timing of the Meiyu Front as the dominant synoptic to mesoscale phenomena during the late spring and early summer. However, the Taiwan BSR CFAD structure shows a mix of northern and southern features with a slight brightband enhancement that is not as strong as the southern subregions, but is more prominent than in the northern subregions.

2.4.1 Daily composite maps

To investigate the ingredients supporting these heavy rainfall producing systems, a time-lagged perspective of the ingredients ((2.1)) is analyzed for each extreme echo type using composite analysis techniques. Vertical moisture flux and vertically integrated moisture divergence are used to represent the moisture and vertical motion perspective within the ingredient-based framework ((2.1); Doswell et al. 1996a). 700–900 hPa low-level shear is selected as a parameter to identify the general Meiyu Front location (Akiyama 1973b).

Summary composites are presented based on the occurrences of each storm type in the Taiwan subregion for some of the ingredients important to producing heavy rainfall to identify the large-scale forcing and features supporting the occurrence of local extreme events.

Figure 2.11 shows the composite map of daily-mean vertical moisture flux and the horizontal wind at 850 hPa on the day when TRMM-identified storm types occurred in the Taiwan subregion.

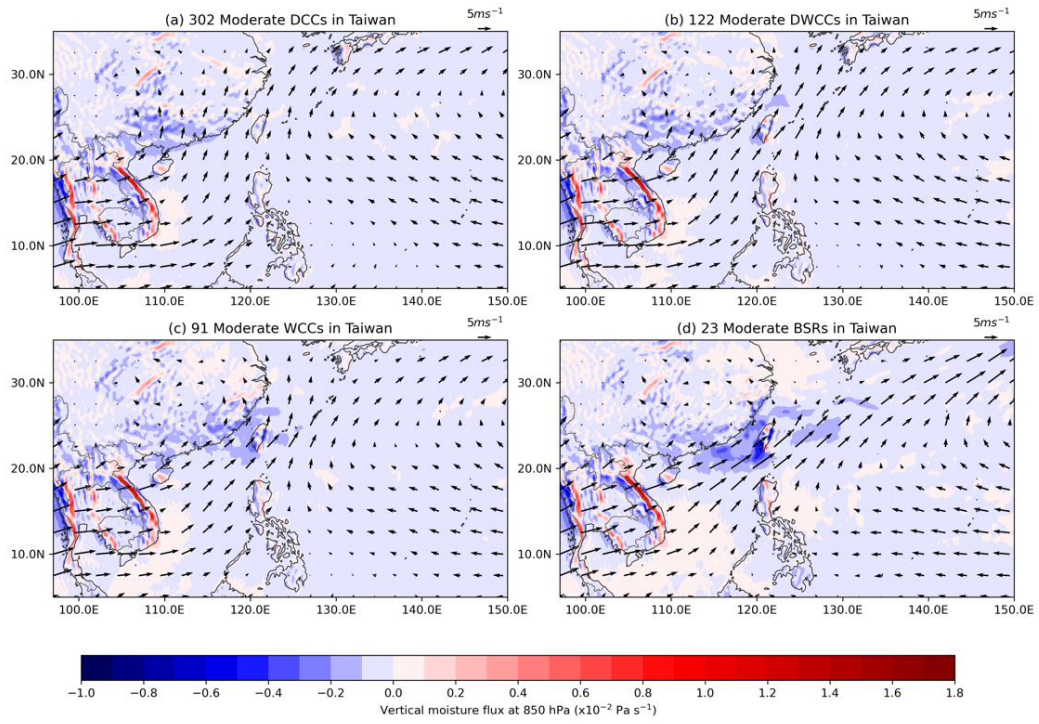


Figure 2.11: Composite maps of vertical moisture flux (filled) and 850 hPa horizontal wind (vector) on the day the storms were observed by TRMM during May–September.

The vertical moisture flux (ωq flux) is the vertical forcing for rainfall intensity in the Doswell et al. (1996a) framework ((2.1)). We expect to see higher ωq flux in the environments of storms with higher rain rates. The composite map shows overall weak negative flux (upward direction in the pressure coordinate) over the TSEA region (Figure 2.11), as is expected of this high-moisture tropical region. Mid-level southwesterly wind from the South China Sea is seen near Taiwan for all extreme echo types. For the DCC and DWCC composites, southerly winds over the South China Sea are directed toward the Southeast China region (Figure 2.11a, b), where the ωq flux is enhanced over this area.

The ωq flux for days when DCCs were observed in the Taiwan subregion shows negative peaks of -0.002 Pa/s over Taiwan, which is not much stronger in magnitude than the moisture flux of the surrounding Pacific (Figure 2.11a). Thus, DCCs over Taiwan may not need meso- or larger scale ωq flux ingredients and are likely more influenced by strong diurnal heating of the Central Mountain Range and orographic effects (Kerns et al. 2010; Lin et al. 2011). However, it is likely that the ERA5 resolution is not fine enough to represent the strong local-scale forcing expected in strong, convective DCCs to draw any conclusions about the local scale vertical forcing.

The 850 hPa winds for days when DWCCs were observed in the Taiwan subregion is stronger than for DCCs over the Pacific and the South China Sea (Figure 2.11b). The downward and upward ωq flux over Taiwan are larger in magnitude. The upward ωq flux over the southwest region of Taiwan also covers a broader area. The upward ωq flux over Taiwan covers an even broader area in the composite for the WCCs (Figure 2.11c). The region of negative ωq flux extends from the northwest to southwest regions of Taiwan and connects with the negative flux area over the Southeast China region.

The storm type with the most prominent pattern of strong negative ωq fluxes is BSRs (Figure 2.11d). The downward ωq flux peaks over the southwest coast of Taiwan with a zonal orientation from the Southeast China to the Pacific Ocean east of Taiwan. Coincidentally, the southwesterly wind from the South China Sea that flows over Taiwan is stronger relative to the other storm types, supporting the large upward ωq flux in the Taiwan subregion. Thus, broader and

longer-lived storms over the Taiwan subregion require a larger-scale ωq flux. A large amount of moisture available for WCCs and BSRs is possibly supported by the mid-level wind transporting moisture from the South China Sea to the Taiwan subregion, and possibly by the Meiyu front that may explain the upward ωq flux region from the north of South China Sea toward West Pacific Ocean.

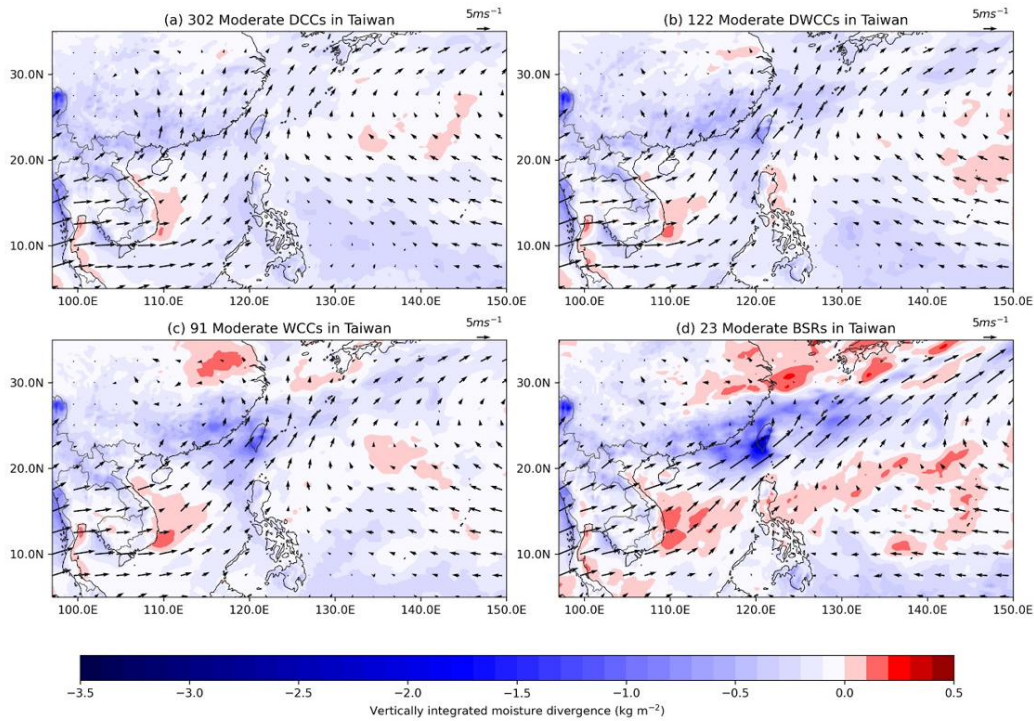


Figure 2.12: Same as Figure 2.11 but for vertically integrated moisture divergence (filled) and 850 hPa wind (vector).

To further explore the horizontal transport of moisture, Figure 2.12 shows composites of vertically-integrated moisture divergence (VIMD) for days when the extreme echoes were observed in the Taiwan subregion. The overall TSEA region shows moisture convergence consistent with Figure 2.11. Thus, the area does not only produce its moisture locally as expected from a tropical oceanic environment, but also supplies the moisture to the nearby regions. Notable positive VIMD regions are located in the central Pacific Ocean centering at 20°N associated with the subtropical

high region. Figure 2.12a shows the moisture divergence composite for the DCCs over the Taiwan subregion. Similar to its counterpart in ωq flux (Figure 2.11), the negative VIMD over the Taiwan subregion is small in both magnitude and horizontal coverage, indicating that larger-scale forcing is not the only possible source of moisture for DCCs over Taiwan. However, the limitation of the resolution of ERA5 on the local-scale forcing still holds.

The moisture convergence for DWCCs in Taiwan (Figure 2.12b) is stronger in magnitude and covers a larger area than during the DCC days (Figure 2.12a). The VIMD composite for the WCCs over Taiwan (Figure 2.12c) shows broader and larger moisture convergence over the Taiwan subregion relative to the two deep convective categories. This negative region broadens and connects with the Southeast China and the Philippines regions, similar to its ωq flux counterpart (Figure 2.11c). The moisture convergence pattern off the west coast of Indochina is also larger in magnitude than that in the DCC and DWCC composite.

Figure 2.12d shows the VIMD composite for BSRs over the Taiwan subregion. Clearly defined moisture divergence regions are notably stronger relative to the other storm types, especially off the west coast of Indochina and over the north coast of China where it broadens. The moisture convergence over Taiwan is the strongest of any storm type shown here and connects with the south of China and spreads further west to the Pacific along 20–30°N. Moisture convergence corresponds to the upward ωq flux over the same region (Figure 2.11d), but covers a larger horizontal area especially in the zonal direction.

Comparing Figure 2.11 and 2.12, regions with upward ωq flux generally also have vertically integrated moisture convergence, and regions with downward ωq flux generally also have vertically integrated moisture divergence. Over the Taiwan subregion, the broader and longer-lived storms require stronger and larger-scale upward ωq flux and moisture convergence, which is supported by the mid-level southwesterly flow over the South China Sea carrying the moisture toward the Taiwan subregion.

One of the most prominent phenomena in the TSEA region during the monsoon season is the Meiyu front. To investigate the relationship between the Meiyu front and each extreme echo type,

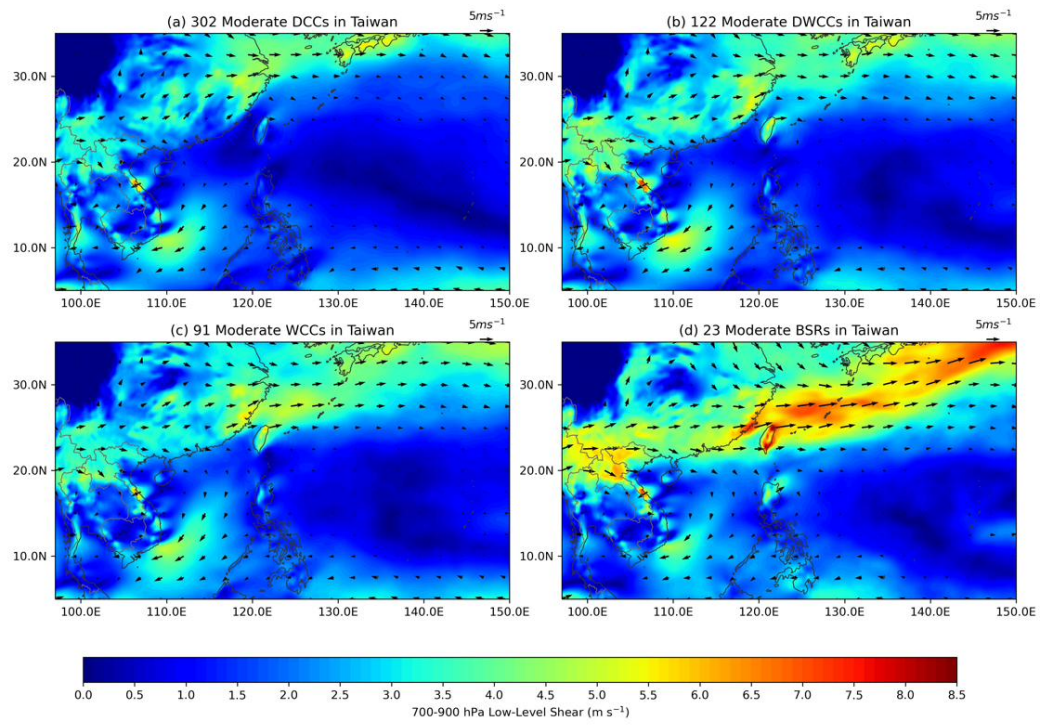


Figure 2.13: Same as Figure 2.11 but for 700–900 hPa wind shear magnitude (filled) and direction (vector).

we use low-level shear (LLS) to estimate the location of the Meiyu front on the day the extreme echo occurred. Figure 2.13 shows the daily-mean composite of the magnitude and direction of 700–900 hPa LLS. The tropical environment of TSEA shows weak LLS, especially over the Pacific ocean and other regions without terrain. Over land, high LLS induced by the mountains is clear, as seen over the north of Indochina that connects with the Himalayan range to the west. The strong westerly LLS band extending east from China to the Pacific Ocean marks the location of the Meiyu front (Akiyama 1973b; Sampe and Xie 2010b).

Figure 2.13a shows the LLS composite for days when DCCs occurred over the Taiwan subregion. The LLS band is located near the northern border of the TSEA region. As the Meiyu front moves northward from May to July and is directly over Taiwan in the first half of June (Wu et al. 2017), the location of the LLS region in Figure 2.13a indicates that the peak environment for DCCs in Taiwan is after the first half of June, consistent with Taiwan DCCs peaking in July (Figure 2.3a). The Meiyu front is generally located to the north of Taiwan and does not directly affect the environment supporting DCCs over the Taiwan subregion. However, there is moderate LLS over Taiwan, possibly due to orographic effects. This local LLS is not strong or broad in horizontal area, indicating that DCCs do not require a strong mesoscale or larger shear environment and are likely more local in scale, consistent with the previous analyses.

Figure 2.13b shows a similar LLS pattern for DWCCs compared to DCCs, but with a stronger magnitude. The LLS over Taiwan also extends northeastward and connects with the main Meiyu-front-associated LLS band. This suggests that the LLS environment and season that supports DWCCs is similar to that of DCCs. The stronger LLS composite for DWCCs could be because of two reasons. First, the upscale organization of DWCCs benefits from the stronger shear environment supporting the development of MCSs (LeMone et al. 1998). This would explain the monthly occurrence of DWCCs peaking a month earlier than that of DCCs in the other northern subregions (Figure 2.3) due to the higher LLS in the environment from proximity of the Meiyu front, which moves north through the summer months. Second, the number of DWCCs is smaller than that of

DCCs, so the composite of DCCs has higher variability among the cases and the final composite is not as strong as the composite for DWCCs.

The LLS composite for WCCs shows the strong westerly LLS band located closer to Taiwan (Figure 2.13c) compared to the DCC and DWCC composites (Figure 2.13a, b). The presence of the Meiyu front located further south indicates that WCCs tend to occur earlier in the monsoon season, consistent with the WCC monthly occurrence distribution (Figure 2.3c). Strong LLS located near the Taiwan subregion should help support the organization of MCSs over the region, benefiting the development of WCCs. The extra LLS from the Meiyu front may also support the stronger development and reflectivity of WCCs in the northern subregion than the southern region counterpart (Figure 2.9).

The LLS composite for BSRs (Figure 2.13d) shows an even stronger westerly LLS band located directly over Taiwan with a maximum magnitude of ~ 9 m/s over the southeast coast of China. Such a strong mesoscale LLS environment over the Taiwan subregion supports the development of long-lived and larger storm systems, such as BSRs over the subregion. Strong LLS is known to support the organization of convection into MCSs (Rotunno et al. 1988; Weisman and Rotunno 2004; LeMone et al. 1998). The furthest southward location of the Meiyu front corresponds with the early occurrence of BSRs that peak in May (Figure 2.3d).

As the high westerly LLS band marks the location of the Meiyu front, the LLS composite shows that as the Meiyu front moves across the Taiwan subregion northward, the likelihood of observing extreme storms also shifts from BSRs and WCCs to DWCCs and DCCs, consistent with the monthly occurrence distributions (Figure 2.3). The stronger mesoscale LLS that accompanies the Meiyu front also helps support the organization of larger MCSs like BSRs. However, the role of smaller-scale LLS on smaller MCSs, i.e., DCCs, is not notable in this analysis possibly due to the resolution of ERA5.

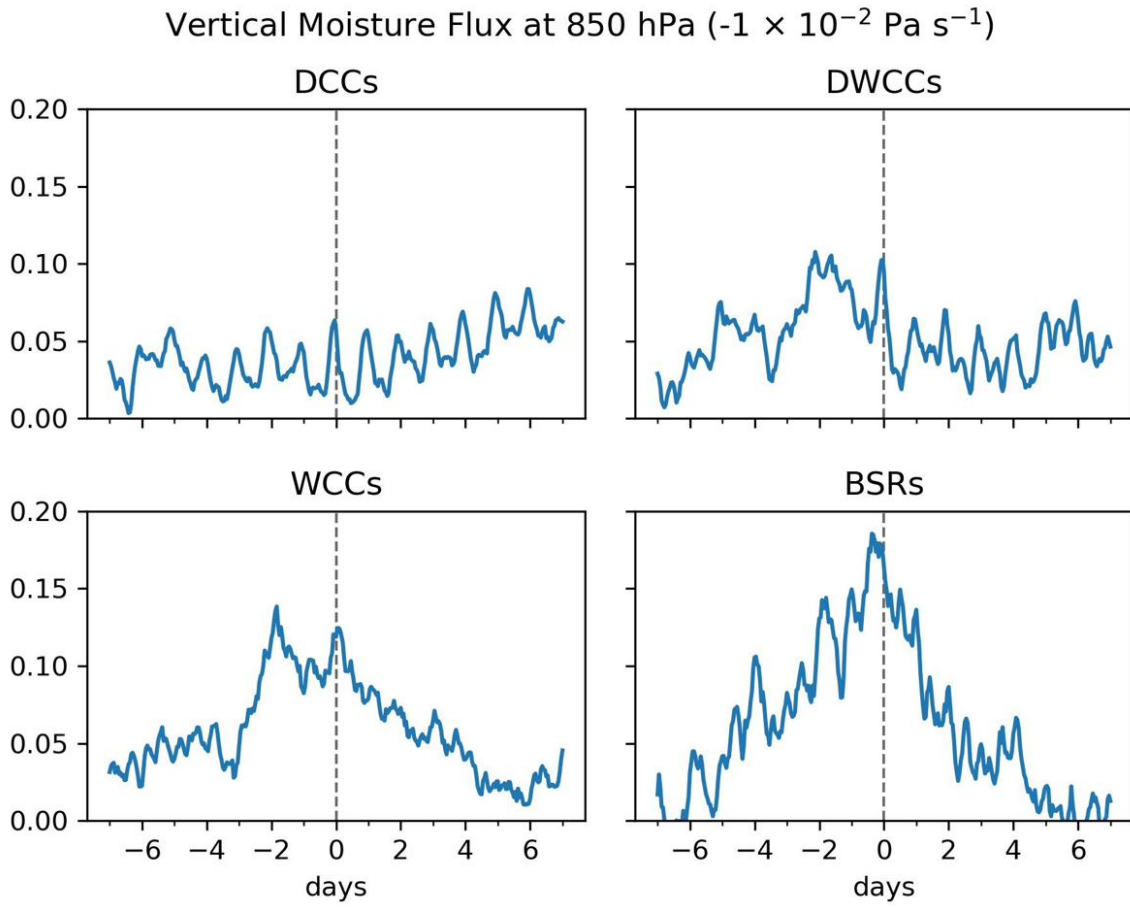


Figure 2.14: Time-lags of vertical moisture flux at 850 hPa seven days before and after the storms were observed by TRMM during May–September.

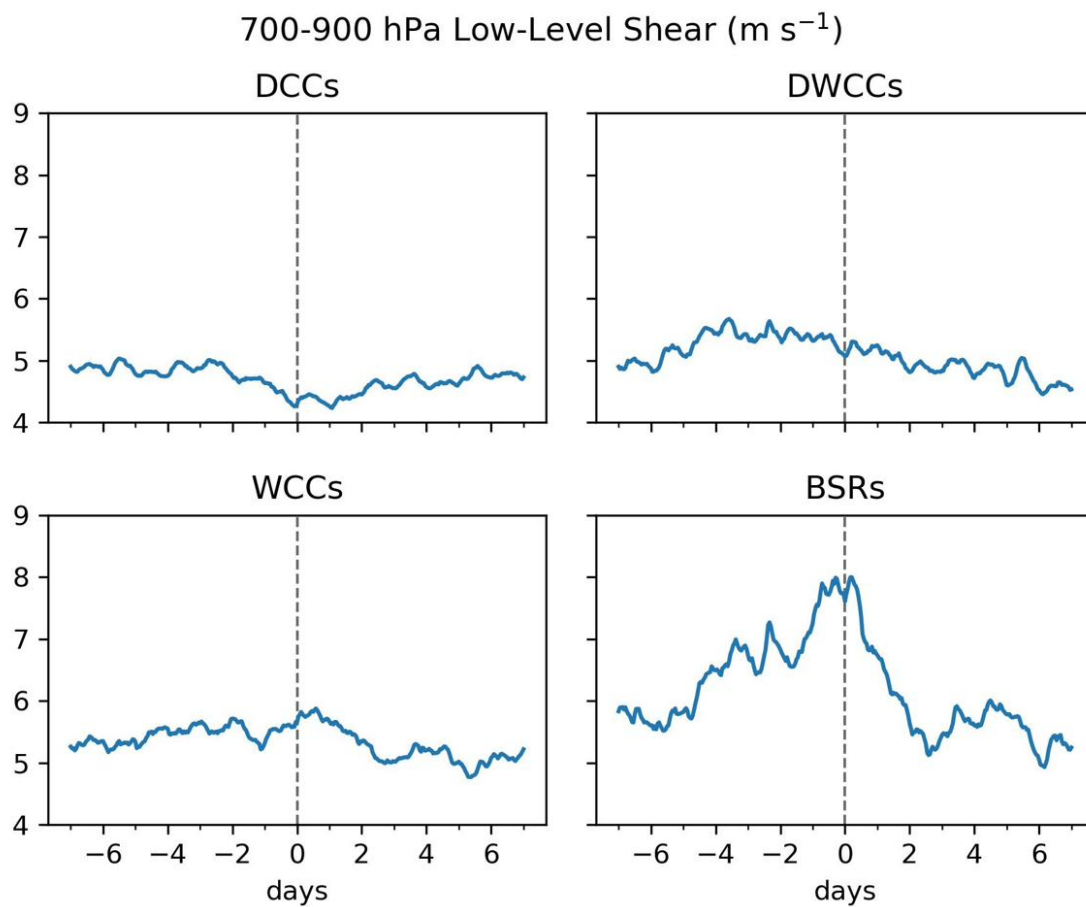


Figure 2.15: Same as Figure 2.14 but for 700–900 hPa wind shear.

2.4.2 Time-lagged composite analysis of heavy rainfall ingredients

To explore the different time scales of the synoptic and mesoscale factors that vary before and after each extreme echo type over Taiwan, time-lagged hourly averaged ωq flux and LLS over the Taiwan subregion are shown in Figure 2.14 and 2.15. The vertically-integrated moisture divergence time-lag analysis is omitted due to its similarity to ωq flux time-lag. The hourly average is computed over two weeks centered on the time that the echoes were observed to investigate how the ingredients change over this longer time scale to partially address the duration aspect of the ingredients-based framework ((2.1)).

Significant differences in how the ingredients vary both before and after the occurrence of the TRMM-observed echo at Day 0 are apparent in Figure 2.14. The build-up and dissipation of ωq flux varies from a notable diurnal cycle in DCCs (Figure 2.14a) to over a week-long cycle in BSRs (Figure 2.14d). This time scale variability coincides with the length scale of the upward ωq flux over the Taiwan region (Figure 2.11) and connects to the ingredients-based equation through the duration term ((2.1)). To illustrate, BSRs often have large-scale moisture supplied from the Meiyu front converging the moisture over Taiwan (Figure 2.11–2.13d), and the buildup of moisture in that large-scale perspective is reflected in the week-long build-up and dissipation of ωq flux (Figure 2.14d).

A shorter time scale of ωq flux is shown in DWCCs and WCCs, which show 2–3 days build-up of ωq flux and up to a week of dissipation after the echoes were observed (Figure 2.14b–c). This is consistent with meso- and larger-scale ωq flux on the day the echoes were observed (Figure 2.11b–c). The composite of LLS also suggests that the Meiyu front was still close to the north of Taiwan (Figure 2.13b–c) and may be the reason for moisture convergence in the area (Figure 2.12b–c), allowing for the longer time scale of moisture to influence the development of storms with a wide component. However, DWCCs occur most frequently from 5–9am UTC or 1–5pm Taipei standard time in the analysis of the diurnal cycle (not shown). Thus, the DWCCs are of afternoon storm in nature that develop into larger convective storms. WCCs and BSRs do not show significant diurnal cycle distribution.

On the other hand, DCCs exhibit a clear diurnal cycle associated with the ωq flux that corresponds to the relatively weak pattern of ωq flux over Taiwan (Figure 2.11a), suggesting a more local phenomena. Diurnally-driven afternoon thunderstorms in the Taipei basin have been shown to produce significant rainfall and flooding in the region (Kerns et al. 2010; Lin et al. 2011). Analysis of the diurnal cycle of the extreme echoes shows that DCCs and DWCCs occur most frequently in the afternoon from 4–9am UTC or 12–5pm Taipei standard time (not shown). It is likely that afternoon storms are a primary type of event corresponding to DCCs and DWCCs. WCCs and BSRs shows weaker diurnal cycle, peaking in the earlier in the day from 5–10am and 11am–1pm Taipei standard time respectively (also not shown). The diurnal cycle signal might not show clearly in the time-lag analysis (Figure 2.14–2.15) due to the stronger influence of longer-timescale signal. Nonetheless, the diurnal cycle signal found is consistent with prior research of DCCs, WCCs, DWCCs, and BSRs (Zuluaga and Houze 2013).

The hourly average of 700–900 hPa LLS over the Taiwan subregion shows a similar build-up and dissipation time scale to the ωq flux composite (Figure 2.14–2.15). The weeklong buildup of LLS for BSRs is pronounced (Figure 2.15d), showing the influence of the Meiyu front slowly moving over the Taiwan region (Figure 2.13d). The week-long build-up of LLS coincides with the week-long build-up of the ωq flux (Figure 2.14d), further supporting the hypothesis that the Meiyu front converges the moisture to the region associated with BSRs.

The build-up of LLS is weaker but still apparent for DWCCs and WCCs (Figure 2.15b–c), showing that the Meiyu front likely influences these storm types, but not as strongly as BSRs. The build-up complements the composite map of LLS that the Meiyu front location is to the north of Taiwan and not directly over the Taiwan region like BSRs (Figure 2.13b–d).

Lastly, the average LLS is very weak for DCCs the week before and after DCCs were observed by TRMM (Figure 2.15a), coinciding with the weak and small spatial scale of the signal of LLS (Figure 2.13a). This reinforces the hypothesis that large-scale LLS or large-scale moisture convergence from the Meiyu front is not a primary factor for DCC development. However,

it does not discount the effect of ERA5 resolution on the results related to the smaller-scale storm environments.

Thus, the broader storms require stronger meso- and larger scale LLS and ωq flux to support the large-scale development and organization, associated with large-scale phenomena in the vicinity of Taiwan—i.e., the Meiyu front and the East Asian monsoon. In contrast, smaller storms like DCCs are associated with weaker LLS and ωq flux on the synoptic scale without a longer time scale buildup. The diurnal cycle is apparent in ωq flux especially in DCCs, in which the impacts of afternoon heating on storm occurrence is pronounced.

2.5 Conclusions

In this study, we analyze the climatology of storms with extreme horizontal and vertical dimensions related to heavy rainfall observed by the TRMM satellite's PR from 1998–2013 over the TSEA region, which is a high moisture environment affected by the West Pacific warm pool and the East Asian monsoon.

The climatology over TSEA shows that DCCs and DWCCs have a higher probability to occur over the land than the sea environments. On the other hand, WCCs and BSRs are more likely to occur over the seas. DCCs and DWCCs share similar monthly occurrence distributions, peaking in the late monsoon season in the northern subregions (i.e., the North Pacific, Southeast China, and Taiwan), and in early monsoon season in the southern subregions (i.e., Indochina, South China Sea, the Philippines, and the Philippines Sea). However, the WCCs occur early in the monsoon season for the northern subregions in association with the local spring rain season and later in the season for the southern subregions in association with the maritime-continent monsoon. BSRs monthly occurrence distributions differ from the convective categories, suggesting different environments that may support the storms. The BSRs in the northern subregions are strongly associated with the East Asian monsoon and the Meiyu front at the onset of the monsoon.

The CFAD analysis shows the DCCs and the DWCCs have similar strong high-reflectivity in low-level and low-reflectivity, with land-and-sea variability in structure. The WCCs structure

is weaker and varies depending on whether they occur over north or south subregions. The BSRs structure also reflects north-south subregions differences, and a stronger bright band over the southern subregion.

DCCs and DWCCs produce a higher rain rate when occurring over the land environments and have different storm structures over land and sea subregions, possibly due to the orographic lifting and coastal effects. Together, they contribute to the highest rain rates observed over TSEA. However, due to the small area DCCs contribute small volumetric rain rates across the TSEA region. WCCs and DWCCs contribute slightly larger volumetric rain rates due to broader horizontal areas. BSRs produce the lowest mean rain rates among the extreme echo categories, but ultimately contribute the largest volumetric rain thanks to the broad horizontal areas and long duration.

The ingredients-based analysis over the Taiwan subregion shows that the larger systems (i.e., WCCs and BSRs) have broader areas and longer-timescale buildup of ωq flux and moisture convergence over the region of interest (i.e., Taiwan), implying that they require mesoscale or larger-scale moisture and vertical motion to support their development. On the other hand, the smaller, more vigorous systems (i.e., DCCs) only have weak, small areas of ωq flux and moisture convergence near Taiwan in the reanalysis data. The time-lagged analysis also shows a smaller-amplitude diurnal cycle of the ωq flux. However, we cannot conclude that the DCCs do not require stronger vertical moisture flux due to the ERA5 resolution limitation.

In contrast, when broader systems occur near Taiwan (i.e., WCCs and BSRs), a broad area of LLS is over the region and a week-long timescale buildup of LLS prior to the event, suggesting that the broader systems require mesoscale or larger LLS to support the development of broader, more organized systems. The prominent LLS contributor is the Meiyu front, which comes at the onset of the East Asian monsoon corresponding to the WCCs and BSRs monthly occurrence distributions.

Across TSEA regions, storm and rain characteristics shows that diverse environments of TSEA contribute to various storm structures and distributions, as shown in the differences between land and sea subregions, and north and south subregions. These variations suggest that there are many dynamics or phenomena playing the role in the production of extreme rainfall in the region. Over

the Taiwan subregion, the Meiyu front is a key phenomenon that brings large-scale ingredients favorable for extreme storm development and sustenance over large regions and long periods of time. However, because of the limitation of the ERA5 resolution, we cannot draw conclusion about storm-scale ingredients.

Future work will include using higher resolution datasets, both from observations and model simulations, to further analyze the relationship between extreme storms in the TSEA region and the ingredients that support heavy rainfall. Comparisons between observations from the recently conducted PRECIP field campaign in Taiwan and Yonaguni Island (May–August 2022) and the TRMM climatology from this chapter would be of interest to further explore the convective through mesoscale perspectives of the ingredients-based framework in a moisture-rich environment. Enhanced understanding of how specific storm modes relate to heavy rainfall in a moisture-rich environment provides important information on the ingredients supporting such high-impact events, the relevant physical processes, and global implications for the production of heavy rainfall in moisture-rich and moisture-limited environments globally.

Chapter 3

The impact of topography on the storm characteristics and precipitation associated with the June 2017 Meiyu front in Taiwan²

3.1 Introduction

Heavy rainfall is a high-impact weather phenomenon that affects millions of people worldwide each year, ranging from intense storms causing flash floods to prolonged periods of moderate rain leading to significant water accumulation. When rainfall occurs in complex topography, such as mountainous regions, predicting its behavior becomes particularly challenging. A recent example is Hurricane Helene (2024) that produced devastating flooding in the U.S. Appalachian Mountains. Terrain can significantly change the characteristics, intensity, and distribution of rainfall. These variations contribute to challenges in forecasting extreme rainfall, as the same storm system can produce vastly different precipitation patterns depending on the underlying topography. As rainfall increases from light to extreme rates, the associated dangers and impacts also increase, making it crucial to understand and predict these events accurately. Understanding orographic interactions in different storm systems is essential for improving weather forecasts and effectively managing water resources.

To understand how different rainfall events vary, the ingredients-based framework introduced by Doswell et al. (1996b) examined the net rainfall produced (P) in terms of intensity (I) and duration (D):

²The results outlined in Chapter 3 are in revision at *Terrestrial, Atmospheric and Oceanic Sciences*: Panasawatwong, W., K. L. Rasmussen, M. M. Bell, and L. Swinney, 2026: The impact of topography on the storm characteristics and precipitation associated with the June 2017 Meiyu front in Taiwan. *Terr. Atmos. Ocean. Sci.*, in revision.

$$P = I \times D. \quad (3.1)$$

An extreme rainfall event can be contributed by the rainfall intensity, duration, or both. The intensity I can be further represented by the precipitation efficiency (E), vertical velocity (w), and water vapor mixing ratio (q):

$$I = Eqw. \quad (3.2)$$

While terrain does not appear explicitly in these expressions, Lin et al. (2001) extended the ingredients-based methodology to represent orographic forcing directly. For flow over a mountain range, the low-level vertical velocity can be partitioned into a topographically forced component and an environmental component:

$$w = w_{\text{oro}} + w_{\text{env}}, \quad (3.3)$$

where the first term is the ascent forced by flow ascending the terrain and the second is the ascent forced by the large-scale environment. The orographic component can be approximated from the low-level wind impinging on the terrain slope:

$$w_{\text{oro}} \approx \mathbf{V}_h \cdot \nabla h, \quad (3.4)$$

where $h(x, y)$ is the mountain height and $\mathbf{V}_h$ is the low-level horizontal wind velocity. Substituting this decomposition into the intensity relation makes the terrain contribution explicit, so that heavy orographic rainfall scales with both the strength of the low-level flow and the steepness of the underlying topography.

Beyond this explicit orographic term, terrain influences all three factors that modulate rainfall intensity and the duration of the rainfall event. The terrain affects the vertical velocity through orographic lifting on the windward side (Lin et al. 2001) and can block the lee side from the potential

moisture carried by the incoming air mass (Jiang 2003). Terrain may also favor the development of quick, intense storms or redirect convection by mechanical and thermal means (Kirshbaum et al. 2018; Nugent and Rios-Berrios 2018), thus affecting the duration of rainfall events. Terrain can also enhance precipitation efficiency through enhanced condensation and reduced raindrop evaporation (Huang et al. 2014). Understanding the relationship between mountains and their impact on weather patterns is essential for climate adaptation and decision making, particularly when adapting forecasting models from one type of terrain to another.

The Meiyu season is the principal mode of warm-season precipitation over Taiwan and southern China, organized along a quasi-stationary frontal zone that marks the transition from the winter northeast monsoon to the summer southwest monsoon from mid-May through mid-June (Chen 1992; Ding and Chan 2005a). As the continental air mass weakens and the western Pacific subtropical high strengthens, the front advances southward and frequently stalls near Taiwan, where warm, moisture-laden southwesterly flow from the South China Sea and Bay of Bengal converges with cooler northeasterlies from the continent. Occasionally, intense rainbands may form when the Meiyu front approaches Taiwan from the north and becomes stationary, causing extreme rainfall accumulation due to both high intensity and long duration. This phenomenon poses significant hazards, particularly in populous metropolitan areas such as Taipei in northern Taiwan. Such quasi-stationary rainbands represent a considerable challenge for forecasting beyond nowcasting, as they are highly transient and are influenced by mesoscale and local environmental variations.

The interaction of this front with the steep windward slopes of Taiwan's terrain repeatedly triggers organized convection that produces Taiwan's most intense warm-season rainfall and the flooding, mudslides, and debris flows associated with it (Kuo and Chen 1990; Arakane et al. 2019; Chen et al. 2022). The Central Mountain Range (CMR), spanning over 310 km and peaking at 3,860 m just 140 km from the west coast, is a key geographic feature of Taiwan and is among the steepest mountain ranges in the world (Taiwan Tourism Administration 2022). This steep, asymmetric relief—abrupt on the east and more gradual on the west—makes the CMR a strong modulator of low-level flow and orographic rainfall. The CMR significantly modulates Meiyu-season rainfall,

as highlighted by numerous field campaigns, such as the Taiwan Mesoscale Experiment (TAMEX) in 1987 (Kuo and Chen 1990), the combined Terrain-influenced Monsoon Rainfall and Southwest Monsoon experiments (TiMREX/SoWMEX) in 2008 (Jou et al. 2011), and the recently completed joint campaigns of the Prediction of Rainfall Extremes Campaign in the Pacific (PRECIP) and Taiwan-Area Heavy rain Observation and Prediction Experiment (TAHOPE) in 2022.

Over the past decade, there have been two notable cases in northern Taiwan during the Meiyu season that met the “extremely heavy rainfall” criterion (≥ 500 mm in 24 hours) of the Central Weather Bureau (CWB): one on 11–12 June 2012 and another on 2 June 2017 (Arakane et al. 2019). On 2 June 2017, northern Taiwan experienced heavy rainfall that continued into the following day. The observed rainfall, exceeding 600 mm in 12 hours, was record-breaking for Meiyu front events in the preceding 26 years. The CWA attributed this heavy rainfall to a Meiyu front associated with strong southwesterly winds. The front brought intense rainfall over the Taipei Basin in northern Taiwan before shifting south into central Taiwan, where rainfall persisted on the windward side of the CMR. Enhanced moisture transport linked to Tropical Cyclone Mora, which formed on 28 May 2017 in the Bay of Bengal, contributed to this anomalously strong rainfall event (Arakane et al. 2019). The event has since been the subject of several modeling and observational studies, all of which document a prominent prefrontal low-level jet feeding the front (Chung et al. 2020; Tu et al. 2020, 2022; Wang et al. 2023).

Prior field campaigns and model-based studies have revealed that one of the key mesoscale features induced by orography during the Meiyu season is the barrier jet (Chen et al. 2022). Additionally, the CMR influences the Meiyu front through frontal splitting effects. As the front approaches the CMR, it splits into a windward front west of the CMR and a leeside front east of the CMR, with the windward front typically associated with extreme rainfall (Chen 1992). Studies such as Xu et al. (2012) have shown that rainfall is closely linked to both the placement of the front and the topography. Cornejo et al. (2024), using the same simulations of the June 2, 2017, case analyzed here, showed that halving the Taiwan terrain reduced both rainfall intensity and duration through weaker orographic lifting and a diminished barrier jet.

To build on these prior studies, a discrete storm-modes framework is used here to address the influence of the terrain on storm structures and rainfall distributions. The extreme storm modes classified in this paper are the same TRMM-heritage categories used to document the variable nature of convection across the global tropics and subtropics (Houze et al. 2015a), placing the results of this regional, event-scale study within a globally comparable framework. The share of total rainfall contributed by each extreme storm mode varies markedly from region to region. In the subtropical La Plata basin of South America, for example, storms containing wide convective cores (WCCs) alone produce roughly 44% of the warm-season rainfall, and the extreme storm modes together account for about 95% of it (Rasmussen et al. 2016). These rainfall distributions are very different from the rainy season over Taiwan, where wide cores and stratiform regions dominate the rain contributions (Panasawatwong et al. 2022). By using the same extreme storm-modes analysis across such disparate environments, quantifying how terrain modification redistributes rainfall among the modes places the results into a global context that can be compared directly with the orographic and convective behavior of other extreme-rainfall regions, rather than remaining specific to a single Taiwan case.

This study aims to advance previous work in three ways. First, high-resolution modeling is used to resolve the convection and the storms into TRMM-heritage extreme storm modes. Second, the analysis isolates which atmospheric ingredients (vertical velocity, moisture flux, low-level shear) reorganize under terrain reduction, rather than treating rainfall as a single endpoint. Lastly, by focusing on a record-breaking event, the analysis examines and isolates how the extreme nature of the case is influenced by the orographic effect.

This chapter is organized as follows: Section 3.2 describes the WRF model setup, storm classification, and ingredient-based analysis. Section 3.3 presents results in four subsections that map directly onto the stated objectives: storm-mode response and rainfall redistribution (Section 3.3.1), horizontal and vertical wind changes (Section 3.3.2), moisture flux (Section 3.3.3), and low-level shear (Section 3.3.4). Section 3.4 provides the summary and conclusions.

3.2 Methodology

The methodology encompasses three key components: WRF configuration and setup, storm classification, and ingredient analysis in conjunction with a topography sensitivity study.

3.2.1 WRF configuration and setup

The two simulations analyzed for the terrain-sensitivity study here were produced using the Weather Research and Forecasting (WRF) model, a nonhydrostatic, full-physics numerical weather prediction model developed by the National Center for Atmospheric Research together with the operational and research meteorological community. Version 4.1.3 was used (Skamarock et al. 2019). The model was run with the aerosol-aware Thompson microphysics scheme (Thompson and Eidhammer 2014), the Rapid Radiative Transfer Model for general circulation models for both longwave and shortwave radiation (Iacono et al. 2008), the Monin–Obukhov surface-layer scheme (Janjić 2001), the Noah land surface model (Tewari et al. 2004), and the Yonsei University boundary-layer scheme (Hong et al. 2006). This combination of schemes follows recent Meiyu-front modeling practice (Paul et al. 2021; Tu et al. 2022; Zhang et al. 2023; Zhao et al. 2023).

Model initialization and boundary conditions were obtained from the Global Forecast System (GFS) to initialize an ensemble of 40 members with a dual-nested grid configuration following Zhang et al. (2019), in which the 9-km outer grid, spanning 9.39–38.86°N, 105.05–141.95°E, provides boundary conditions for the higher-resolution 3-km inner grid of 20.00–27.49°N, 116.86–125.05°E. Both nested grids used 50 vertical levels. The ensemble was simulated from 1200 UTC 1 June to 1200 UTC 3 June 2017, with output saved every 12 hours on the outer 9-km grid and every 3 hours on the 3-km grid. The ensemble member that most closely resembled the timing and accumulation of rainfall associated with this event was selected for this analysis.

The inner 3-km grid from that member was subsequently downscaled to a one-way-nested 1-km grid spanning 21.25°–26.26°N, 118.19°–123.66°E using NDOWN, with output saved every 15 min to resolve the rapid evolution of the convective systems. Because the 3-km forcing data are extrapolated to sea level, the extrapolated fields were interpolated onto the sigma coordinates

of the 1-km grid during preprocessing to suppress data-gap discrepancy at the nest boundary, and the first 6 h of each 1-km simulation were discarded to remove model spin-up artifacts. This inner 1-km grid is hereafter referred to as the “analysis domain” and this simulation is referred to as the control (CTRL) run.

The Terrain Modification (TMOD) experiment was conducted by halving only the terrain height of Taiwan. This halved terrain simulates the more gradual terrain, in comparison to the steep topography of the CMR in the control run. The same downscaling configuration is applied to both CTRL and TMOD. The Taiwan area restricted to grid points with land surface elevation greater than zero is hereafter referred to as the “Taiwan land area.”

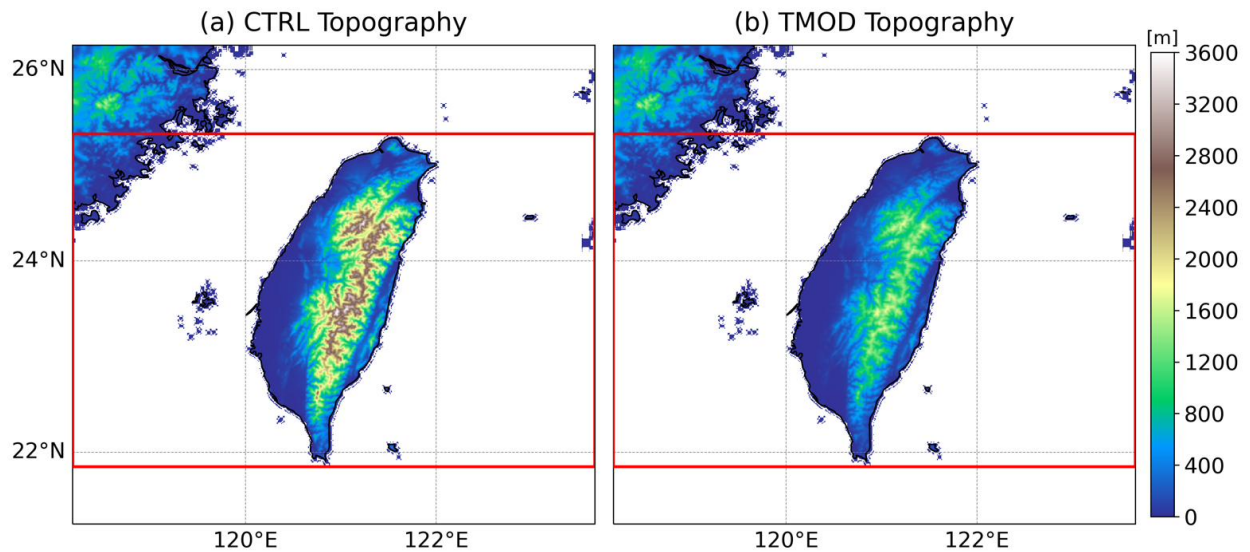


Figure 3.1: Topography of control (CTRL) and modified terrain (TMOD) simulations. Shaded relief showing the model domain topography (meters) for (a) the CTRL and (b) the TMOD simulations over the 1-km inner domain (21.25° – 26.26° N, 118.19° – 123.66° E). The Central Mountain Range (CMR) runs north–south through the island; in TMOD all terrain heights are reduced to 50% of their CTRL values, preserving the horizontal extent of the island. The red box marks the area used for Hovmöller analyses (21.85° – 25.33° N, 118.19° – 123.66° E).

3.2.2 Extreme storm-mode classification

The storm classification followed the methodology of Panasawatwong et al. (2022), which was motivated by the TRMM-heritage storm modes defined by Houze et al. (2007a), categorizing convective storms into four distinct extreme storm modes based on radar reflectivity characteristics. These TRMM-heritage thresholds were originally derived from TRMM PR pixel resolution (~ 5 km) and are applied here to the 1-km WRF simulated reflectivity:

- **Deep Convective Cores (DCCs):** Storms exhibiting intense reflectivity (≥ 30 dBZ) extending vertically above 8 km, indicative of vigorous deep convection.
- **Wide Convective Cores (WCCs):** Storms demonstrating extensive horizontal coverage, with reflectivity ≥ 30 dBZ over contiguous areas exceeding 800 km^2 , yet lacking significant vertical extension above 8 km.
- **Deep and Wide Convective Cores (DWCCs):** Storms combining the characteristics of both DCCs and WCCs, featuring intense reflectivity (≥ 30 dBZ) vertically extending above 8 km and horizontally covering contiguous areas exceeding 800 km^2 .
- **Broad Stratiform Regions (BSRs):** Storm regions characterized by widespread stratiform precipitation, covering extensive horizontal areas greater than $40,000 \text{ km}^2$ but lacking significant deep vertical convective features.

Raining grid points that did not satisfy the intensity, depth, or areal-coverage thresholds of any of the four extreme storm modes were assigned to a residual category, denoted “Other.” Physically, this category represents weak, shallow, and largely unorganized precipitation—predominantly light stratiform rain and isolated shallow convective cells whose intensity and spatial extent fall below the DCC, WCC, DWCC, and BSR thresholds. At each model output time, every raining grid cell of the simulation domain is assigned to one of five mutually exclusive categories. This categorization is applied identically and independently to the CTRL and TMOD experiments, each using its own mask set.

3.2.3 Ingredient-based analysis

An ingredient-based analysis approach was employed to elucidate the environmental characteristics influencing storm evolution and precipitation processes. Key environmental parameters, including rainfall distribution, storm frequency, vertical velocity, moisture transport, and wind shear, were calculated from the WRF outputs of the terrain sensitivity experiments (CTRL and TMOD), facilitating the examination of topographic impacts on storm characteristics. Specifically, the analysis examines the spatial distribution and intensity via composite analyses to improve understanding of the mechanisms governing extreme precipitation events over complex terrain.

For a given ingredient field, the corresponding two-dimensional field is computed for each output time. Composite analyses were derived by temporally averaging the ingredients from the entire run of each simulation from 1200 UTC 1 June to 1200 UTC 3 June 2017.

The ingredient distributions by each storm mode were derived by pairing the mask files and ingredient files by sorted temporal order. At each time step, the ingredient field is sampled at every grid cell flagged by each mode, and the resulting grid-cell values are pooled into a single population for each storm mode in the entire CTRL or TMOD run. The pooled grid-cell values are then binned into a one-dimensional histogram, showing how each terrain modification shifts the frequency distribution of the ingredient within each storm mode.

Significance of differences in storm-mode means is assessed with a two-sided Welch t -test (which does not assume equal variances and is appropriate for the unequal sample sizes between storm categories), and equality of variances is assessed with an F -test. Throughout the chapter, $p < 0.05$ is taken as the threshold for statistical significance, and $p < 0.01$ is highlighted where the result is robust to multiple-comparison concerns. Both tests assume independent samples; temporal autocorrelation is mitigated by aggregating to event-level storm statistics rather than grid-point time series.

To characterize the spatiotemporal evolution and zonal propagation of convection, longitude–time (Hovmöller) diagrams were constructed from the ingredients of both the CTRL and TMOD simulations. The procedure isolates the diurnal and propagating signal in the convective field by

averaging over the meridional dimension, retaining longitude as the spatial coordinate and model output time as the temporal coordinate. The sub-domain of 21.85°–25.33°N, 118.19°–123.66°E isolates the terrain effect to be only over Taiwan (Figure 3.1).

Vertically integrated moisture flux (VIMF) was computed from WRF output using pressure-coordinate integration of the horizontal moisture flux through the model column. At each model level, the moisture flux components were calculated for each wind dimension. The vertically integrated moisture flux components were obtained by trapezoidal integration over pressure:

$$Q_u = -\frac{1}{g} \int q u dp, \quad (3.5)$$

where g is gravitational acceleration and q is the specific humidity. The negative sign accounts for pressure decreasing upward in the WRF vertical coordinate, giving positive values for physically upward-integrated fluxes. The VIMF magnitude was defined from the horizontal components as

$$\text{VIMF} = \sqrt{Q_u^2 + Q_v^2}. \quad (3.6)$$

Vertically integrated moisture flux divergence (VIMD) was computed from the horizontal VIMF components:

$$\text{VIMD} = \nabla_h \cdot \mathbf{Q} = \frac{\partial Q_u}{\partial x} + \frac{\partial Q_v}{\partial y}, \quad (3.7)$$

with derivatives evaluated on the WRF projected grid using the model grid spacing and map-factor correction. Positive VIMD indicates net horizontal moisture flux divergence, or moisture export from the column. To show moisture convergence into the column, negative divergence ($-\text{VIMD}$) is plotted.

The vertical moisture flux variable (wq) was computed as vertical wind times specific humidity at each model level and integrated through every layer above the surface.

The maximum upward vertical velocity in each column ($w_{\text{up,max}}$) was defined as the maximum positive value of vertical wind (w) over all vertical levels, and was set to a missing value where the entire column exhibited no upward motion.

Low-level shear (LLS) is computed as the magnitude of the difference of the horizontal wind between 700 and 900 hPa.

3.3 Results

To understand the dynamics and environmental conditions driving changes in the storm systems due to terrain modification, an ingredient-based framework is employed to examine regional and storm-related atmospheric changes, analyzing the storm modes, wind patterns, low-level shear, and vertical moisture flux (wq).

3.3.1 Storm modes

Here the analysis examines how the terrain reduction modifies the spatial distribution of rainfall and the storm modes of the rainfall-producing systems over the 1–3 June 2017 event. The classification scheme, model configuration, and statistical methods have been described in Section 3.2.

Figure 3.2 shows a comparative analysis between the CTRL and TMOD experiments, which illustrates substantial variations in the rainfall distribution influenced by terrain modifications. The “analysis domain” denotes the full inner 1-km domain (21.25°–26.26°N, 118.19°–123.66°E), and the “Taiwan land area” denotes grid points with land surface elevation greater than zero. Aggregated over the analysis domain, the total rainfall decreased by 9% from the CTRL run with significant spatial redistribution of rainfall that shows the response to topographical modifications. Rainfall systems west of Taiwan, associated with the Meiyu front in the CTRL run, presented more structured and linear formations. In contrast, these systems appear more dispersed and unorganized in the TMOD run, indicating that the reduction in orographic barriers not only directly influenced local precipitation but likely alters regional atmospheric dynamics, resulting in less coherent and more scattered rainfall patterns. Over Taiwan, the CMR significantly enhances orographic lifting

in the CTRL scenario, resulting in pronounced rainfall accumulation over the mountains. This orographic effect was drastically reduced in the TMOD setup, where a 50% reduction in the CMR height led to considerably less uplift. Consequently, rainfall over the Taiwan land area (land grid points only) decreased by 31%, highlighting the profound impact of mountain height on local precipitation patterns.

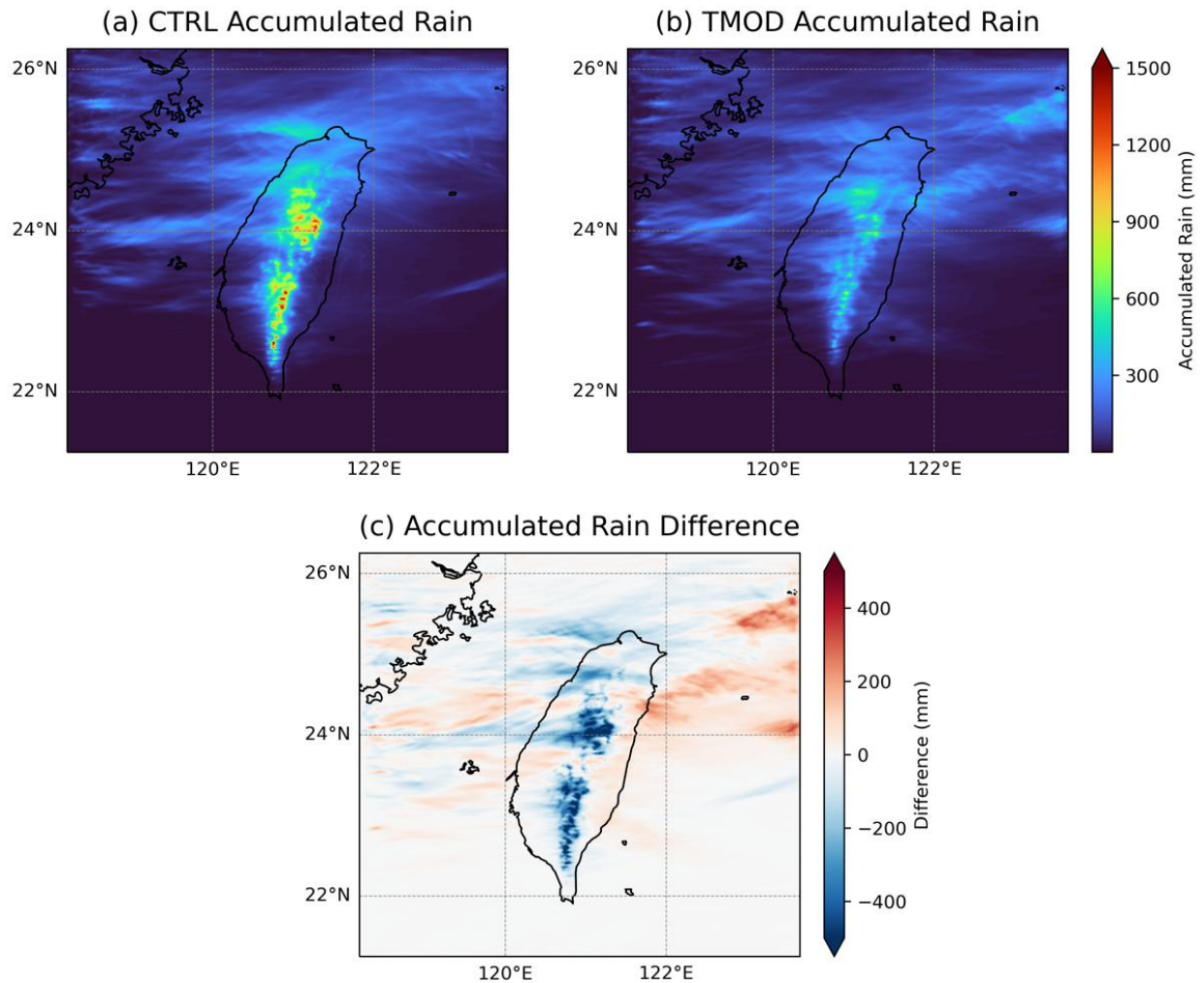


Figure 3.2: Rainfall accumulation during 1–3 June 2017 (UTC). Three-panel map of 72-h accumulated precipitation (mm) over the inner 1-km WRF domain (Domain 03), comparing (a) Central Weather Administration QPESUMS observed rainfall, (b) the Control (CTRL) simulation, and (c) the difference between the Terrain-Modification and Control runs (TMOD – CTRL), with negative values indicating reduced rainfall under terrain modification.

Simulated radar reflectivity patterns observed in the longitude–time Hovmöller diagrams (Figure 3.3) further emphasize the impact of terrain on the temporal and spatial distribution of heavy rainfall. In the CTRL run, pronounced reflectivity peaks on the west (windward) side of the CMR indicate higher reflectivity typically associated with intense orographic precipitation and robust convective activity. The reflectivity diminishes as precipitation extends eastward across the CMR, illustrating the role of the mountain range as a significant barrier that enhances convective activity on the windward side while sharply reducing it on the leeward side.

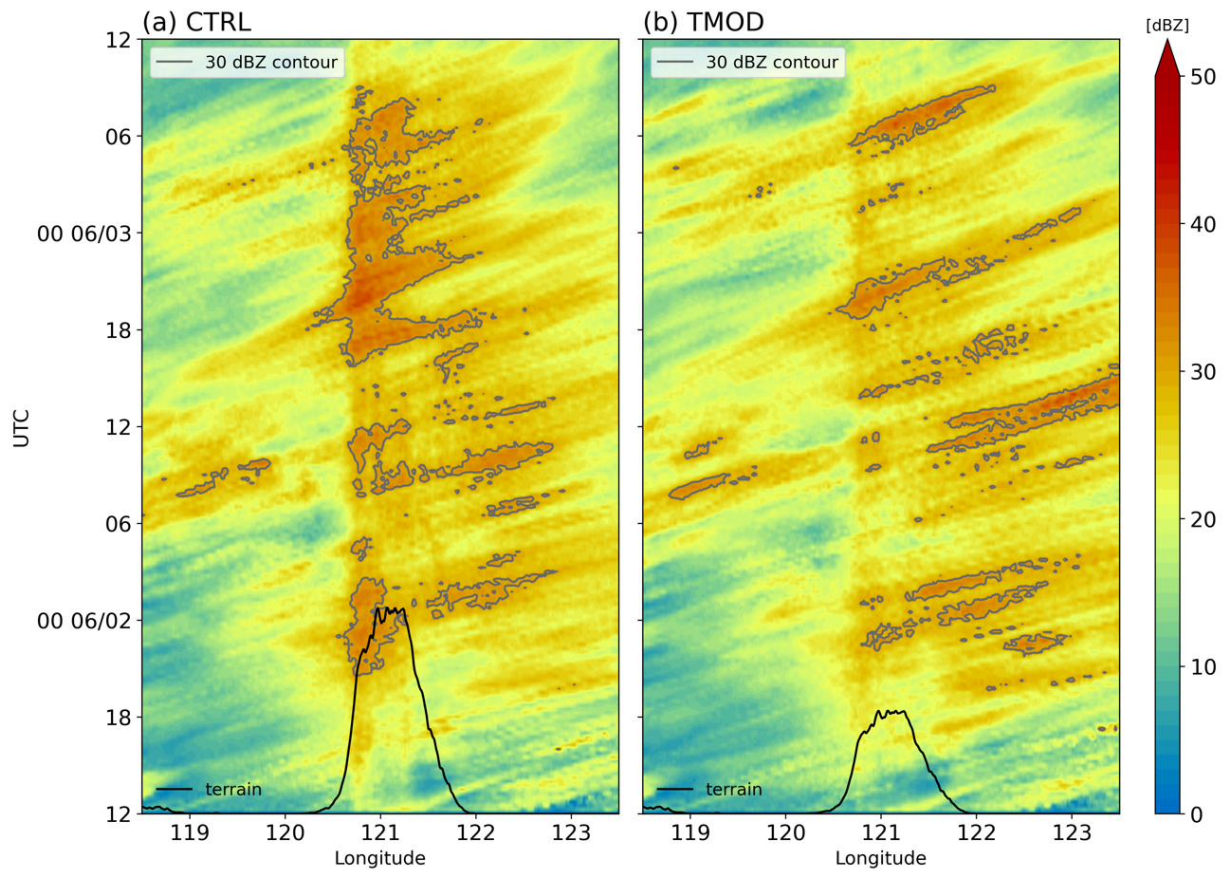


Figure 3.3: Longitude–time Hovmöller plots of composite radar reflectivity in (a) the CTRL run and (b) the TMOD run, averaged meridionally over Taiwan (21.85° – 25.33° N). Colors show reflectivity (dBZ). The contour line indicates 30 dBZ. The terrain is shown as a black line.

Conversely, the TMOD run displays a distinct shift in the reflectivity pattern (Figure 3.3b). The peaks of reflectivity over the CMR are lower in magnitude and less concentrated over the

mountains, with a noticeable increase in reflectivity on the east (leeward) side. This enhanced reflectivity on the leeward side not only persisted but also shifted eastward over time, suggesting a less obstructed atmospheric flow. The reduction in reflectivity over the CMR and enhancement on the leeward side suggests that the reduced mountain height allowed for changes in synoptic-to-mesoscale flows around Taiwan, leading to higher reflectivity over the ocean to the east of the island. A detailed analysis of the flow patterns associated with the terrain modifications is presented below.

The findings from both the rainfall distribution analysis and Hovmöller diagrams underline the critical role of terrain in shaping local and regional precipitation characteristics during extreme weather events, likely associated with changes in orographic flows around the island of Taiwan. These rainfall changes highlight the sensitivity of orographic and frontal rainfall systems to topography, which alters the distribution and intensity of convective processes and subsequent weather patterns.

To understand the impact of terrain modifications on the types of precipitation systems that occurred in the simulations, an extreme storm classification scheme originally developed to analyze spaceborne radar observations from the Tropical Rainfall Measuring Mission (TRMM) (Houze et al. 2015a) was employed to analyze the storm modes generated under the CTRL and TMOD scenarios.

Figure 3.4 presents the distribution of rain rates from each grid point over the analysis domain for each storm mode. The average storm area and total rainfall contribution from each storm mode are also computed for the entire study area and only over Taiwan, as shown in Table 3.1 and Table 3.2, respectively. DWCCs exhibit the highest rain rates, followed by WCCs, aligning with previous studies such as Panasawatwong et al. (2022). DCCs show minimal change in average rainfall rates between the CTRL and TMOD scenarios (Figure 3.4), maintaining a similar intensity with rain rates adjusting from 3.91 mm h^{-1} in CTRL to 3.93 mm h^{-1} in TMOD ($p = 0.82$). The total rainfall from DCCs increases due to a rise in both the number of DCCs and their individual storm area, as evidenced by the increase from 218 to 294 storms and from 33.0 to 41.1 km^2 in

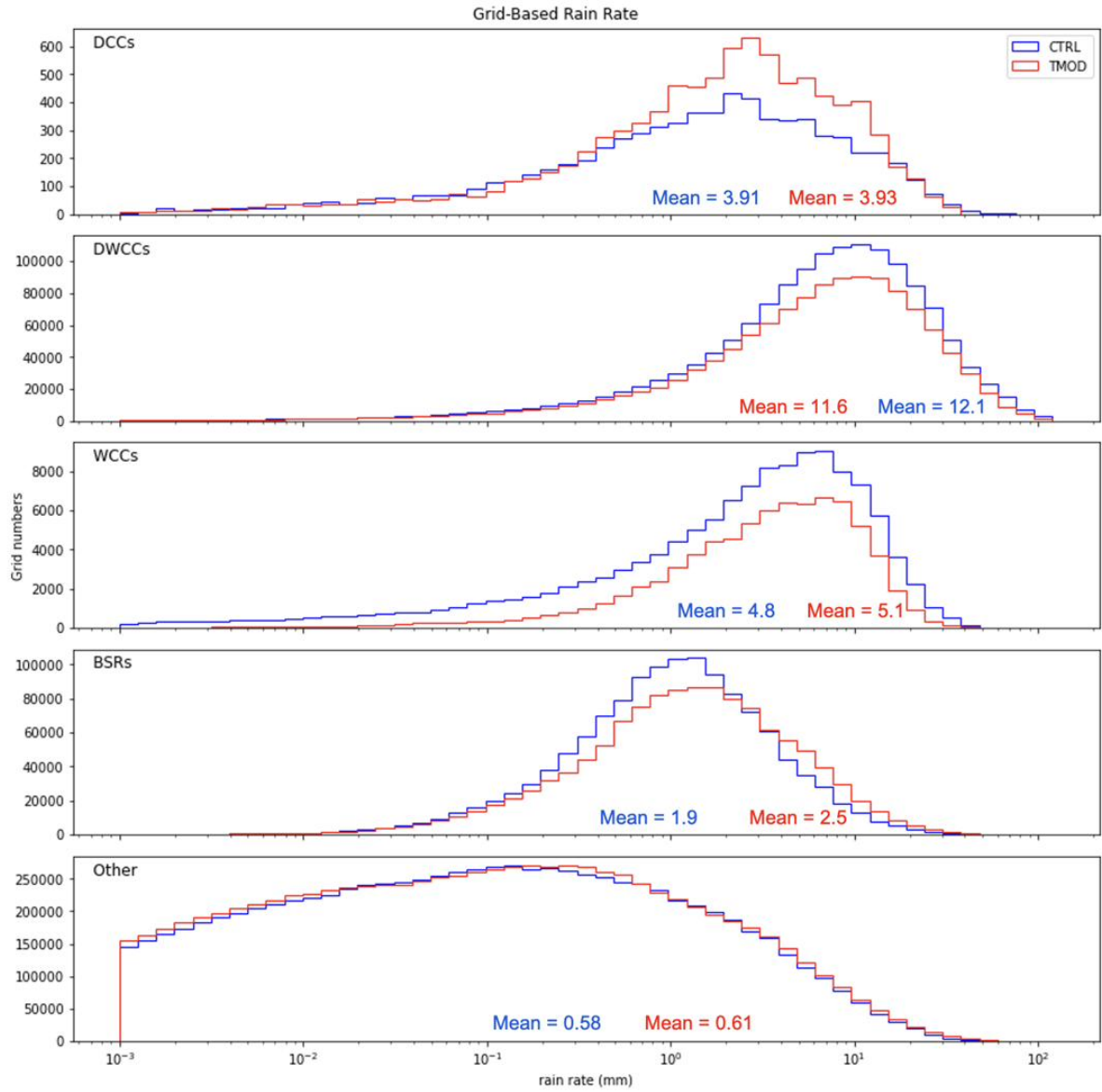


Figure 3.4: Rain rate distribution by storm mode. Grid-based probability density functions of hourly rain rates for each storm category (deep convective, deep and wide convective, wide convective, broad stratiform regions, and other) in the Control (blue) and Terrain-Modification (red) runs. Vertical dashed lines mark the mean values.

average area (Table 3.1). However, the contribution of DCCs to the total rainfall in this event is only around 0.1% (Table 3.2). The comparison between the CTRL and TMOD scenarios reveals nuanced shifts in storm intensities, as indicated by their respective changes in average rain rates and area coverage. For the BSRs, the Figure 3.4 grid-point count is larger in CTRL, while the area-weighted contribution in Table 3.2 is larger in TMOD. The two metrics are not contradictory because rainfall contribution scales with both the number of grid points and the mean rain rate per grid point, and the BSR mean rate increases from 1.9 mm h^{-1} in CTRL to 2.5 mm h^{-1} in TMOD; the TMOD BSRs are fewer but produce more rain per unit area, yielding the larger area-weighted contribution.

Table 3.1: Extreme storm average area and event count. Mean storm area (km^2) and number of storm events for each storm mode (DCCs, DWCCs, WCCs, BSRs, Other) in the Control (CTRL) and Terrain-Modification (TMOD) simulations.

Storm mode	CTRL #storm	CTRL avg area (km^2)	TMOD #storm	TMOD avg area (km^2)
DCCs	218	33.0	294	41.1
DWCCs	202	7,247	243	6,034
WCCs	46	2,830	57	1,703
BSRs	23	56,151	23	52,491

Table 3.2: Rainfall contribution by storm mode. Total rainfall contribution from each storm mode, expressed as the product of storm area and accumulated rainfall ($\text{mm} \cdot \text{km}^2$; first value in each cell) and as a percentage of the total precipitation in the indicated region (second value, in parentheses), for the CTRL and TMOD simulations over the full analysis domain and over the Taiwan land area.

Storm mode	CTRL (full)	TMOD (full)	CTRL (Taiwan)	TMOD (Taiwan)
DCCs	2.8×10^4 (0.1%)	3.5×10^4 (0.1%)	4.9×10^2 (0.0%)	6.9×10^3 (0.1%)
DWCCs	1.7×10^7 (60.3%)	1.4×10^7 (52.6%)	9.4×10^6 (82.1%)	5.3×10^6 (67.0%)
WCCs	6.2×10^5 (2.1%)	4.0×10^5 (1.5%)	2.5×10^5 (2.2%)	1.7×10^5 (2.1%)
BSRs	2.4×10^6 (8.4%)	3.0×10^6 (11.2%)	2.5×10^5 (2.1%)	5.5×10^5 (6.9%)
Other	8.5×10^6 (29.1%)	9.3×10^6 (34.6%)	1.5×10^6 (13.5%)	1.9×10^6 (23.8%)

DWCCs show the highest rain rate of all storm modes and are the main contributor to the total rainfall in the full region and over Taiwan. Despite an increase in the frequency of total raining

pixels from the CTRL to the TMOD run, DWCCs experience a decline in rainfall intensity from 12.1 mm h^{-1} to 11.6 mm h^{-1} ($p < 0.01$). This reduction in intensity, coupled with a significant decrease in their storm area from $7,247 \text{ km}^2$ to $6,034 \text{ km}^2$, results in a decrease in both the total rainfall amount and percent contribution from DWCCs for the total region and especially over Taiwan.

WCCs have the second highest rain rate and show mean rainfall rate increases from 4.8 mm h^{-1} in CTRL to 5.1 mm h^{-1} in TMOD ($p < 0.01$). However, the average area of WCCs sees a sharp reduction from $2,830 \text{ km}^2$ to $1,703 \text{ km}^2$. This significant decrease in area corresponds to the reduced total rainfall contribution from the WCCs from CTRL to TMOD.

BSRs show an increase in mean rain rate from 1.9 mm h^{-1} to 2.5 mm h^{-1} ($p < 0.01$). Unlike other storm modes, the number of BSRs remains the same, and the area only slightly decreases with no significance ($p = 0.27$). However, the increase in rain rate reflects an increase in rainfall contribution from the CTRL to the TMOD run, especially over Taiwan, where their percentage contribution doubles. The apparent inversion between Figure 3.4 (more BSR grid points in CTRL) and Table 3.1–Table 3.2 (larger BSR area-weighted contribution in TMOD) is reconciled by noting that the area-weighted rainfall contribution depends on both the BSR grid-point count and the per-grid-point rain rate. The per-grid-point BSR rain rate increases by $\sim 30\%$ (1.9 to 2.5 mm h^{-1}), which more than compensates for the reduced BSR grid-point count, yielding a larger total BSR contribution in TMOD.

The other storm category, representing the non-extreme storm systems, shows only a small but significant increase of their low rain rates, from 0.58 mm h^{-1} in CTRL to 0.61 mm h^{-1} in TMOD ($p < 0.01$). Due to their large number of occurrences as shown in the number of pixels counted in Figure 3.4, this other category contributes one-third of the entire rainfall region. The slightly increased rain rate is also accompanied by an increased rainfall area of the non-extreme rainfall contribution, especially over Taiwan.

The reduction in topographic elevation modulates storm characteristics including precipitation intensity, frequency, and storm area. Specifically, a diminished contribution from high-rain-rate

systems such as DWCCs, coupled with an increased contribution from lower-rain-rate systems, leads to a net decrease in accumulated rainfall over the domain, with the most pronounced reduction occurring over Taiwan.

The storm-mode rainfall contributions in this case study are consistent with the regional climatological analyses. Panasawatwong et al. (2022) showed that DCCs and DWCCs exhibit the highest mean rain rates across tropical and subtropical East Asia, yet their small storm sizes limit their volumetric rain contributions compared to the broader WCCs and BSRs. Similarly, in the June 2017 event, DWCCs maintained the highest intensity but contributed less rainfall under reduced terrain, whereas the spatially extensive BSRs increased their relative role. These results further align with radar observations from the PRECIP campaign, where DeHart and Bell (2025) found that only 6% of raining grid points with moderate rain rates of 10–50 mm h⁻¹ contributed nearly half of the total rainfall. Together, these findings highlight that heavy rainfall accumulations in the Meiyu environment typically arise from contributions from intermediate rain rates and spatially larger storm systems rather than from the most intense convective cells.

To provide a broader context for the location and changes in topography reduction in the simulations, the spatial frequencies for each storm mode for the two simulations are presented in Figure 3.5 and Figure 3.6, with the differences shown in Figure 3.7. In the CTRL run (Figure 3.5), DCCs are distributed sporadically over the sea around Taiwan, with a notable concentration along the southeastern shores of Taiwan, indicating that this region is potentially a hotspot for intense convective development. DWCCs display a preference for the northwestern part of the study area, with peaks over the CMR and along the western stretches, likely aligning with the position of the Meiyu front. This spatial arrangement suggests an interaction between the Meiyu front and the complex terrain in triggering these storms (Cornejo et al. 2024). WCCs also show a maximum frequency over the CMR, with an additional cluster situated northeastward, tracing the main Meiyu front path. For BSRs, which represent large-scale stratiform precipitation, the frequency plot shows a tendency to form north and east of Taiwan, particularly behind the CMR, illustrating the range's influence on regional precipitation patterns. The non-extreme storms in the CTRL run,

shown as Other, cover almost all the studied area except for the southern part, where the Meiyu front may not travel further during the model run. The Other storm mode was also less prevalent over the CMR.

The TMOD simulation (Figure 3.6) with reduced topography presents some shifts in storm patterns. DCCs remain scattered but have more inland locations and a less dense cluster along the eastern shores, suggesting a possible migration of convection inward of Taiwan due to the lower elevation of the terrain. DWCCs, which span the northern two-thirds of the region, demonstrate a broadened influence with peaks persisting over the CMR. Their distributions are located across the Meiyu front's possible locations, signifying the terrain's influence on the storm system. WCCs also demonstrate a dispersed pattern but maintain their peak occurrence over the CMR, indicating a stable focal point for convective activity. Meanwhile, BSRs show an expanded coverage across the north, with a pronounced peak on the CMR's leeward side, indicative of a shifted precipitation regime due to terrain modification. For the non-extreme Other storm mode in the TMOD run, the storm coverage was similar to that of the CTRL run with a more evenly distributed frequency over the CMR, likely due to the halving of the CMR height.

The difference between the two simulations (TMOD – CTRL, Figure 3.7) accentuates the shift in storm clustering and intensity with terrain modification. While no clear pattern emerges for DCCs, DWCCs reveal a stronger presence over the CMR in the CTRL run and a wider spread to the east in the TMOD run, suggesting the important role of terrain in the presence and formation of organized convection over the CMR. The clusters of WCCs that were prominent over the CMR and northeast in the CTRL run are less defined in the TMOD run, possibly due to a more uniform distribution of convective cells.

BSRs are located more to the west in the TMOD run as opposed to the east in the CTRL run, which is consistent with changes in mountain-flow regimes associated with reduced terrain height. By lowering the CMR, the effective Froude number increases and the low-level flow blocking is lowered, reducing the barrier jet (Cornejo et al. 2024). Under such conditions, the flow transitions from a more blocked, “flow-around” regime toward enhanced “flow-over” the terrain, allowing

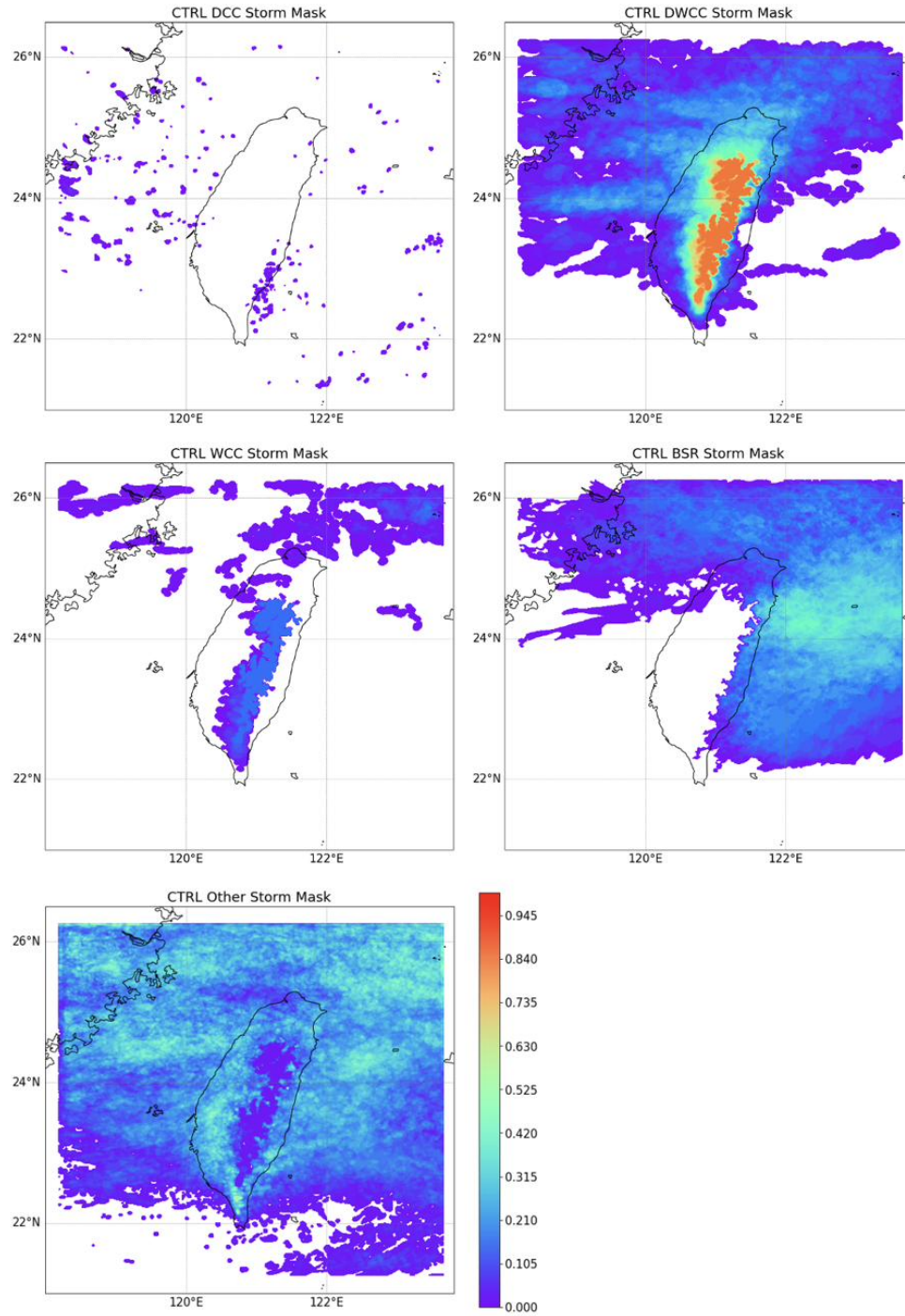


Figure 3.5: Spatial frequency of storm modes in the Control run. Map of storm-mode frequency expressed as the percentage of occurrence of storm events per grid cell over the 48-h simulation period.

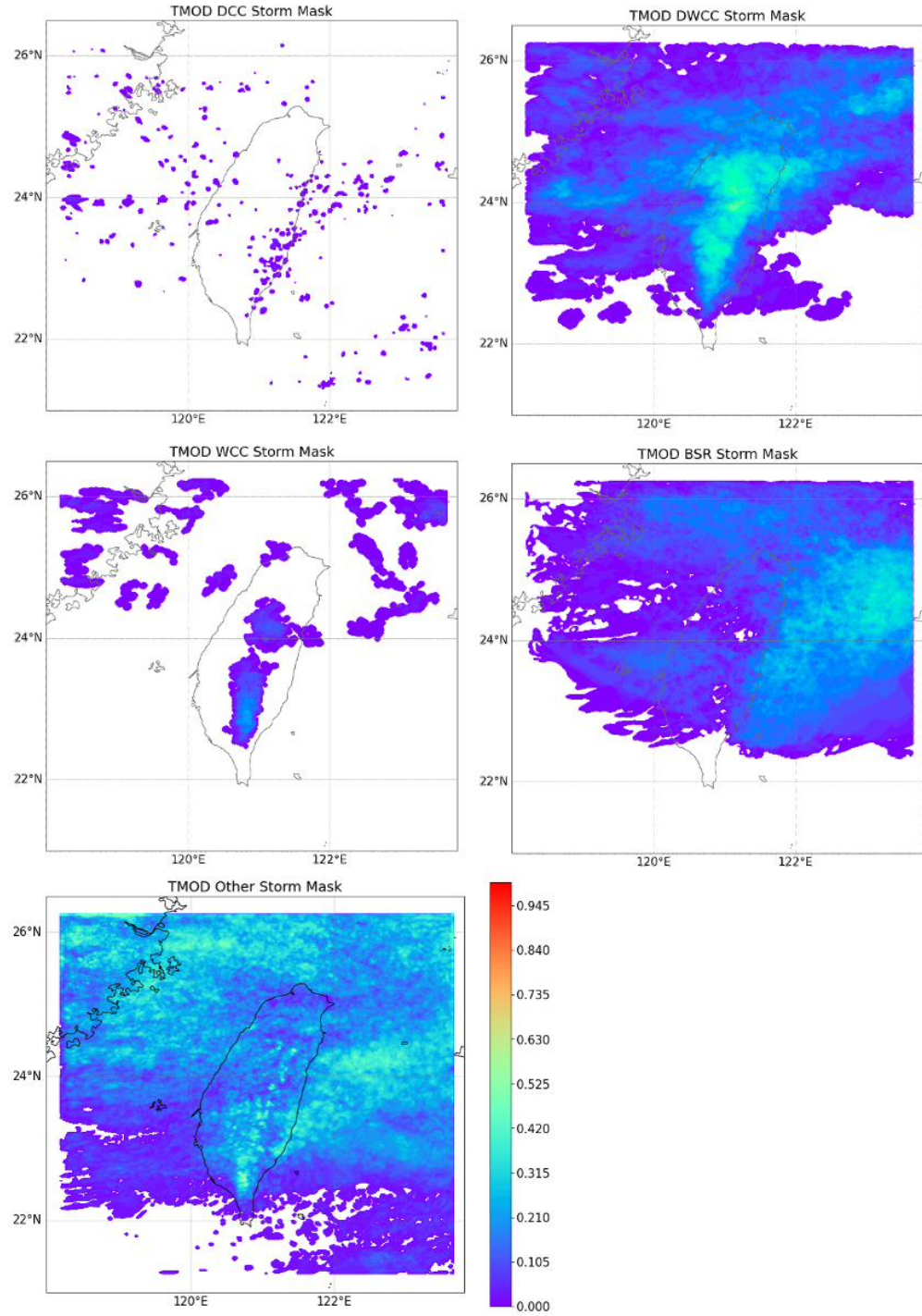


Figure 3.6: Spatial frequency of storm modes in the Terrain-Modification run. Map of storm-mode frequency expressed as the percentage of occurrence of storm events per grid cell over the 48-h simulation period.

stratiform precipitation regions to extend farther upstream and westward of the mountain crest. In the CTRL run, stronger blocking and lee-side convergence favor the confinement of BSRs to the eastern and northeastern sides of Taiwan, whereas in the TMOD run, diminished blocking enables broader, more symmetric stratiform coverage across the island and adjacent upstream regions. The Other storm frequency also reflects the broader and more even distribution of less extreme storms across the CMR.

Although individually weak, with mean rain rates of only $\sim 0.6 \text{ mm h}^{-1}$, these systems occur over a large fraction of the domain and collectively account for roughly one-third of the total rainfall. Their limited intensity and vertical development, together with their broad and spatially diffuse distribution (Figure 3.4–Figure 3.7), confirm that the “Other” category aggregates the background population of non-extreme precipitating cells rather than concealing an additional, physically meaningful storm mode.

Overall, the reduced terrain height in TMOD leads to less clustering of the large convective cores (DWCCs and WCCs) over the CMR and along the Meiyu front, whereas DCCs are located closer to the CMR in the TMOD run. The reduced terrain also allows BSRs to expand their coverage from only the north and east sides of the studied region toward the west.

3.3.2 Horizontal and vertical wind velocity

Figure 3.8 shows a comparison of the winds at the 850-hPa level between the CTRL and TMOD runs. In the CTRL run, the main wind direction is from the west-southwest to the west of Taiwan. As the winds approach the CMR, some of the flow appears to be blocked on the windward side, with flow diversion around the island to the north and south sides of Taiwan (Figure 3.8a). In the lee, a wake flow region is present with lower wind speeds because of the windward blocked flow and split flow around Taiwan. Research on flows around the Big Island of Hawaii demonstrated a very similar phenomenon, with blocked flows on the windward side of the island (near Hilo, HI) and a much lower wind regime in the lee wake flow region (near Kona, HI) as a result of split flow around the island (Rasmussen et al. 1989).

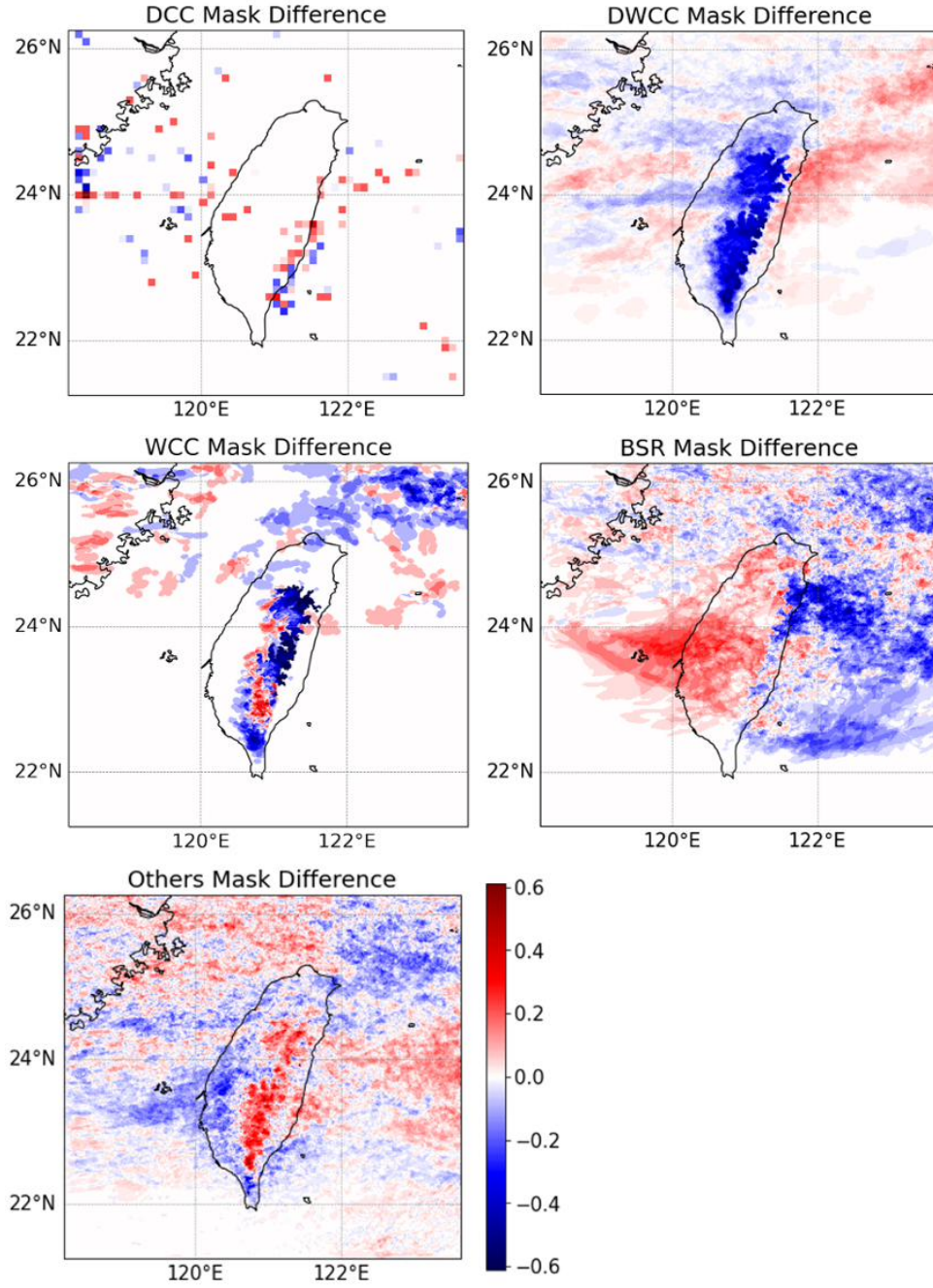


Figure 3.7: Difference in storm-mode frequency (TMOD – CTRL). Spatial difference in storm-mode event counts per grid cell as a percentage between the Terrain-Modification and Control runs. Negative values indicate reduced occurrence under terrain modification.

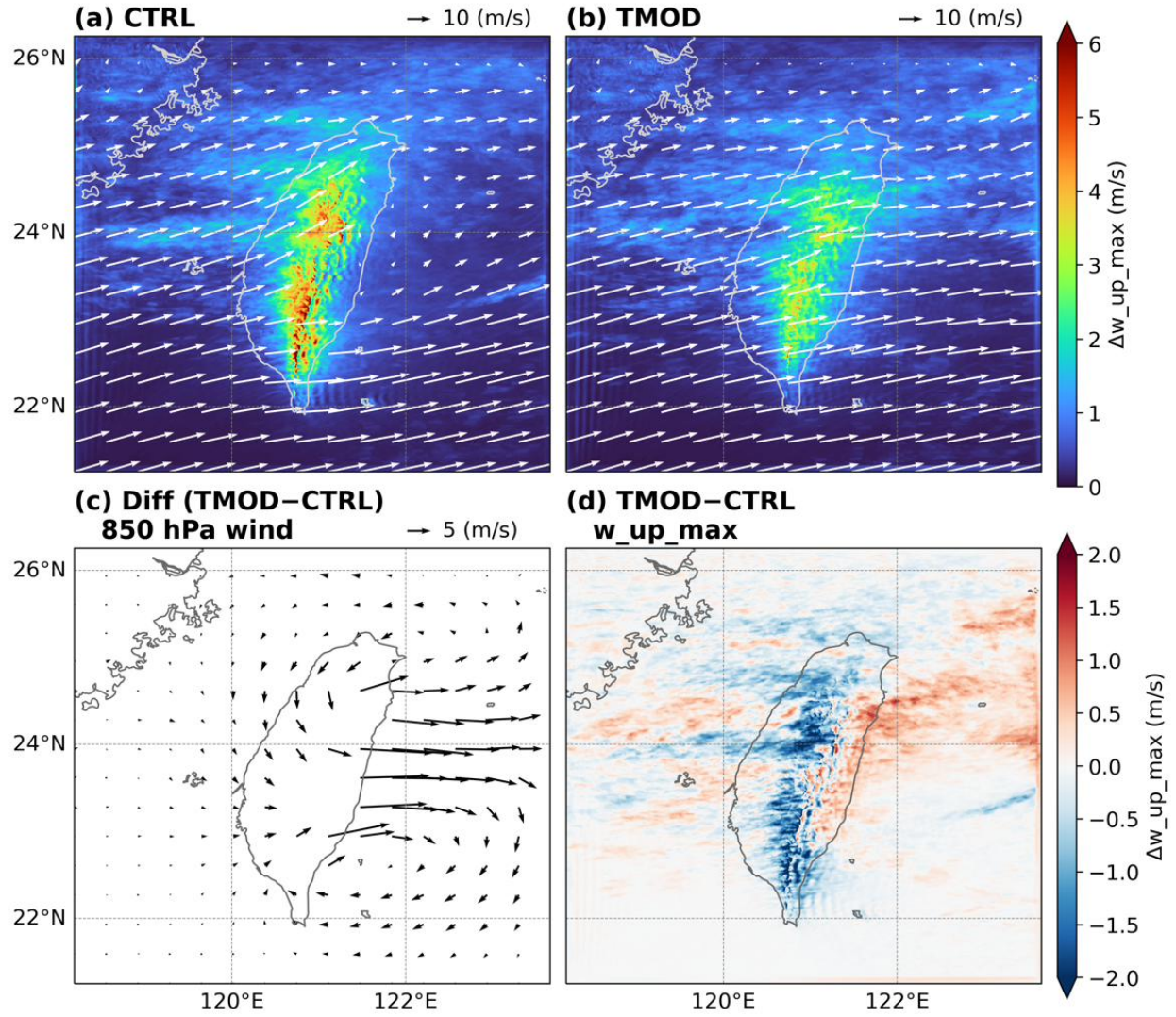


Figure 3.8: 850-hPa horizontal wind and 700-hPa vertical velocity comparison. (a) Control (CTRL) and (b) Terrain-Modification (TMOD) composite fields. The difference (TMOD – CTRL) of (c) the 850-hPa horizontal wind shown as black arrows, and (d) the 700-hPa vertical velocity w (m s⁻¹, positive upward) shown in colors. Negative values indicate weaker updraft under terrain modification.

For the TMOD run, the wind pattern is notably different and more uniform across the domain, maintaining its west-southwest direction (Figure 3.8b). The flow changes include the region over the mountains, where the wind is more unidirectional and has less flow deflection and splitting compared to the CTRL run (Figure 3.8a). The 700-hPa vertical velocity is generally weaker in TMOD than in CTRL, with peak composite-mean values of only $\sim 5.6 \text{ m s}^{-1}$, which is proportional to the 50% lower height of the CMR.

The TMOD run exhibits increased merging of winds from the north and south toward the center of the CMR on its western side (Figure 3.8c), along with stronger westerly flow on the eastern side. These horizontal wind changes are accompanied by a redistribution of vertical motion (Figure 3.9), with weakened updrafts on the windward side and enhanced updrafts in the lee. The regions of enhanced ascent do not coincide with the strongest low-level convergence on the western slopes but instead align with the strengthened westerly flow downstream of the terrain.

Figure 3.9 shows time–longitude plots of the maximum upward velocity in both the control (CTRL) and terrain modification (TMOD) simulations. The analysis shows that the overall flow of the system across time and longitudes remains consistent between the two runs, suggesting that the broad meteorological conditions driving these events are similar in both model configurations. The full-CMR CTRL simulation shows higher upward vertical motion magnitudes compared to the TMOD simulation, particularly over the windward side of Taiwan. In the CTRL run, the windward slopes of the CMR have stronger updrafts, which is characteristic of orographic enhancement where the air mass is lifted over the mountains.

In contrast, the TMOD run shows a decrease in the peak upward velocity. While the windward side still experiences higher vertical velocity, there is a detectable increase in the intensity immediately in the lee of the CMR. This result suggests that the reduction in mountain height allows for a more efficient transport of upward air mass over the barrier with less blockage from the CMR height, resulting in increased upward velocity on the leeward side. These observations indicate that lowering the CMR allows more of the prevailing west-southwesterly (Meiyu-front southwesterly

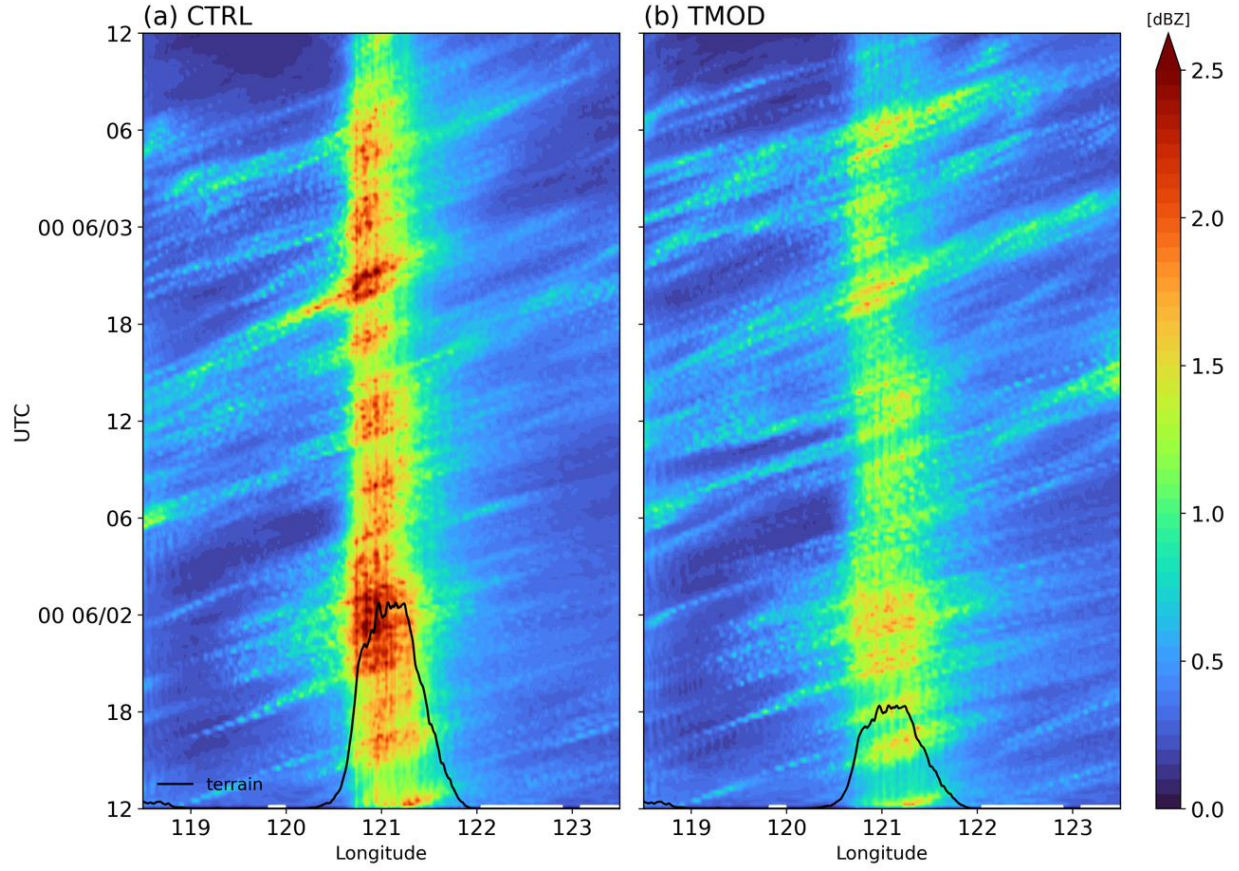


Figure 3.9: Longitude–time Hovmöller plots of the maximum upward vertical velocity ($w_{up,max}$) in (a) the CTRL run and (b) the TMOD run, averaged meridionally over Taiwan (21.85° – 25.33° N). Colors show updraft magnitude ($m s^{-1}$). The terrain is shown as a black line.

monsoonal) flow to pass over the CMR, less upward wind on the west side of the CMR, and more upward wind on the east side of the CMR.

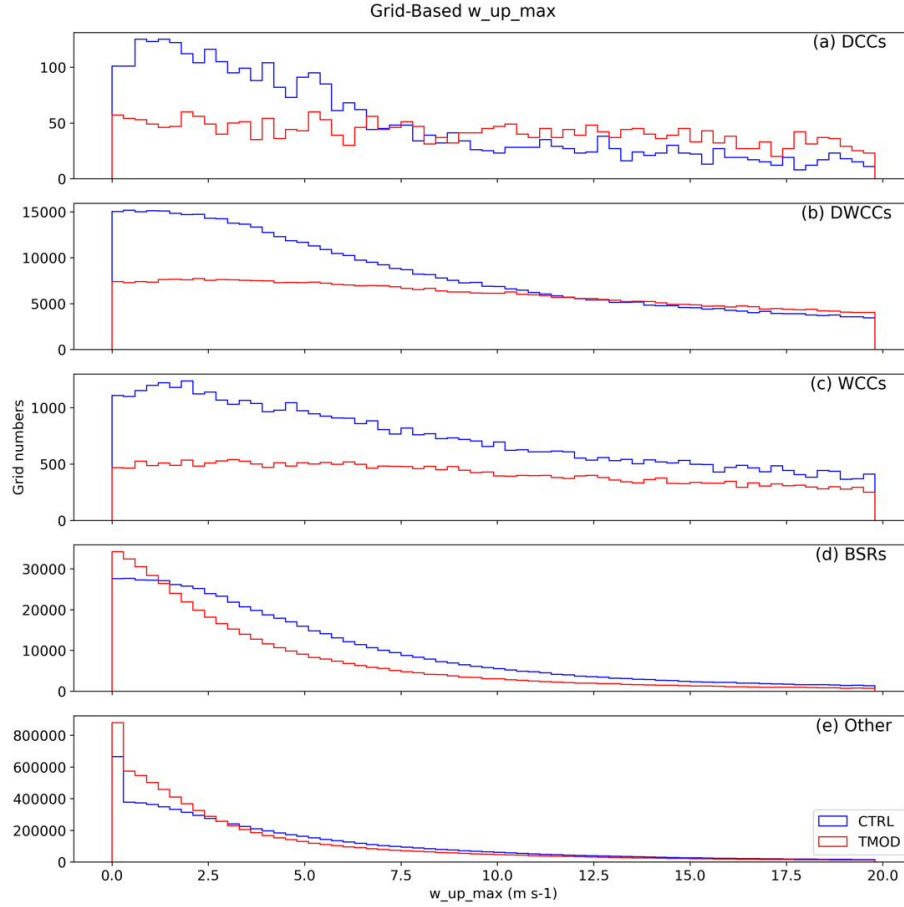


Figure 3.10: Maximum upward wind distribution by storm mode. Histogram of maximum upward wind for each storm mode in the Control (blue) and Terrain-Modification (red) runs.

Figure 3.10 shows a grid-based distribution of maximum upward velocity for each storm mode, calculated within the footprint of each storm. Even though the statistical mean and mode of updraft speed of every type is close to zero, the ranges of the convective-core updraft velocities are much wider than the BSRs and the other types, reflecting the convective core's stronger maximum upward velocity.

DCCs show a significant increase of the average of the maximum upward velocity from 3.85 m s^{-1} in CTRL to 4.12 m s^{-1} in TMOD ($p < 0.01$), due to the location distribution of DCCs in TMOD

being closer to the CMR (Figure 3.6, Figure 3.7) where the stronger maximum upward velocity is located. When restricted to grid points only over Taiwan, an increase in the average of maximum upward velocity from 14.5 m s^{-1} in CTRL to 15.0 m s^{-1} is seen in the TMOD simulation ($p < 0.01$). DWCCs and WCCs also show significant increases in the average of the maximum upward velocity from CTRL to TMOD ($p < 0.01$), due to the increasing number of storms located over the ocean around Taiwan, where the upward maximum velocity was slightly stronger in TMOD. Calculation of the mean of maximum upward velocity for DWCC and WCC grids that are only over Taiwan shows that the wind weakens from 19.0 m s^{-1} in CTRL to 17.0 m s^{-1} in TMOD for DWCCs and from 15.9 m s^{-1} in CTRL to 12.1 m s^{-1} in TMOD for WCCs. The results imply that although DWCCs and WCCs do not require particularly strong upward velocities to form, the stronger upward velocities from the orographic effects around the CMR in CTRL help increase the rain rate and rainfall amount produced by these storms. BSRs show a small range of maximum upward velocity, with their averages close to zero in both the CTRL and TMOD runs. However, the upward velocity does significantly increase from CTRL in the TMOD run ($p < 0.01$).

Together, these wind and vertical-motion changes reflect a terrain-driven shift in the orographic flow regime. Following Cornejo et al. (2024), lowering the CMR raises the effective Froude number and moves the flow from a blocked, flow-around regime—in which windward ascent concentrates rainfall over the western slopes—toward flow-over that displaces ascent to the lee. Estimated from the CTRL upstream environment ($N \approx 0.012 \text{ s}^{-1}$, $U \approx 12 \text{ m s}^{-1}$), the dimensionless mountain height $M = Nh/U$ falls from ≈ 3.0 ($h \approx 3 \text{ km}$, firmly blocked) to ≈ 1.5 ($h \approx 1.5 \text{ km}$, near the regime transition), so the 50% reduction is the minimum needed to change the regime qualitatively and explains why the split-flow wake and barrier jet vanish in TMOD and ascent migrates eastward (Figure 3.8d). This shift is strongest in central Taiwan, where the $\sim 3\text{-km}$ ridge is nearly perpendicular to the Meiyu flow, and weakest over the lower, more obliquely approached northern terrain that already lies near flow-over in CTRL—explaining why TMOD reduces central-Taiwan rainfall sharply while leaving northern lee rainfall largely unchanged.

3.3.3 Moisture flux

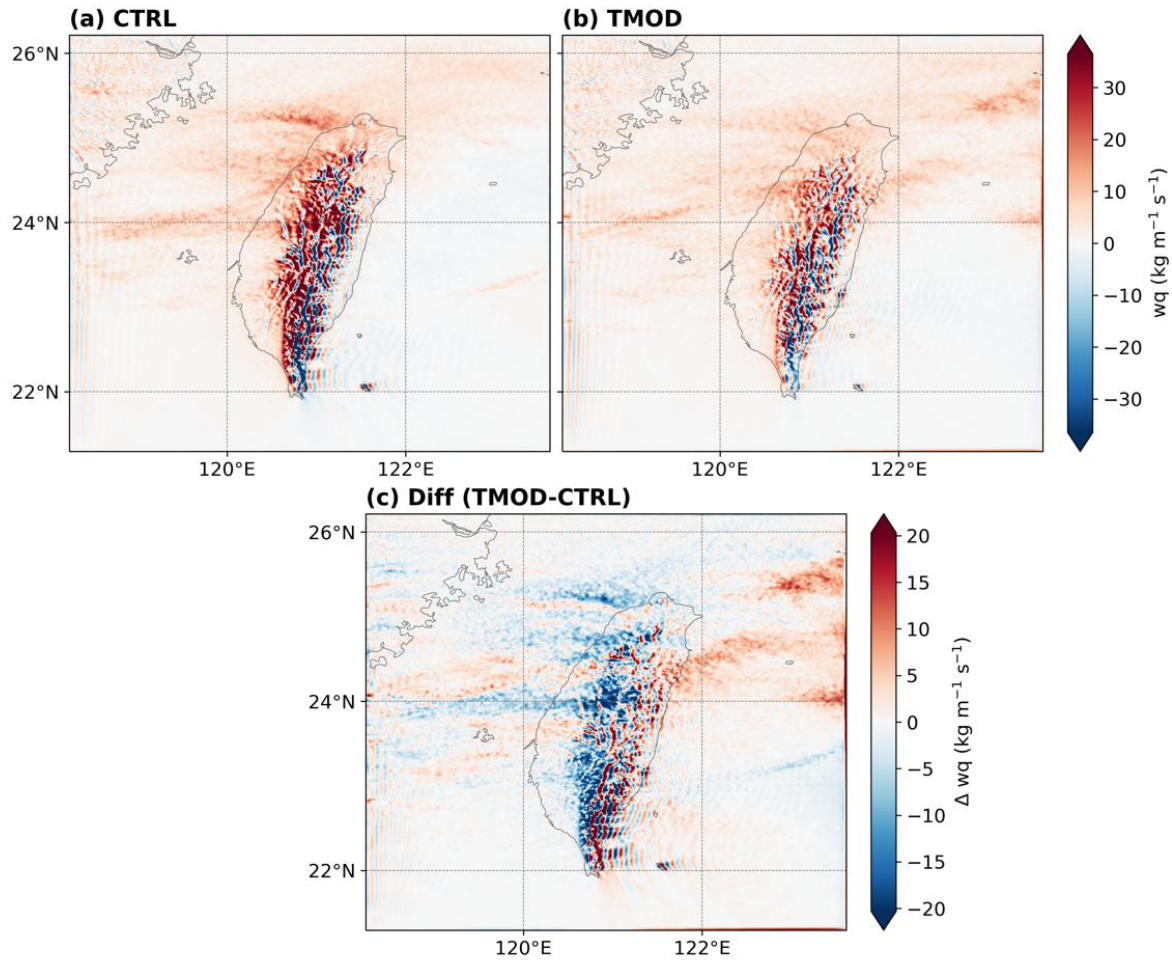


Figure 3.11: Vertical moisture flux (wq , $\text{kg m}^{-1} \text{s}^{-1}$) for (a) the Control run, (b) the Terrain-Modification run, and (c) the difference (TMOD – CTRL). Negative values indicate reduced moisture flux under terrain modification.

In Figure 3.11, the CTRL run shows a distinctive wq pattern, with positive values on the west side of the CMR where moisture is transported toward the mountains. This pattern is consistent with the observed wind patterns, indicating an influx of moisture-laden air impinging on the CMR. Conversely, on the east side the wq values are negative, suggesting that the moisture flux is directed away from this area. This divergence aligns with the sheltering effect often seen on the leeward side of significant topographical barriers, where air descends and dries.

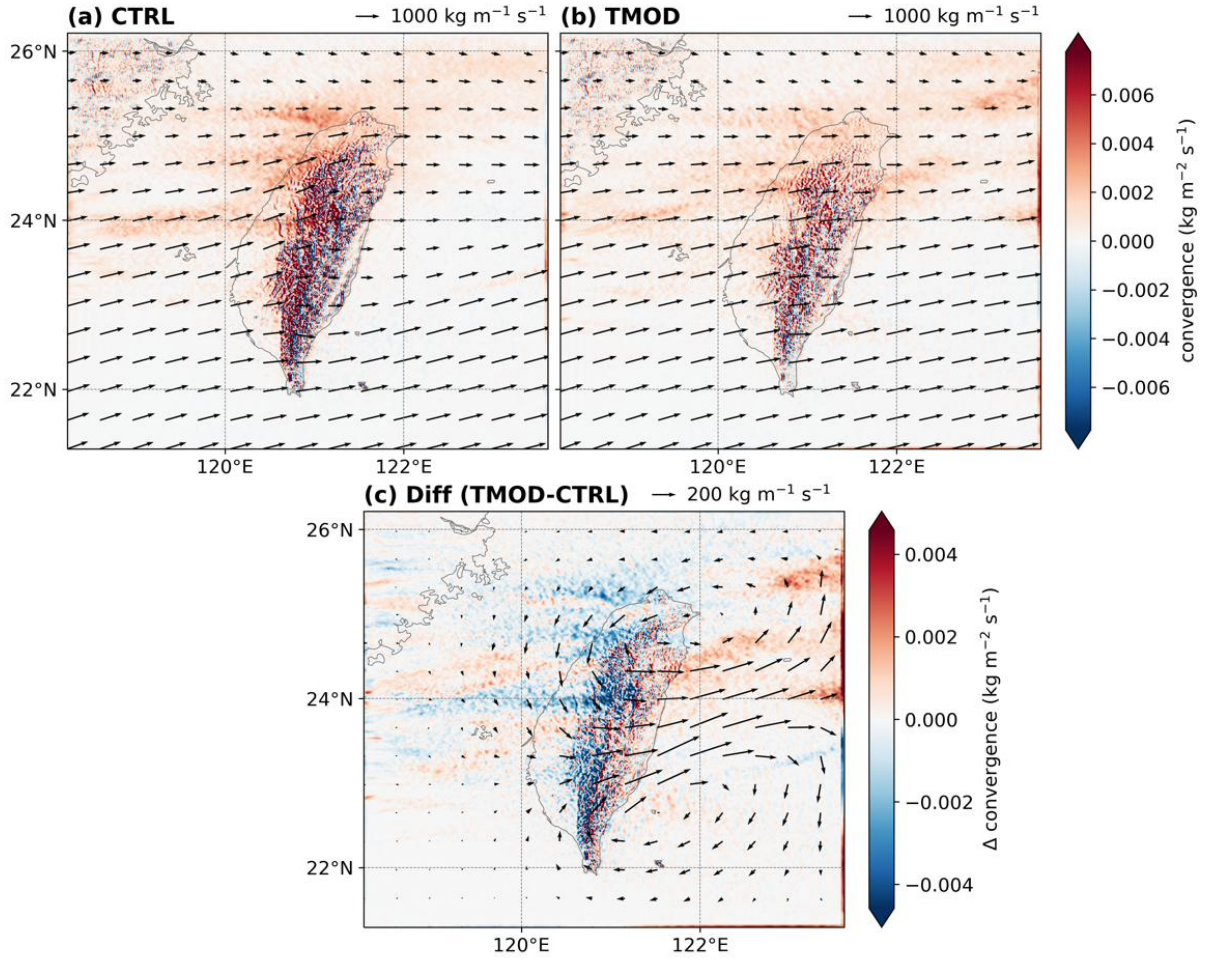


Figure 3.12: Vertically integrated moisture flux (VIMF, $\text{kg m}^{-1} \text{s}^{-1}$, quiver) and vertically integrated moisture flux convergence (or negative vertically integrated moisture flux divergence, $-\text{VIMD}$, $\text{kg m}^{-2} \text{s}^{-1}$, colored), for (a) the Control run, (b) the Terrain-Modification run, and (c) the difference (TMOD – CTRL). Negative values indicate reduced moisture flux under terrain modification.

The TMOD run shows a similar wq pattern to the CTRL, but the magnitudes are reduced. This decrease suggests that lowering the CMR elevation diminishes orographic lifting and, consequently, moisture fluxes on both the windward and leeward sides of the mountain range.

The wq differences between the TMOD and CTRL runs indicate a decrease in the moisture flux magnitude over the CMR, affirming the role of terrain in modulating atmospheric moisture transport. Additionally, an increase in the negative moisture flux was observed to the northeast of Taiwan in the TMOD run. The change in moisture flux could indicate that modifications in terrain height not only reduce orographic uplift but also possibly alter the moisture pathways and distribution downwind of the CMR.

Figure 3.12 separates the upward transport of moisture from its horizontal convergence. The vertically integrated moisture flux (VIMF, vectors) and the moisture-flux convergence ($-VIMD$, shading) are shown together, and the $-VIMD$ field closely matches the wq field of Figure 3.11 in both location and magnitude, with strong moisture convergence along the windward (western) flank of the CMR and divergence in the lee. Although the two fields are nearly collocated, they describe complementary processes. The wq field measures the rate at which moisture is carried upward, as shown in the Doswell et al. (1996b) intensity framework, while $-VIMD$ measures the net horizontal import of moisture into a column from the surrounding flow. Their close correspondence indicates that, over the windward CMR, the moisture converging horizontally into each column is efficiently lifted, so that the horizontal supply and the vertical export of moisture are tightly coupled along the barrier.

Notably, the VIMF vectors closely follow the 850-hPa horizontal wind (Section 3.3.2) in both direction and the location of their maxima, while the wq and $-VIMD$ fields track the pattern of maximum upward velocity rather than the moisture field. The moisture-flux signal is therefore set primarily by the wind, both the low-level flow that delivers the moisture and the orographically forced ascent that lifts it, rather than by spatial variations in moisture content, which remain comparatively uniform across the warm, nearly saturated Meiyu air mass.

This wind-dominated control links the Meiyu and orographic aspects of the event. The Meiyu front supplies a deep, moisture-laden southwesterly flow in which moisture itself is not the limiting ingredient; what determines where heavy rain falls is where that flow is forced to ascend. The CMR provides that forcing, concentrating both the horizontal moisture convergence ($-VIMD$) and the vertical moisture flux (wq) over its windward slopes, collocated with the maximum upward velocity. When the terrain is lowered, the weakened orographic ascent decreases the moisture transports as shown by wq and $-VIMD$ over the CMR and shifts the convergence downstream, consistent with the windward-to-lee redistribution of rainfall diagnosed in the storm-mode analysis.

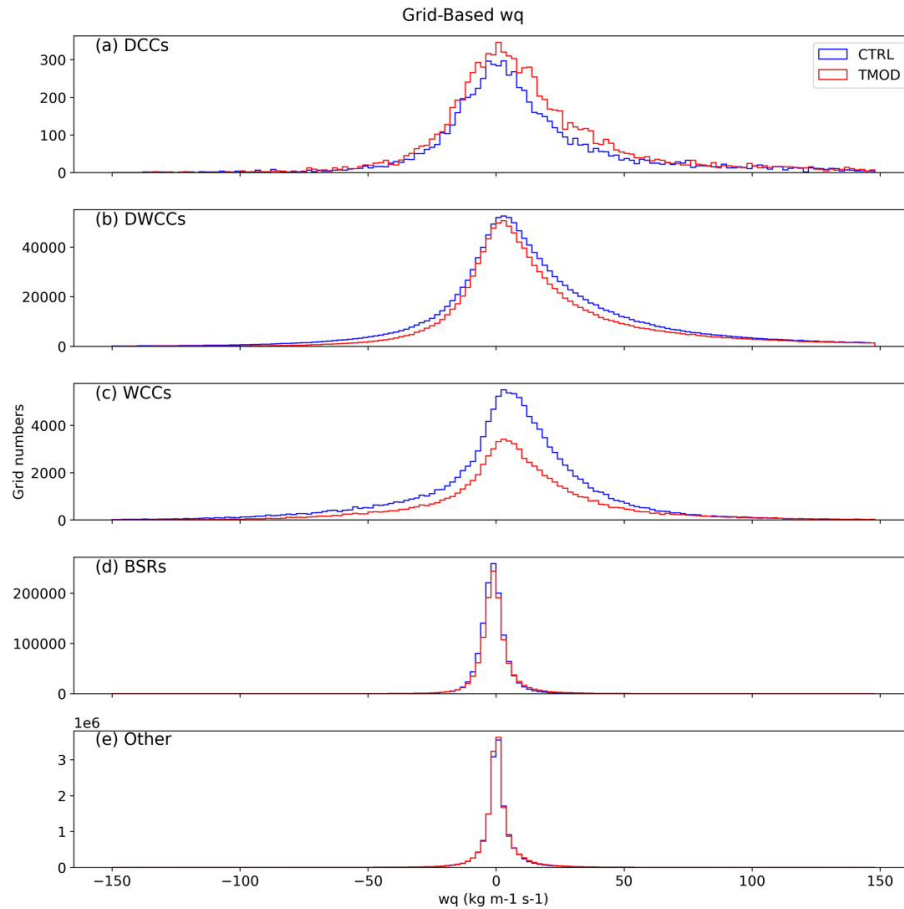


Figure 3.13: Vertical moisture flux (wq) distribution by storm mode. Histogram of wq for each storm mode in the Control (blue) and Terrain-Modification (red) runs.

Figure 3.13 shows that for the DCCs and DWCCs, the wq histograms reveal a consistent pattern between CTRL and TMOD, with no significant change in the variability of the moisture flux (F -test = 0.99). The mean wq values show no significant change for DWCCs (t -test = 0.0), suggesting that these storm modes maintain their moisture transport characteristics regardless of terrain modification. DCCs exhibit a slight variation in mean values (t -test = 0.11), though not statistically significant, indicating a minor influence of terrain on their moisture dynamics.

WCCs display a notable difference in wq distribution between CTRL and TMOD, with significant changes in both the variability (F -test = 0.02) and the mean (t -test = 0.0). The experiment indicates a substantial alteration in moisture flux for WCCs under terrain-modified conditions, reflecting a sensitive response to changes in topography that affect both the amount and distribution of moisture transport.

Both BSRs and other non-extreme storm modes show significant changes in their wq profiles. The histograms indicate a marked shift in the moisture flux distribution, with both the variability and mean values showing significant differences (F -test and t -test = 0.0). The experiment suggests that terrain modifications significantly impact the moisture transport processes in these storm modes, potentially affecting their development and precipitation outcomes.

The wq analysis underscores the differentiated impact of terrain modification on storm modes, particularly highlighting the sensitivity of WCCs, BSRs, and other categories to changes in topography. The significant alterations in moisture flux for these storm modes may influence their potential for precipitation, affecting not only the intensity but also the spatial distribution of rainfall. The consistent wq behavior observed in DCCs and DWCCs suggests that these storm modes, typically characterized by strong convective activity, are less influenced by changes in the underlying terrain than more broadly distributed systems, such as BSRs.

Lowering the CMR reduces not just the vertical moisture flux but also the orographic residence time of air parcels by weakening blocking and accelerating flow-over. Within the Doswell et al. (1996b) ingredient framework $P = I \times D$, the total rainfall is impacted in both the intensity $I = Ewq$ via the vertical moisture flux, and also the duration via lessened residence time, D . This

change in the ingredients is consistent with the reduced contribution of DWCCs, which is shown to be the strongest rain-rate producer in the region (Panasawatwong et al. 2022) and the largest convective cores (Table 3.1).

3.3.4 Low-level shear

Figure 3.14 shows the effects of altering the height of the CMR on the wind shear between the 700–900-hPa level. In the CTRL run, the shear strength reaches approximately 15 m s^{-1} within the northern Meiyu band, which is significantly higher than the 5 m s^{-1} shear observed in the southern areas of the studied region. On the eastern side of the CMR immediately after the mountain range, the shear spikes to over 20 m s^{-1} and then gradually decreases in the northeast direction, following the wind flow pattern detailed in the previous wind section.

In the TMOD run, the pattern within the Meiyu band remains largely unchanged, with the northern region still showing shear values of approximately 15 m s^{-1} and the southern region maintaining its low shear of 5 m s^{-1} . On the eastern side of the CMR, however, there is a noticeable change, with the shear directly behind the mountain reduced to approximately 15 m s^{-1} , which is lower than that observed in the CTRL run. The shear diminishes in the northeast direction, consistent with the altered wind flow.

The comparative analysis shows that the TMOD run indicates a general weakening of shear on the eastern side of the CMR. Additionally, a subtle southward shift is noticed in the zonal shear associated with the Meiyu band from the CTRL run to the TMOD run. Interestingly, the areas with stronger shear on the east side of the CMR coincide with stronger easterly and upward winds (Figure 3.9).

Figure 3.15 shows the low-level shear distribution for each extreme storm mode in the CTRL and TMOD runs. The histograms indicate the frequency distribution of the shear values within each storm category, reflecting variations in storm dynamics influenced by terrain modifications.

Both DCCs and DWCCs show a low magnitude of low-level shear, with a similar distribution between the CTRL and TMOD scenarios. *F*-tests indicate no significant difference in the vari-

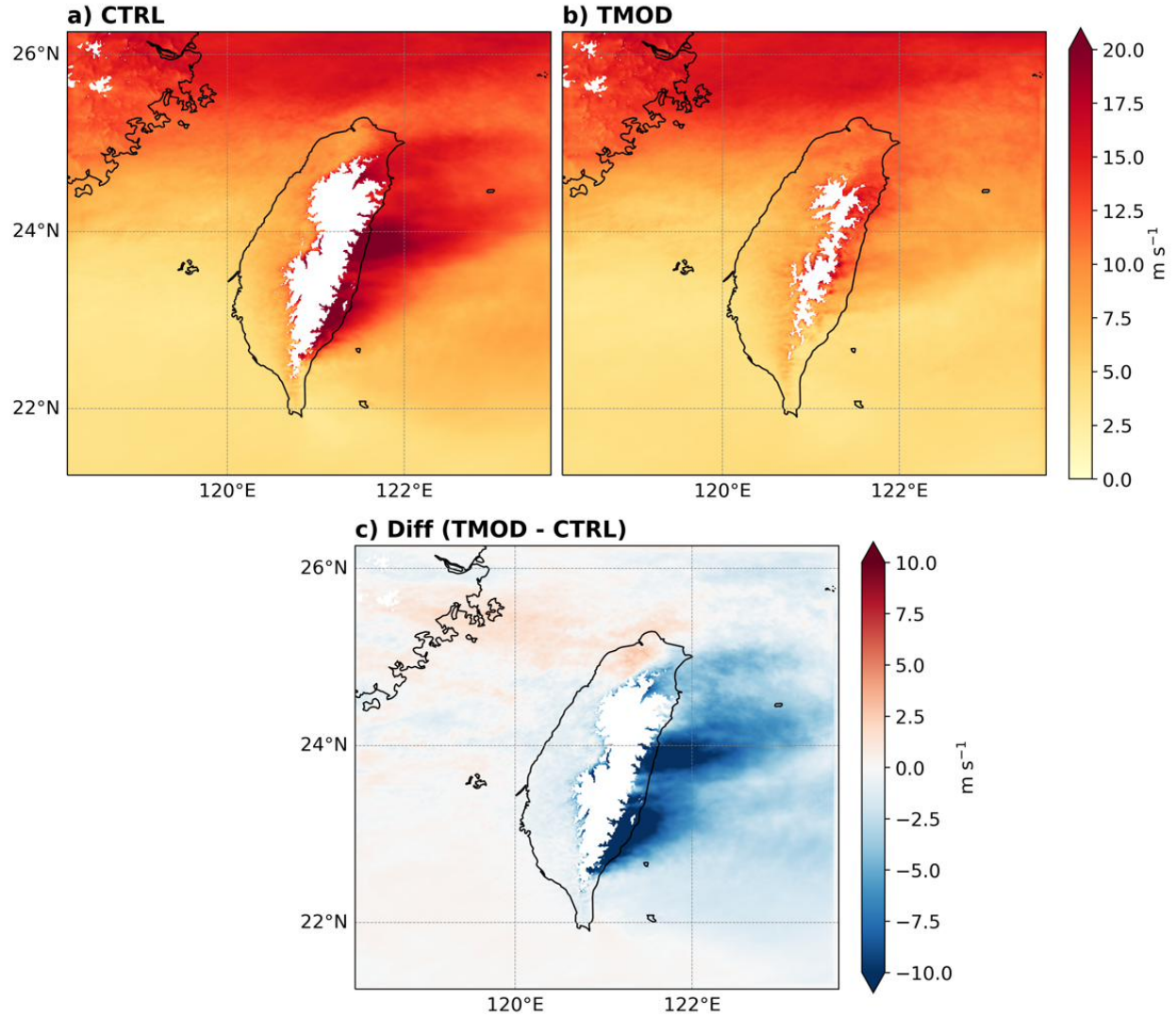


Figure 3.14: Low-level shear (900–700 hPa) fields. Spatial distribution of the 900–700-hPa vector wind shear magnitude (m s^{-1}) for (a) the Control simulation, (b) the Terrain-Modification simulation, and (c) the difference (TMOD – CTRL); the diverging palette shows positive values where TMOD shear exceeds CTRL shear. Negative values indicate reduced shear under terrain modification.

ance of the shear values ($F = 0.99$ for both). However, the t -tests reveal significant decreases in the mean shear values ($p = 0.0$), suggesting that while the variability of shear within these storm modes remains constant, the average intensity of shear is significantly affected by terrain modifications.

WCCs exhibit a markedly different pattern in TMOD compared to CTRL, with the histograms showing a more dispersed distribution in the TMOD. The statistical tests underscore this observation, with an F -test result of 0.0 indicating a significant difference in the variance of the shear distributions and a t -test result of 0.0 confirming a significant decrease in the mean shear values. The analysis suggests that WCCs are particularly sensitive to changes in terrain, affecting both the variability and average intensity of the low-level shear.

BSRs and Other non-extreme storm modes display minor shifts in the distribution of low-level shear between CTRL and TMOD. The F -tests show no significant differences in variance ($F = 0.99$), whereas the t -tests indicate significant changes in mean values ($p = 0.0$). The analysis suggests that while the overall variability of shear remains consistent, the mean intensity is altered, likely due to the broad and diffuse nature of these storm modes, which may be influenced by subtle shifts in atmospheric dynamics induced by terrain changes.

The analysis of low-level shear distributions provides valuable insights into how terrain modifications influence storm dynamics. Significant changes in the mean and variance of shear in storm modes, such as WCCs, highlight their sensitivity to orographic effects, which can alter wind profiles and subsequently the storm's development and behavior. For DCCs and DWCCs, the consistent variance but altered mean suggests that these storm modes maintain their dynamic structure under terrain modifications, but their overall intensity or shear-related properties change.

This responsiveness of storm shear to topographical changes underscores the importance of considering terrain effects in weather forecasting and storm modeling, particularly in regions with complex landscapes, such as Taiwan. The results indicate that terrain-induced modifications can have profound implications for storm behavior, potentially affecting the predictability and severity of the weather events.

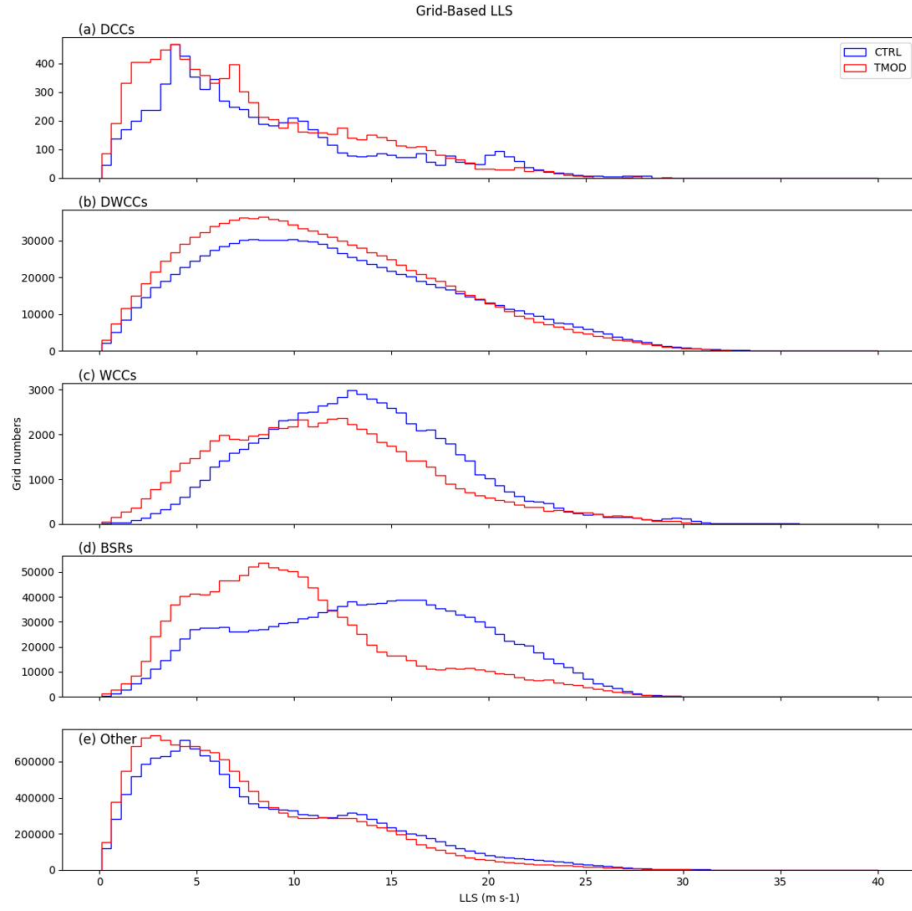


Figure 3.15: Low-level shear distribution by storm mode. Histograms of 700–900-hPa shear for each storm mode in the Control (blue) and Terrain-Modification (red) runs.

These findings highlight the significant impact of terrain modification on the distribution of atmospheric moisture. The reduction in the CMR height appears to facilitate greater moisture transport over the mountain range, particularly on its leeward side, which could have important implications for precipitation patterns and weather systems downstream of the mountains. Conversely, the areas surrounding this increased wq band experience a decrease in moisture flux, suggesting a redistribution rather than a simple increase in atmospheric moisture.

When viewed in a broader context, the results of this terrain-sensitivity case study are at the intersection of the climatological and process-based perspectives. The climatology of Panasawatwong et al. (2022) established that volumetric rainfall in East Asia is dominated by broader WCCs and BSRs despite their lower mean intensities. The PRECIP radar analyses of DeHart and Bell (2025) further demonstrated that moderately intense convective rain rates ($10\text{--}50\text{ mm h}^{-1}$) disproportionately drive total accumulations, reflecting the balance between frequency and intensity. These results provide a mechanistic explanation for these statistical findings: the height of Taiwan’s Central Mountain Range modulates the Froude number and associated orographic lifting (Cornejo et al. 2024), which in turn reshapes the distribution of shear, vertical motion, and moisture flux that determines which storm modes dominate. Thus, mountain–flow interactions not only displace storm location but also regulate the storm-mode balance and the effective rainfall contribution, linking topographic dynamics with climatological rainfall outcomes.

3.4 Summary and Conclusions

This study analyzed the impact of reduced terrain on rainfall and the extreme storms in the moisture-rich environment of the Meiyu event in Taiwan on 1–3 June 2017. Two mesoscale simulations were conducted with the terrain height halved in the terrain modification (TMOD) experiment. The TMOD simulation shows a significant reduction in rainfall over Taiwan compared to the control (CTRL) simulation, especially over the Central Mountain Range (CMR).

An analysis of extreme storm mode shows that the deepest extreme storm mode, Deep Convective Cores (DCCs), occurred around the Taiwan coast in the CTRL run and moved closer to the

CMR in the TMOD run. The DCCs are associated with strong maximum upward wind velocity and vertical moisture flux (wq), and the reduced terrain decreased the area that supported these factors. Despite these changes, DCCs do not contribute significantly to the rainfall owing to their small size compared to the spatiotemporal scale of the Meiyu event.

The main rainfall contributor, Deep and Wide Convective Cores (DWCCs), were smaller in overall area and produced less rainfall in the TMOD run than in the CTRL run. DWCCs occurred along the Meiyu front in both simulations but had a higher frequency in the CTRL simulation over the CMR, where the highest rainfall was located. DWCCs were associated with strong upward velocity areas and also had strong wq , although not as strong as DCCs. DWCCs are also located in areas with some low-level shear (LLS), but the magnitudes are moderate compared to Broad Stratiform Regions (BSRs).

Wide Convective Cores (WCCs), which lack deep convective characteristics that distinguish them from DWCCs, are smaller in overall area than DWCCs. Their average area decreased in the TMOD run, leading to less rainfall. They are associated with moderate maximum upward velocity and wq , compared to other convective core types. They were associated with slightly stronger LLS that was reduced around the CMR in the TMOD run, especially on the east side of the CMR. The smaller LLS is hypothesized to contribute to their reduced overall area.

The largest of the extreme storm modes, Broad Stratiform Regions (BSRs), increased their rainfall contribution in the TMOD run compared to the CTRL run. They were mostly located in the north and east sides of the CMR in the CTRL run where the LLS was strongest, but expanded to the west side in the TMOD run. The windward side shear was slightly stronger in comparison to the weakened LLS everywhere else, suggesting a strong association between BSRs and the stronger LLS regions. BSRs were not associated with strong maximum upward velocity or wq , in contrast to the convective storm modes.

The results presented in this study show that orographic effects have a complex interaction with the Meiyu front that can increase rainfall in a variety of ways. At a primary level, the CMR enhances vertical velocity and rainfall production through direct lifting in moist southwesterly

flow. The reduction of the mountain barrier produces a consequent reduction in the vertical motion and rainfall over the CMR, which is accomplished in a morphological context as a reduction in the number and area of the DWCC extreme storm mode. These results suggest that the threshold for vertical motion and wq conditions that support extreme DWCC convection are not met as often with reduced terrain, and therefore shift towards other modes such as non-extreme rain and BSRs.

In addition to the reduction in DWCCs and increase in BSRs, terrain modification experiments have shown a location shift related to changing wind patterns. The modified ingredients that produce heavy rain decreased on the windward side of the CMR and increased over and on the leeward side of the CMR through reduced blocking. As a result, the DWCC locations shift from over the CMR to off the east coast of Taiwan, while BSRs shift their location westward over Taiwan. The reduction in CMR height also reduces low-level shear due to less blocking from the CMR, making the condition even more favorable for DWCCs to develop offshore east of Taiwan, away from the CMR. These secondary effects in the shear and blocking wind patterns contribute to the change in storm mode in addition to the direct effect of reduced vertical motion from orographic lifting.

Crucially, this storm-mode reorganization appears to be a signature of the event's extremity rather than a purely generic orographic response. Because the unmodified Meiyu flow placed the CMR deep in the nonlinear, strongly blocked regime, with a dimensionless mountain height of $M \approx 3$ over central Taiwan, halving the terrain did not simply scale the rainfall down in proportion to the reduced barrier height; it collapsed the dimensionless mountain height toward $M \approx 1.5$ and forced a qualitative transition from blocked flow-around to flow-over dynamics, shifting ascent from the windward slopes to the lee and reorganizing the storm-mode population.

The results presented herein are from a single event that produced extreme rainfall, but the physical mechanisms elucidated from the analysis are believed to play a role in other Meiyu front events over Taiwan. Future work is recommended to examine these mechanisms and changes in storm modes and rainfall ingredients in other heavy rainfall cases. Further analysis using the PRECIP/TAHOPE 2022 field campaign observations and numerical simulations will help to clarify the

key mechanisms contributing to extreme rainfall in the presence of complex terrain and abundant moisture to improve forecasts in the future.

The limitations of this single-event, two-configuration design should be kept in mind when interpreting the results. A single ensemble member at full resolution does not sample the forecast-spread uncertainty; the CTRL–TMOD differences reported here are therefore best interpreted as a single realization of the terrain response, not a probabilistic estimate. Furthermore, the 50% terrain reduction samples only two points on the orographic-sensitivity curve, and the conclusions about regime transition rest on the Froude-number framework rather than on a multi-step terrain sweep. A single ratio cannot fully map out the regime dependence, and a multi-step terrain sensitivity (e.g., 25%, 50%, 75%) is identified as an important follow-on experiment. These limitations motivate the extension of this work to a graded terrain sensitivity and a multi-event analysis using the PRECIP/TAHOPE 2022 dataset.

Beyond the specific case of the 1–3 June 2017 event, the ingredient-based and storm-mode framework demonstrated here provides a transferable diagnostic for evaluating extreme-rainfall sensitivity to topography in other mountainous, moisture-rich regions, including the East Asian Meiyu/Baiu/Changma belt, the Western Ghats, and tropical orographic systems. Because these storm modes are the same TRMM-heritage categories used to characterize convection globally (Houze et al. 2015a), the terrain-driven redistribution documented here can be compared directly against the very different mode partitioning of other extreme-rainfall regions, e.g., the wide-convective-core-dominated rainfall of subtropical South America (Rasmussen et al. 2016). In particular, the same extreme-storm-mode taxonomy underlies the multi-season East Asian climatology of Panawatwong et al. (2022), in which deep-and-wide convective cores and broad stratiform regions dominate the warm-season rainfall; the present case therefore extends that climatological picture from long-term statistics to the terrain mechanism operating within a single extreme event, and the common taxonomy lets the rainfall contributions reported here be compared mode-by-mode across cases and regions. Practically, the result that storm-mode redistribution is the dominant response of extreme rainfall to terrain modification has implications for downscaling

climate projections over complex terrain, for designing observational networks, and for interpreting operational forecasts.

Chapter 4

Ensemble spread in storm-mode organization and extreme rainfall during a Meiyu front event observed during PRECIP 2022

4.1 Introduction

Heavy rainfall events during the East Asian Meiyu season are among the most consequential high-impact weather phenomena affecting Taiwan, Japan, Korea, and South China, capable of producing flash floods, debris flows, and widespread societal disruption (Chen 1983; Ding and Chan 2005a; Chen and Tu 2024). The Meiyu front is a quasi-stationary frontal zone that develops over East Asia during the late-spring to early-summer transition between the East Asian winter and summer monsoon circulations, along which moist, convectively unstable air from the South China Sea and western Pacific converges with drier, cooler air to the north (Lau et al. 1988; Chen 1992; Ding and Chan 2005a). When this frontal system interacts with the steep topography of Taiwan, and in particular with the Central Mountain Range (CMR) that rises to nearly 4000 m, it can produce extreme rainfall accumulations that challenge both operational forecasting and theoretical understanding (Arakane et al. 2019; Cornejo et al. 2024).

Forecasting Meiyu rainfall is particularly difficult because the precipitation amount, timing, and spatial distribution depend on a delicate balance of ingredients (moisture supply, vertical motion, low-level shear, and thermodynamic instability), each of which can vary substantially at the spatial scales of mesoscale systems (Doswell et al. 1996b; Lin et al. 2001). Ensemble numerical weather prediction provides a powerful tool for quantifying forecast uncertainty in such events by sampling the distribution of possible atmospheric states consistent with observations (Berner et al. 2017). However, the physical interpretation of ensemble spread and the identification of which at-

mospheric ingredients drive rainfall divergence across members and how that spread evolves with time remains an open question for Meiyu-season convection.

Recent work has made substantial progress in characterizing the storm structures and synoptic conditions responsible for heavy Meiyu rainfall over Taiwan. Using 41 years of gridded rainfall observations, Henny et al. (2023) showed that Meiyu-season extreme precipitation days associated with atmospheric-river-like moisture transport have become more frequent and more intense since 1979, with a small number of long-duration events (in 2005, 2006, 2012, and 2017) contributing disproportionately to the positive season-total precipitation trend. The synoptic conditions that set up these events have been examined case by case. Chien and Chiu (2023), for example, documented the early-2020 record-breaking Meiyu rainfall in southern Taiwan and traced it to an intensified Pacific subtropical high, an anomalously strong southwesterly monsoonal flow, and an eastward-propagating southwest vortex that acted as a moisture conveyor toward the Taiwan Strait.

Recent convection-permitting modeling has sought to isolate the mechanisms by which Taiwan's terrain shapes Meiyu rainfall. Using the extreme rainfall over Taiwan during the Meiyu season of 1–3 June 2017 as a look into the orographic effect, Cornejo et al. (2024) showed through halved-terrain WRF experiments that reducing the CMR height weakens the orographic barrier jet, accelerates Meiyu-front propagation, and shortens rainfall duration in northern Taiwan and over the CMR. Panasawatwong et al. (2026), which forms the basis of Chapter 3 of this dissertation, performed a parallel halved-terrain experiment on the same event and identified upward vertical velocity and vertically integrated moisture flux as the key variables linking terrain, storm-mode organization, and rainfall.

The 2022 joint field campaigns PRECIP (Prediction of Rainfall Extremes Campaign in the Pacific) and TAHOPE (Taiwan-Area Heavy rain Observation and Prediction Experiment) provided a comprehensive set of radar, radiosonde, and surface observations of Meiyu-season convection over Taiwan and the surrounding ocean. The first Intensive Observation Period (IOP 1) of the campaign, on 26–28 May 2022, captured a two-day extreme rainfall event associated with a persistent Meiyu front impacting northern Taiwan. Ensemble numerical weather prediction simulations conducted

during PRECIP (Penn State University Ensemble Kalman Filter simulations; hereafter PRECIP PSU-EnKF simulations) provide the basis to examine how ensemble spread in storm-mode organization and ingredient fields relate to spread in total rainfall (Zhang et al. 2023).

In this study, we address three research questions: (1) What are the dominant atmospheric ingredients that drive the rainfall spread between high-rainfall and low-rainfall ensemble members during the PRECIP 2022 IOP 1 event? (2) How does the spatial organization and relative rainfall contribution of extreme storm modes differ between high- and low-rainfall members? (3) When during the event does the ingredient separation between high- and low-rainfall members emerge, and how does it evolve through the event? Addressing these questions extends the storm-mode and ingredients-based frameworks of Panasawatwong et al. (2022) and Panasawatwong et al. (2026) from climatological and deterministic contexts to an ensemble forecasting context, providing new insights into the physical drivers of Meiyu rainfall uncertainty.

This chapter is organized as follows. Section 4.2 describes the PRECIP PSU-EnKF WRF ensemble configuration, the storm-mode classification methodology, and the ingredient-based analysis framework. Section 4.3 presents the results. Section 4.3.1 shows the relationship between the ensemble rainfall spread and the ingredients. Section 4.3.2 shows storm-mode organization and rainfall contribution. Section 4.3.3 shows ingredient distributions within each storm mode. Lastly, Section 4.3.4 shows the temporal evolution of ensemble spread. Section 4.4 provides a summary and discusses implications for Meiyu rainfall predictability and future work.

4.2 Data and Methods

4.2.1 Event overview: PRECIP 2022 IOP 1

The first Intensive Observation Period (IOP 1) of the PRECIP 2022 field campaign occurred from 26–28 May 2022 over Taiwan and the surrounding western North Pacific. The event was characterized by a persistent Meiyu front that produced sustained heavy rainfall over northern and central Taiwan across a roughly 48-hour active window. Synoptically, the front was associated with strong southwesterly moisture transport from the South China Sea, consistent with typical Meiyu

configurations in late May. The event was sampled by the PRECIP and TAHOPE observational networks, which provided radar, radiosonde, and surface measurements for the region.

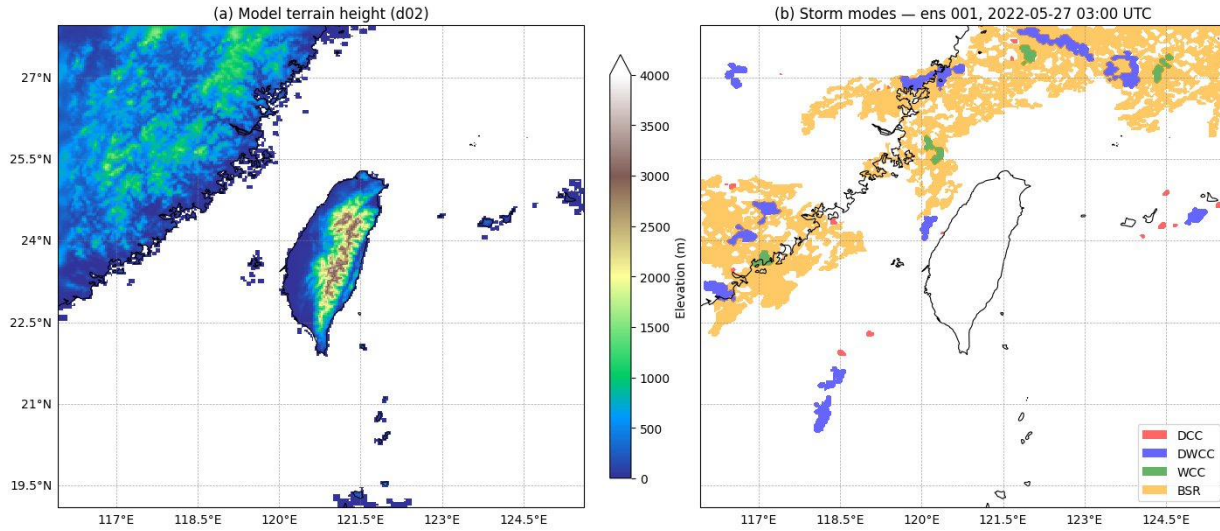


Figure 4.1: Model domain and example storm-mode classification. (a) Topography of the 3-km inner domain (d02) used for all analyses in this study, centered on Taiwan (approximately 19.1°–28.0°N, 115.9°–125.6°E). (b) Example storm-mode classification mask for ensemble member 1 at 03 UTC 27 May 2022, showing DCC, DWCC, WCC, and BSR categories. The classification scheme follows Houze et al. (2007a).

4.2.2 PRECIP PSU-EnKF WRF ensemble configuration

We use a 40-member ensemble generated with the Weather Research and Forecasting (WRF) model version 4.1.3 (Skamarock et al. 2019), configured with a nested domain centered over Taiwan and the surrounding region of the western North Pacific. The outer domain (d01) is run at 9-km grid spacing to provide lateral boundary conditions for the inner domain (d02) at 3-km grid spacing, covering latitudes 19.1°–28.0°N and longitudes 115.9°–125.6°E (Figure 4.1a). All analyses in this study use the d02 output.

All 40 ensemble members were initialized at 00 UTC 26 May 2022. Members 1–20 were integrated for 48 hours through 00 UTC 28 May 2022, yielding 49 hourly output files and covering the full active phase of the event. Members 21–40 were integrated for only 12 hours through 12 UTC 26 May 2022 and therefore do not span the peak rainfall period. Given that the analyses

presented here require 48-hour lifetime-integrated or time-resolved output, all figures in this study use members 1–20 only.

Initial and lateral boundary conditions were derived from Global Forecast System (GFS) analyses, with ensemble spread generated by perturbations to the initial conditions following the PSU-EnKF system described in Zhang et al. (2023). The physics suite follows that used in Panasawatwong et al. (2026): the aerosol-aware Thompson microphysics scheme (Thompson and Eidhammer 2014), the Rapid Radiative Transfer Model for both longwave and shortwave radiation (Iacono et al. 2008), the Monin–Obukhov surface-layer scheme (Janjić 2001), the Noah land surface model (Tewari et al. 2004), and the Yonsei University planetary boundary layer scheme (Hong et al. 2006).

4.2.3 Storm-mode classification

We apply the TRMM-heritage storm-mode classification scheme of Houze et al. (2007a), adapted for WRF output in Panasawatwong et al. (2022) and Panasawatwong et al. (2026). The scheme uses simulated three-dimensional reflectivity to categorize precipitating systems into four extreme storm types:

- **Deep Convective Cores (DCCs):** contiguous regions of reflectivity ≥ 30 dBZ extending vertically above 8 km, representing the deepest convection.
- **Deep and Wide Convective Cores (DWCCs):** contiguous regions with reflectivity ≥ 30 dBZ that both extend above 8 km in height and cover horizontal areas exceeding 800 km^2 , representing the most intense and spatially organized deep convection.
- **Wide Convective Cores (WCCs):** contiguous regions with reflectivity ≥ 30 dBZ covering horizontal areas exceeding 800 km^2 but lacking the deep vertical extension of DWCCs.
- **Broad Stratiform Regions (BSRs):** contiguous stratiform rain regions with area $\geq 40,000 \text{ km}^2$, representing the extensive stratiform rain regions of mature mesoscale convective systems.

Classification is performed at each hourly output time for members 1–20. An example of the storm-mode classification for member 1 at 03 UTC 27 May 2022 is shown in Figure 4.1b.

4.2.4 Ingredient-based analysis

Following Doswell et al. (1996b), describing the ingredients-based methodology for flash flood forecasting, and the framework established in Panasawatwong et al. (2022) and Panasawatwong et al. (2026), we analyze four environmental ingredients that have been connected to heavy rainfall production. The Ingredients-based Storm aLgorithm Applied to the eNsemble Data (ISLAND) is developed to compute the storm modes and the ingredients for the PSU-EnKF WRF members. In this study, we apply ISLAND to diagnose the following four ingredients:

- **Maximum column upward vertical velocity (w_{up_max} , hereafter referred to simply as w):** at each horizontal grid point and each hourly timestep, the maximum upward vertical velocity in the model column, in m s^{-1} . This quantity represents the strength of the lifting associated with convective updrafts.
- **Vertical moisture flux (wq):** the vertical integral of the product of vertical velocity and specific humidity over pressure coordinates (units of Pa m s^{-1}). Negative values indicate net upward moisture transport in the pressure convention used here. We note that this quantity is the vertical component of moisture flux. It differs from the horizontal vertically integrated moisture flux (VIMF) analyzed in Panasawatwong et al. (2026).
- **Total precipitable water (TPW):** the vertically integrated water vapor (kg m^{-2}), representing column moisture availability.
- **Low-level shear (LLS):** the magnitude of the vector wind difference between the 900 hPa and 700 hPa levels (m s^{-1}), representing low-level kinematic shear with relevance to storm organization.

For each ensemble member, we compute both area-averaged and storm-mode statistics of these ingredients at hourly resolution. To characterize the relationship between ingredients and total rainfall, members are ranked by 48-hour total accumulated rainfall, and the top 5 and bottom 5 members are selected as representative high-rainfall and low-rainfall groups, respectively. Ingredient

distributions are examined (i) across the full model domain, (ii) within each storm mode (DCCs, DWCCs, WCCs, and BSRs), and (iii) as time series of the area-averaged value across the 48-hour event. For selected ingredients, we additionally examine an extreme-tail metric: the lifetime-mean of the top 100 grid-point LLS values in the domain at each hourly timestep ($LLS_{\max 100}$). This quantity isolates the occasional extreme-shear environments in the domain from the broader full-distribution behavior.

Throughout the Results section, we refer to two phases of the event identified from the area-averaged rainfall time series (Figure 4.6a): the active phase (12 UTC 26 May – 12 UTC 27 May 2022), during which area-averaged rainfall rises to and remains near its peak, and the decay phase (12 UTC 27 May – 12 UTC 28 May 2022), during which area-averaged rainfall declines as the Meiyu system weakens.

4.3 Results

4.3.1 Ensemble rainfall spread and ingredient correlates

The 20 PRECIP PSU-EnKF WRF members with full 48-hour output produce substantial spread in total rainfall for the PRECIP 2022 IOP 1 event. The top 5 members (members 10, 19, 5, 6, and 1) produce approximately 70,000–85,000 mm of total accumulated rainfall over the 48-hour event, while the bottom 5 members (members 4, 7, 14, 11, and 20) produce approximately 45,000–50,000 mm. The top quintile therefore produces 1.6–1.9 times as much total rainfall as the bottom quintile. This wide range of outcomes, despite identical model configuration and comparable synoptic setup, motivates the ingredients-based analysis that follows.

To identify which atmospheric ingredients drive the rainfall spread between high-rainfall and low-rainfall members, we examine the relationship between area-averaged, lifetime-mean values of four ingredients and total event rainfall across the 20 members with full 48-hour output (Figure 4.2). Vertical moisture flux (wq) shows a strong negative correlation with total rainfall (Pearson $r = -0.959$, $p = 2.75 \times 10^{-11}$), meaning members with stronger upward moisture transport produce substantially more total rainfall. Area-averaged, lifetime-mean vertical velocity (w) similarly

shows a strong positive correlation with total rainfall ($r = 0.894$, $p = 1.06 \times 10^{-7}$). In contrast, total precipitable water (TPW) shows no statistically significant relationship with total rainfall ($r = 0.187$, $p = 0.429$). Members with more column moisture do not necessarily produce more rain.

The extreme tail of low-level shear ($\text{LLS}_{\text{max100}}$, computed as the lifetime-mean of the top 100 LLS values in the domain at each hourly timestep) shows a moderately strong positive correlation with total rainfall (Figure 4.2d; $r = 0.743$, $p = 1.74 \times 10^{-4}$). This extreme-tail relationship contrasts with the full LLS distribution discussed in Section 4.3.3, where median LLS values show little systematic difference between high- and low-rainfall members. This distinction indicates that the occasional presence of high shear environments, rather than the typical shear, is associated with higher total rainfall, consistent with the role of strong shear in organizing mesoscale convective systems (Houze et al. 2015a).

The top 5 and bottom 5 members cluster distinctly in wq , w , and $\text{LLS}_{\text{max100}}$ space (Figure 4.2a, c, d), with top-rainfall members consistently occupying the stronger-ingredient regions of each distribution. The contrast between wq and TPW is notable: despite both being moisture-related quantities, only the dynamically active component, namely moisture flux through upward motion, drives the rainfall contrast between high- and low-rainfall members. This result indicates that the rainfall spread in this ensemble is driven by differences in the strength and organization of upward moisture transport, rather than by differences in column moisture content.

4.3.2 Storm-mode organization and rainfall contribution

To understand the spatial patterns of convective organization that accompany the ensemble rainfall spread, we examine the frequency of occurrence of each storm mode for the top 5 and bottom 5 rainfall members (Figure 4.3). The spatial distributions of storm modes differ systematically between the two groups in ways that clarify the ingredient differences identified in Section 4.3.1.

In Figure 4.3a, DCCs show only minor differences between top and bottom members. Both groups produce sporadic, low-frequency DCC coverage scattered across the domain, with the dif-

Total Rain vs Environment Variables

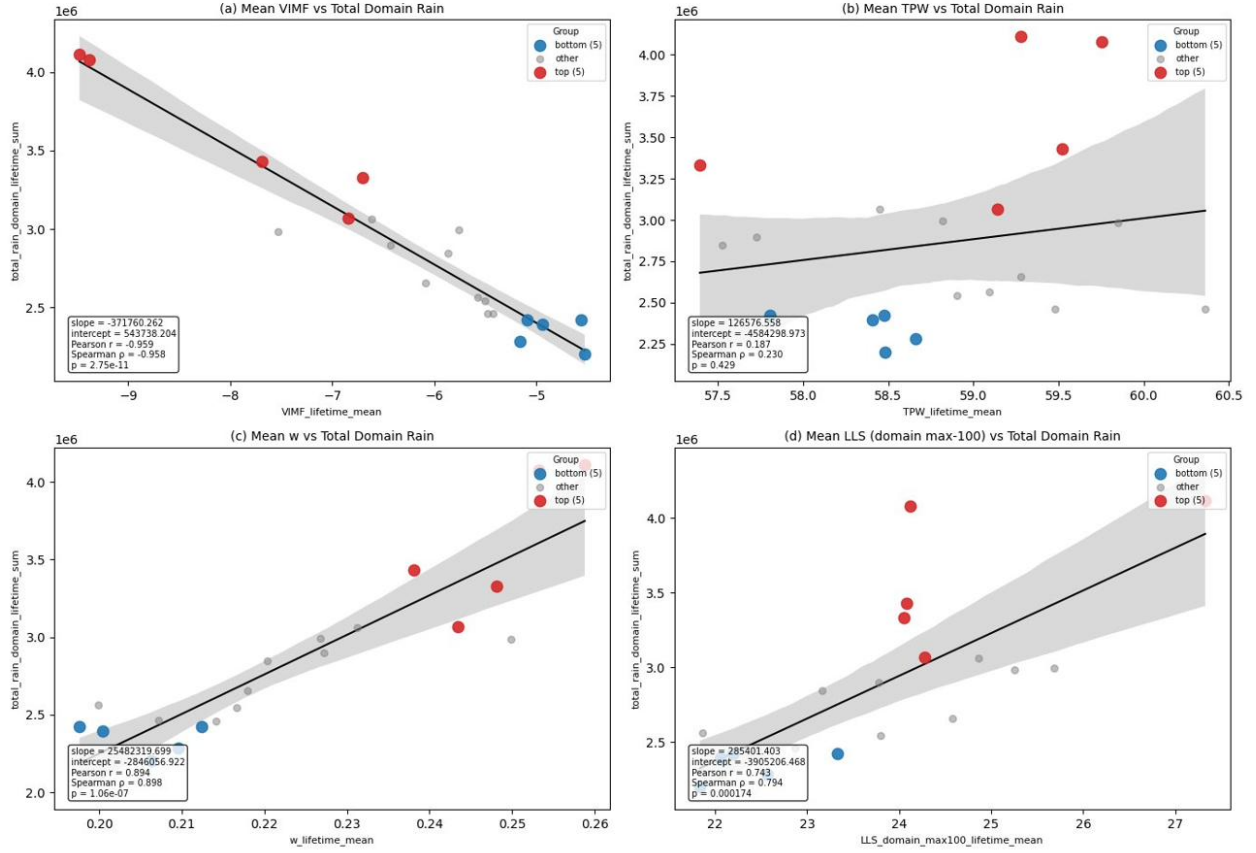


Figure 4.2: Scatter plot and linear regression of atmospheric ingredients and total rainfall across the ensemble. (a) vertical moisture flux (wq , negative means upward) magnitude decreases as total rainfall decreases, (b) total precipitable water (TPW) kg m^{-2} increases as total rainfall increases, (c) area-averaged maximum updraft increases as total rainfall increases, (d) area-averaged of top 100 pixels of low-level shear ($\text{LLS}_{\text{max}100}$) increases as total rainfall increases. Red and blue dots show top 5 and bottom 5 rainfall ensemble members, respectively. Gray dots show the remaining ensemble members. Black line shows a linear regression fit with the 95 percent confidence interval shaded.

ference panel showing no coherent spatial pattern. This result is consistent with the climatological finding of Panasawatwong et al. (2022) that isolated DCCs contribute little to total rainfall, and with the present finding in Section 4.3.1 that DCC-associated wq and w show large variability detached from the broader frontal system.

In contrast, DWCCs show a distinctive spatial redistribution (Figure 4.3b). In top-rainfall members, DWCCs are distributed along the Meiyu front and on the western side of Taiwan, with elevated frequencies extending from northwest of Taiwan across to the ocean east of the island. In bottom-rainfall members, DWCCs are concentrated over northeastern Taiwan, with much lower frequencies along the front and surrounding ocean regions. The difference panel (top – bottom) is positive (top > bottom) in a band extending from northwest of Taiwan to the east of the island, tracing the climatological Meiyu front orientation, and negative (top < bottom) over Taiwan itself. This spatial pattern mirrors the terrain-sensitivity findings of Panasawatwong et al. (2026), in which DWCCs shifted from over the CMR to locations east and west of the island as terrain height was reduced, and of Cornejo et al. (2024), who showed that halving the CMR weakens orographic lifting and accelerates Meiyu-front propagation. These terrain experiments establish that DWCC location is jointly controlled by orographic blocking and by the geometry of moisture convergence along the front. In the present ensemble, which uses a fixed terrain configuration, the DWCC displacement between top and bottom members reflects differences in the effective moisture convergence along the frontal band. The spatial pattern of that convergence is still modulated by Taiwan’s terrain, which influences how upstream flow is lifted, blocked, and channeled toward the CMR, so terrain-induced lifting remains an important contributor to the differences between the two groups, particularly over the CMR itself.

WCCs also favor the northern frontal band in top-rainfall members, with the difference panel showing elevated top-minus-bottom frequencies across the northern portion of the domain (Figure 4.3c). The WCC signal is weaker in magnitude than the DWCC and BSR signals but spatially consistent with them.

The most pronounced contrast appears in BSRs (Figure 4.3d). Top-rainfall members produce BSR coverage across essentially the entire northern portion of the domain, reaching peak frequencies above 35%, while bottom-rainfall members produce markedly sparser BSR coverage concentrated near the front line itself. The difference panel shows a positive signal (top > bottom) across nearly the full northern domain, with amplitudes exceeding 20%.

To investigate how these spatial reorganizations translate into rainfall contributions, we examine the percentage of total rainfall produced by each storm mode as a function of total rainfall across the 20 members with full 48-hour output (Figure 4.4). DCCs show a strong negative correlation between their percentage contribution and total rainfall ($r = -0.712$, $p = 4.3 \times 10^{-4}$): as total rainfall increases across members, DCCs contribute a progressively smaller share. BSRs show the opposite and statistically significant pattern ($r = 0.565$, $p = 9.4 \times 10^{-3}$): higher total rainfall members derive a larger fraction of their rainfall from broad stratiform regions. DWCCs show a positive but marginal correlation ($r = 0.436$, $p = 0.055$), and WCCs show a weak positive trend that does not reach statistical significance ($r = 0.367$, $p = 0.112$).

This storm mode analysis shows that the ensemble spread in total rainfall is not a uniform scaling of precipitation intensity, but differs with mesoscale storm-mode composition. High-rainfall members produce more extensive BSR coverage along the Meiyu front, show elevated DWCC frequencies distributed along the frontal band as well as over western Taiwan and surrounding ocean regions, and derive a larger percentage of their total rainfall from BSRs while deriving less from DWCCs. Low-rainfall members, by contrast, produce more localized convection that contributes relatively more from isolated DCCs and less from organized BSRs. This pattern directly extends the process-based finding of Panasawatwong et al. (2026), that widespread, frontally organized DWCCs produce more total rainfall than convection concentrated over the CMR, from deterministic terrain-sensitivity experiments.

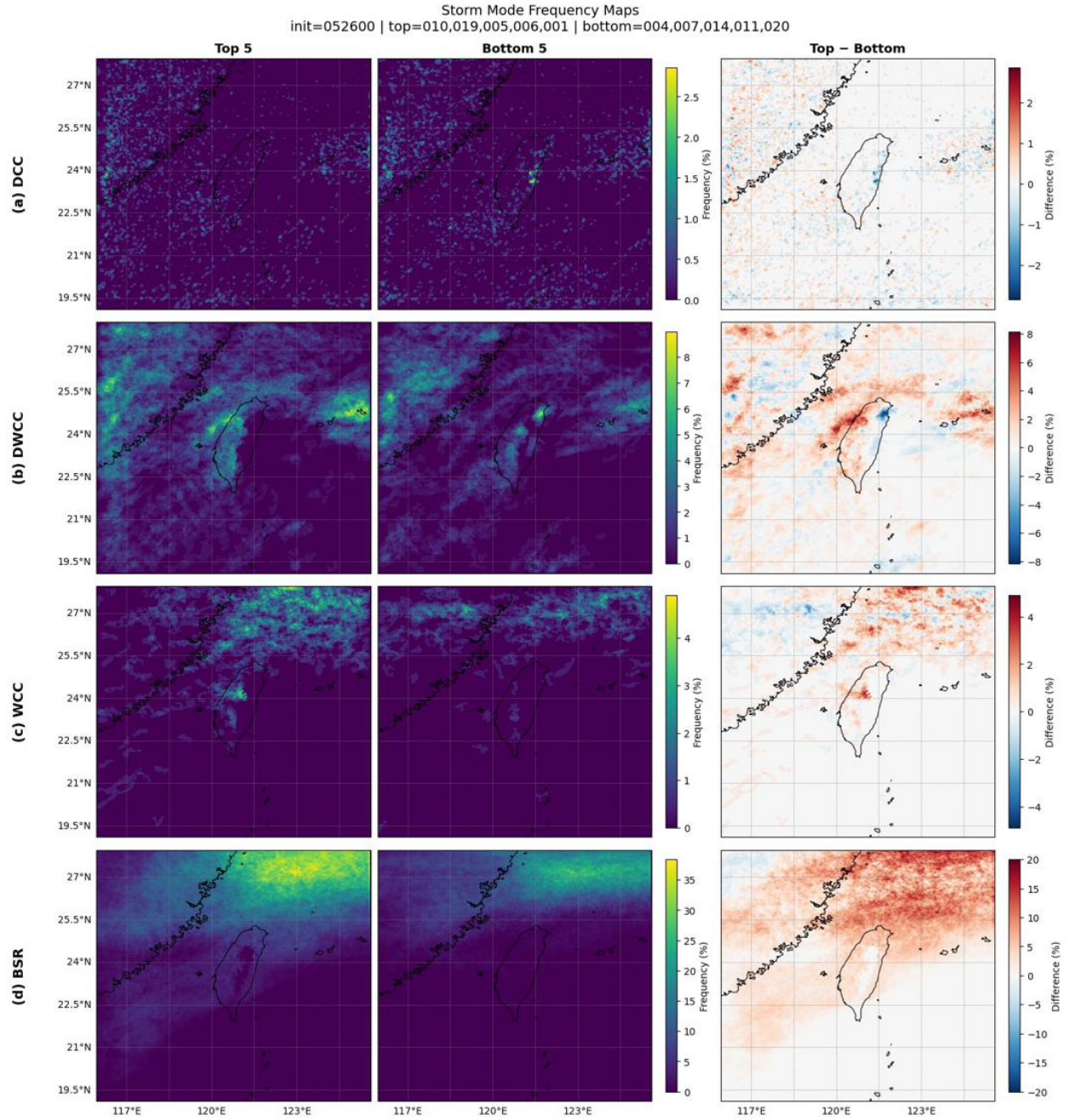


Figure 4.3: Spatial frequency of storm modes for top 5 versus bottom 5 rainfall members. Rows show storm modes: (a) DCC, (b) DWCC, (c) WCC, and (d) BSR. For each row, columns show (left) composite frequency (%) of occurrence for the top 5 rainfall members, (middle) composite frequency for the bottom 5 rainfall members, and (right) difference (top – bottom, %).

Rainfall % vs Total Rainfall — by storm mode

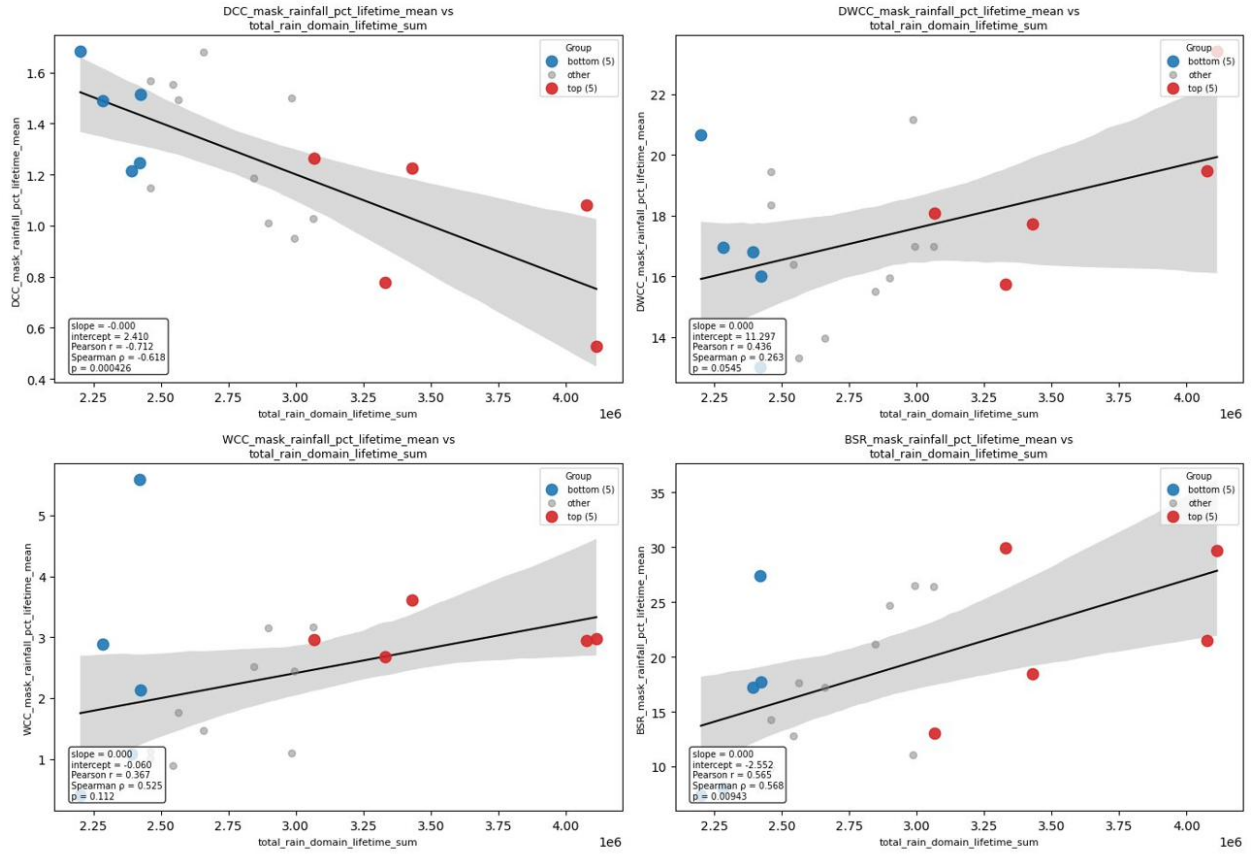


Figure 4.4: Scatter plot and linear regression of ensemble spread of 48-hr rainfall contribution by each storm mode and total rainfall. (a) DCCs contribution decreases as total rainfall increases, (b) DWCCs contribution increases as total rainfall increases, (c) WCCs contribution increases as total rainfall increases, (d) and BSRs contribution increases as total rainfall increases. Red and blue dots show top 5 and bottom 5 rainfall ensemble members, respectively. Gray dots show the remaining ensemble members. Black lines show linear regression fits with 95% confidence intervals shaded.

4.3.3 Ingredient distributions within storm modes

Figure 4.2–4.4 establish that ensemble spread in total rainfall is driven primarily by large-scale ingredient differences (wq , w) and by shifts in storm-mode organization. To examine whether the local environments experienced by each storm type also differ between high- and low-rainfall members, we compute ingredient distributions within each storm mode for the top 5 and bottom 5 members (Figure 4.5). The “Whole” category corresponds to all finite grid points in the d02 domain pooled across all hourly timesteps and the five members within each group, while the DCCs/DWCCs/WCCs/BSRs categories correspond to grid points within the respective storm mask, pooled across all timesteps and the five members of each group.

Vertical moisture flux (wq ; Figure 4.5a) shows the largest separation between top-rainfall and bottom-rainfall members within storm modes. Across DCCs, DWCCs, and WCCs, top-rainfall members show more strongly negative wq , that is, stronger upward moisture transport compared to bottom-rainfall members. The wq distributions within DCCs are notably wide, spanning approximately -900 to $+600 \text{ Pa m s}^{-1}$, reflecting the sporadic and distributed character of DCCs in this event (Figure 4.3a). Individual DCCs occur in a wide variety of local environments because they are not systematically embedded within the Meiyu frontal band, and the 3-km d02 grid may additionally underresolve the updraft cores within individual DCCs, further widening the distribution. DWCCs and WCCs, which are more consistently embedded within the front and are individually large enough to be adequately resolved on the d02 grid, show narrower wq distributions centered on more strongly negative values (i.e., upward mass flux). BSRs show wq values close to zero with slightly negative medians, consistent with BSRs representing the stratiform regions of mature systems where vertical motion is weaker than in the active convective cores.

Total precipitable water (TPW; Figure 4.5b) shows that all extreme storm types occur in high-TPW environments ($60\text{--}72 \text{ kg m}^{-2}$), well above the area-wide median of approximately 60 kg m^{-2} . Within DWCCs, WCCs, and BSRs, top-rainfall members show consistently higher TPW than bottom-rainfall members, but the differences are modest ($1\text{--}3 \text{ kg m}^{-2}$) and the interquartile ranges overlap. Combined with the weak lifetime-mean TPW–rainfall correlation reported in Section 4.3.1,

this suggests that a high-TPW environment is a favorable ingredient for extreme Meiyu convection, but that the modest top-minus-bottom TPW difference within storm modes is not by itself sufficient to explain the factor-of-1.6–1.9 rainfall spread across the ensemble. The spread is instead associated with the dynamical component of moisture transport (wq) and the spatial organization of the convection.

Vertical velocity (w ; Figure 4.5c) follows a pattern similar to wq within storm modes: top-rainfall members show stronger upward w than bottom-rainfall members within DCCs, DWCCs, and WCCs, while BSRs show weaker w with only a small top-versus-bottom difference. The contrast in vertical velocity between DCCs/DWCCs/WCCs and BSRs is consistent with the role of strong vertical motion in producing and sustaining the convective cores and with the role of weaker, more widespread ascent in producing the extensive stratiform rain regions.

For low-level shear (LLS; Figure 4.5d), area-wide distributions (“Whole” category) are similar between top and bottom members, with slightly higher LLS in top 5 members. Within the storm modes, median LLS values increase systematically from DCC to BSR, reflecting that the larger, more organized systems (BSRs, DWCCs, and WCCs) tend to occur in regions of stronger low-level shear, consistent with the role of shear in organizing mesoscale convective systems (Houze et al. 2015a; Panawatwong et al. 2022). Top and bottom members show modest differences in median LLS within DWCC, WCC, and BSRs, with top members trending slightly higher, but the interquartile ranges overlap substantially. This finding is consistent with the full-distribution versus extreme distinction identified in Section 4.3.1: the shear signal that drives the rainfall contrast between top and bottom members lies in the extreme tail of the distribution ($LLS_{\max 100}$), not in the median environment within storm modes.

The ingredient analysis shows that the ensemble rainfall spread is not driven by systematic differences in the local environment within storm modes, but by differences in the area-integrated ingredients that determine how much, how widespread, and how organized the convective response becomes. The local environment within each storm type is broadly similar between high- and low-

rainfall members. What differs is the frequency, extent, and mesoscale spatial organization of the storms themselves.

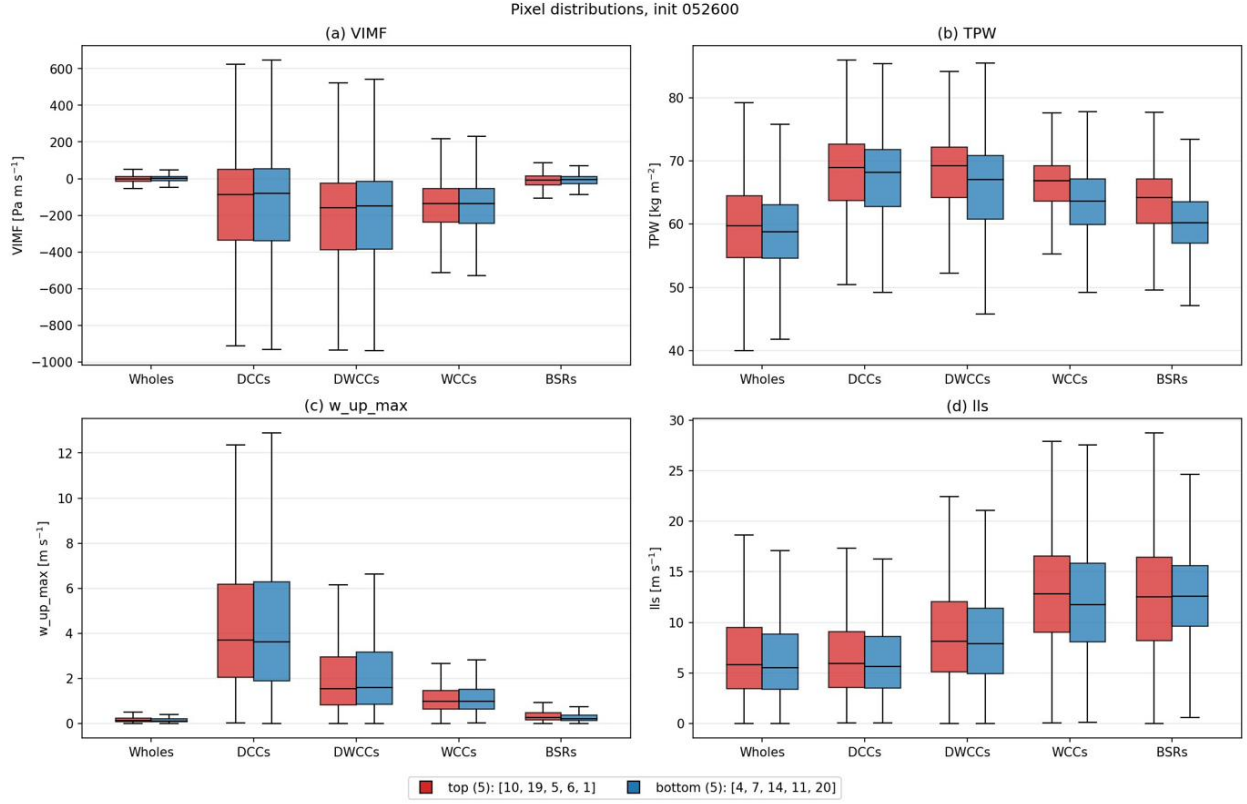


Figure 4.5: Ingredient distributions within storm modes. Boxplots of (a) vertical moisture flux (wq , Pa m s^{-1}), (b) total precipitable water (TPW, kg m^{-2}), (c) vertical velocity (w , m s^{-1}), and (d) low-level shear (LLS, m s^{-1}), across all hourly timesteps for the top 5 (red) and bottom 5 (blue) rainfall members. Horizontal categories show the whole-domain distribution (“Whole”) and grid-point distributions within each storm mode (DCCs, DWCCs, WCCs, BSRs).

4.3.4 Temporal evolution of ensemble spread

To understand how ingredients associated with top and bottom 5 members evolve during the event, time series analysis is presented in this section. We hypothesize that there may be a separation between top and bottom members after initialization of the ensemble and we aim to characterize if this signal emerges and how it evolves if it occurs. Thus, this section shows time series of area-averaged rainfall and ingredients for the 20 members with full 48-hour output (Figure 4.6).

The total rainfall time series (Figure 4.6a) shows that top and bottom members indeed diverge early in the time series within the first several hours of the simulation and maintain distinct area-averaged rainfall level differences throughout the active phase. Both groups share a similar timing of the peak convective activity near 06 UTC 27 May 2022, indicating that the large-scale timing of the Meiyu front passage is well-constrained across the ensemble. The magnitude of the peak, however, differs substantially. Top members reach a total rainfall rate of $1.44 \times 10^9 \text{ m}^3 \text{ h}^{-1}$, while bottom members peak near $0.9 \times 10^9 \text{ m}^3 \text{ h}^{-1}$. During the decay phase (12 UTC 27 May to 12 UTC 28 May), both groups decline as the primary Meiyu system weakens. A secondary rainfall peak appears in some members near 06 UTC 28 May, which we attribute to a distinct, later convective episode rather than a reinvigoration of the primary Meiyu system.

The wq time series (Figure 4.6b) shows the most striking separation between top and bottom members. Top members reach wq values near -15 to -17 Pa m s^{-1} during the peak of the active phase, while bottom members reach only approximately -10 to -13 Pa m s^{-1} . The separation is established at the first model output time (12 UTC 26 May) and persists throughout the active phase, mirroring the temporal structure of the rainfall difference. During the decay phase, both groups converge toward near-zero wq as the Meiyu system weakens and large-scale moisture transport subsides.

The TPW time series (Figure 4.6c) clarifies why area-averaged TPW is a poor predictor of total rainfall (Figure 4.2b). Top-rainfall members begin with slightly higher area-averaged TPW (approximately 61 kg m^{-2}) than bottom members (approximately 58.5 kg m^{-2}), but the two groups converge by 06 UTC 27 May and remain nearly indistinguishable through the remainder of the active phase. This early separation does not persist when averaged over the full event lifetime, explaining the weak lifetime-mean TPW–rainfall correlation. During the decay phase, TPW is largely sustained in the top members while it declines in the bottom members, suggesting that the top members continue to be replenished with moisture by the large-scale southwesterly flow while the bottom members experience faster drying due to a weakening of southwesterly moisture advection into the domain. This interpretation is consistent with Chien and Chiu (2023), who showed

that an intensified southwesterly monsoonal flow acts as a moisture conveyor belt toward Taiwan during heavy Meiyu events, and indicates that the initial column moisture is not what primarily distinguishes high- and low-rainfall members during the event. Rather, the sustained advective supply of moisture into the domain, together with the dynamical conversion of that moisture into upward flux (wq), is what matters for heavier rainfall over Taiwan and the surrounding areas.

The vertical velocity time series (Figure 4.6d) shows a sustained separation between top and bottom members throughout the active phase. Top members maintain higher area-averaged w (approximately $0.25\text{--}0.35\text{ m s}^{-1}$) than bottom members (approximately $0.18\text{--}0.25\text{ m s}^{-1}$), with the separation established from the first timestep and persisting into the decay phase. Two distinct peaks in area-averaged w , near 18 UTC 26 May and 06 UTC 27 May, coincide with the two peaks in rainfall rate, consistent with vertical motion being the proximate dynamical driver of the rainfall.

The temporal analysis shows that the ingredient separation between high- and low-rainfall members is present at the first model output time and then amplifies through the active phase, rather than emerging gradually through the event because of error growth during the simulation. The rainfall spread in this ensemble is therefore, in principle, predictable from an adequate characterization of the initial-condition upward moisture transport, which suggests that improving initial-condition estimates of vertical motion and moisture transport is a productive direction for operational Meiyu forecasting.

4.4 Summary and Conclusions

In this study, we used the ISLAND algorithm to analyze a 20-member subset of a 40-member WRF ensemble of the Intensive Observation Period 1 of the PRECIP 2022 field campaign (a two-day Meiyu front event over Taiwan during 26–28 May 2022) to investigate the physical drivers of ensemble spread in total rainfall. Applying the TRMM-heritage storm-mode classification scheme of Houze et al. (2007a), together with the ingredients-based framework used in Panasawatwong et al. (2022) and Panasawatwong et al. (2026), we identified systematic relationships between atmospheric ingredients, storm-mode organization, and total rainfall across the ensemble members.

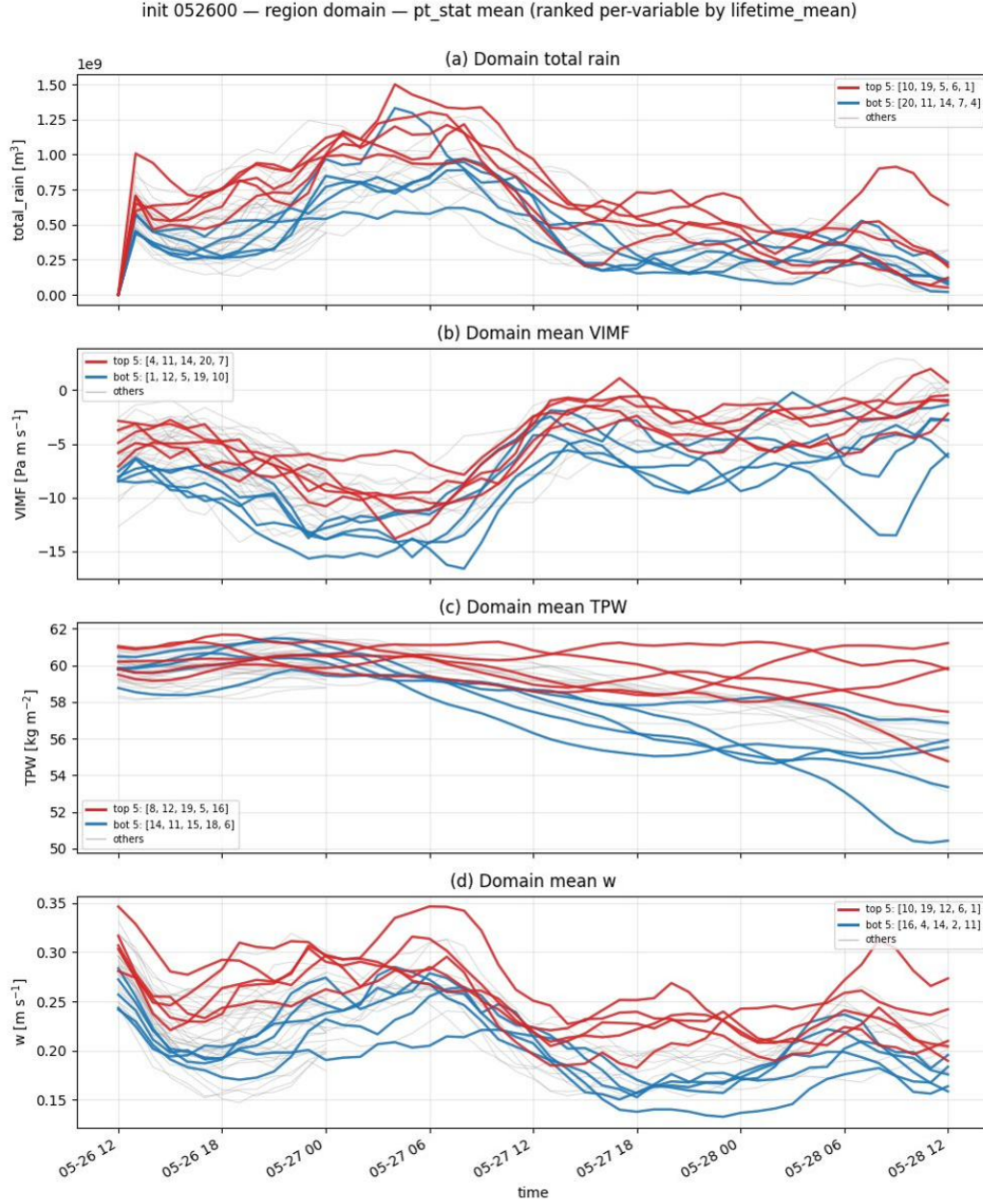


Figure 4.6: Temporal evolution of area-averaged rainfall and ingredients across the ensemble. Time series of area-averaged quantities for the 20 ensemble members with full 48-hour output: (a) total rainfall rate, (b) vertical moisture flux, (c) total precipitable water, and (d) maximum upward vertical velocity. Top 5 rainfall members are shown in red, bottom 5 in blue, and remaining members in gray.

Three principal findings emerge from this analysis. First, high-rainfall and low-rainfall members differ systematically in the mesoscale spatial organization and relative rainfall contribution of extreme storm modes. High-rainfall members produce more extensive BSR coverage along the Meiyu front band and show elevated DWCC frequencies distributed along the front, including over western Taiwan and the surrounding ocean regions. Low-rainfall members show lower DWCC frequencies over these regions and produce markedly less extensive BSR coverage. Correspondingly, BSRs contribute a larger fraction of total rainfall in high-rainfall members ($r = +0.57$), while DCCs contribute a smaller fraction ($r = -0.71$).

Second, ensemble spread in total rainfall is governed primarily by area-integrated upward vertical velocity (w) and upward moisture flux (wq) from initialization and persisting throughout the active phase of the event. Area-averaged, lifetime-mean wq and w explain the vast majority of variance in 48-hour total rainfall (Pearson $r = -0.96$ and $r = +0.89$, respectively). Area-averaged wq differences appear at initialization and track the subsequent rainfall divergence closely, indicating that the rainfall spread in this ensemble originates from initial-condition differences rather than from error growth during the simulation. For forecasting, ground observations of updraft via radar and radiosondes during storm initialization may help improve total rainfall forecasts. The extreme tail of low-level shear (top-100 values) shows a moderate positive correlation with total rainfall ($r = 0.74$), indicating that the occasional presence of strong shear environments, rather than the typical shear, is associated with higher total rainfall.

These results may have direct implications for Meiyu rainfall predictability. The finding that rainfall spread originates from initial-condition differences in upward moisture transport, rather than from column moisture or from unconstrained error growth during the simulation, indicates that improving the initialization of vertical motion and vertical moisture flux has the potential to reduce forecast uncertainty for such events. Targeted improvements could include better data assimilation of upper-air winds and humidity, or better-constrained lateral boundary conditions. Recent work by Yang et al. (2024) has demonstrated that radar data assimilation can improve short-term Meiyu rainfall forecasts by constraining the convective-scale initial state. While not a

direct vertical-motion assimilation, such improvements to the initial state represent one pathway for better-constraining the initial-condition ingredient fields identified here as critical. Chien and Chiu (2023), in diagnosing the record-breaking 2020 southern Taiwan Meiyu event, identified specific synoptic features (the western Pacific subtropical high, the southwesterly monsoon flow, and a propagating southwest vortex) whose accurate representation at initialization would be expected to constrain the initial wq field. Conversely, improvements to column moisture initialization alone are unlikely to substantially reduce rainfall uncertainty, because TPW differences are averaged out during the active phase.

For future work, the generality of the ingredient–rainfall relationships identified here should be tested across multiple Meiyu events and initialization lead times. Comparing the ensemble behavior against radar-derived storm-mode frequencies and rain-gauge-derived rainfall from PRECIP 2022 would also provide an important constraint on which members are physically realistic. Finally, the role of terrain modification, examined in the deterministic context by Panasawatwong et al. (2026), could be reexamined in an ensemble framework to quantify how terrain sensitivity interacts with initial-condition sensitivity during extreme Meiyu events.

Chapter 5

Conclusions

This dissertation has examined the physical controls on warm season heavy rainfall over Taiwan through three complementary studies spanning multiple data sources: satellite observations, a deterministic regional simulation with terrain modification experiments, and ensemble-based convection-permitting simulations. Together, they address three scientific questions: what kinds of extreme storms are most commonly observed in association with heavy rainfall events, how does terrain modulate their occurrence and characteristics, and how do the ingredients associated with each storm mode vary across a 20-member ensemble. Despite the different foci of each chapter, the three studies share a common methodological framework based on the extreme storm-mode classification of Houze et al. (2007a) and the ingredients-based framework of Doswell et al. (1996b). The consistent application of this framework across three independent data sources provides a coherent description of heavy rainfall in Taiwan from the broad perspectives of a satellite-based regional climatology down to detailed analyses of individual ensemble members for a heavy rainfall event. However, by using consistent algorithms and analysis techniques, conclusions can be meaningfully compared across all three chapters of the dissertation.

The climatological study in Chapter 2 established from 15 years of TRMM observations that Deep and Wide Convective Cores (DWCCs) and Broad Stratiform Regions (BSRs) are the dominant volumetric rainfall producers in the Meiyu-season environment of tropical and subtropical East Asia. The terrain-sensitivity study in Chapter 3 showed that halving the Central Mountain Range (CMR) height in a convection-permitting simulation of the 1–3 June 2017 extreme Meiyu event shifts DWCCs offshore, expands BSR coverage westward, and reduces rainfall over Taiwan, with upward vertical velocity and moisture flux as the controlling ingredients. The ensemble study in Chapter 4 analyzed 20 members of the PRECIP PSU-EnKF WRF ensemble of the 26–28 May 2022 IOP 1 event and found that the 1.6–1.9 times spread in 48-hour domain-total rainfall is gov-

erned by domain-integrated upward moisture transport rather than column moisture, and originates from initial-condition differences rather than error growth during the simulation.

Several unifying findings emerge from considering the three studies together. The first is that DWCCs and BSRs are the dominant rainfall-producing storm modes in Taiwan and surrounding regions at every scale examined. The 15-year TRMM climatology in Chapter 2 established that these two modes account for most of the volumetric rainfall across tropical and subtropical East Asia, despite the higher instantaneous rain rates of the smaller Deep Convective Cores (DCCs). The convection-permitting model terrain-sensitivity experiment in Chapter 3 showed that changes in the frequency and spatial distribution of DWCCs and BSRs largely explain the rainfall response to terrain modification during the 1–3 June 2017 event. The ensemble analysis in Chapter 4 showed that the relative contribution of DWCCs and BSRs likewise distinguishes high-rainfall from low-rainfall members of the PRECIP PSU-EnKF ensemble of the 2022 IOP 1 event. The collective dominance of these two modes is therefore not a climatological artifact or a feature peculiar to a single event, but a robust characteristic of warm season (including the Meiyu-season) extreme rainfall that persists from the regional climatology to the individual ensemble members.

On the other hand, the most vertically intense convection, represented by DCCs, is consistently not what drives the highest Meiyu rainfall. The climatology in Chapter 2 showed that DCCs, despite their highest instantaneous rain rates, contribute relatively little to volumetric rainfall because of their small spatial extent. The terrain-sensitivity experiment in Chapter 3 showed that DCC frequency changes little between the control and halved-terrain simulations, and that DCCs contribute less than one percent of the total event rainfall regardless of the terrain configuration. The ensemble analysis in Chapter 4 showed that the DCC contribution is negatively correlated with total rainfall across members, meaning that members dominated by DCCs systematically produce less rain than members dominated by organized DWCCs and BSRs. This convergence of evidence is consistent with the radar-observational finding of DeHart and Bell (2025) that the highest rain totals along oceanic Meiyu fronts preferentially occur in moderately strong rotating convection rather than in the most intense cells. Together, these results indicate that forecast diagnostics focused on the

peak intensity of individual convective cells may systematically miss the signature of highest total rainfall, which is often associated with moderately strong, organized systems distributed along the Meiyu front.

The second unifying finding is that upward moisture transport, rather than column moisture alone, is the controlling ingredient that links the large-scale flow configuration to storm-mode organization and rainfall. In the climatology of Chapter 2, the ingredient time-lagged composites differentiate the environments of storm modes primarily through vertical moisture flux and low-level shear, not through column moisture. In the terrain-sensitivity experiment of Chapter 3, the reduction of the CMR topography alters the locations of each storm mode and the spatial distribution of rainfall by reducing the upward vertical velocity and the vertically integrated moisture flux over the terrain. In the ensemble analysis of Chapter 4, the domain-integrated values of these same quantities explain a majority of the variance in total rainfall across members, while total column-integrated precipitable water is less important, likely because most columns contain sufficient moisture. Column moisture behaves as a necessary background condition in all three studies but does not, on its own, discriminate between high- and low-rainfall outcomes. What matters is the dynamical conversion of available moisture into upward moisture flux.

The third unifying finding is that the spatial organization of convection along the Meiyu front is a consistent marker of high-rainfall regimes. In Chapter 3, the reduced-terrain simulation redistributes DWCCs from over the CMR to locations along the frontal band offshore of Taiwan, with BSRs expanding westward to occupy the frontal zone. In Chapter 4, high-rainfall ensemble members produce extensive BSR coverage along the front and show elevated DWCC frequencies distributed along the front, including over western Taiwan and the surrounding ocean regions, while low-rainfall members show lower DWCC frequencies over these regions and produce sparser BSR coverage.

Because ensemble rainfall spread originates from initial-condition differences in upward moisture transport, improvements in the initialization of vertical motion and vertical moisture flux offer more potential to reduce forecast uncertainty than improvements in column moisture alone. Future

work should test the generality of these findings across additional events and initialization times, extend the storm-mode climatology into the GPM era, and re-examine the terrain-sensitivity question in an ensemble framework that quantifies the interaction between terrain sensitivity and initial-condition sensitivity. Comparing ensemble storm-mode frequencies against the radar-observed storm modes documented by DeHart and Bell (2025) would further anchor the ingredient-based diagnosis in the PRECIP 2022 observational record.

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