

A Comparison Study between Rapidly-Intensifying and Slowly-Intensifying Tropical Cyclones: Observational Analyses and Model Simulations

Ming-Jen Yang(楊明仁)¹, Ching-Wei Lin(林晴葳)¹, Yi-Hsuan Huang(黃詣軒)²

¹National Taiwan University (國立臺灣大學), Taiwan

²Central Weather Administration (中央氣象署), Taiwan



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It is known that the largest forecast errors often occur when storms undergo rapid intensification.
([Fischer et al. 2019](#); [Trabing and Bell 2020](#))

Tropical cyclone intensity evolution controlled by both **environmental factors** and **internal dynamics**.

1. Environmental factors

- Include **vertical wind shear**, **sea surface temperature (SST)**, etc. ([Kaplan and DeMaria 2003](#); [Kaplan et al. 2010, 2015](#); [Wang and Jiang 2021](#))
- Affect whether Rapid Intensification (RI) is likely to occur during TC's lifetime.

2. Internal dynamics

- Include **vortex structure** and **convection organization**. ([Tao and Zhang 2015](#); [Judt and Chen 2016](#); [Fischer et al. 2023](#))
- Play a key role in modulating the timing of RI onset.

1.Environment effects
2.Internal dynamic

affect

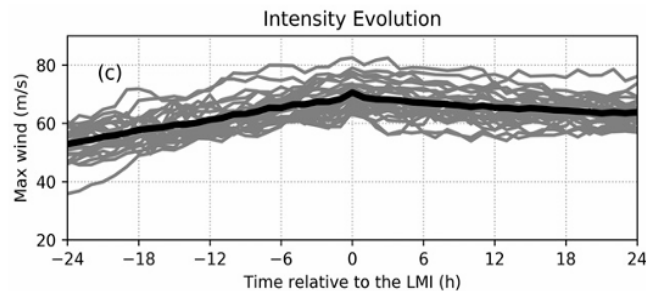
Amount and location
of latent heat
release in storm

affect

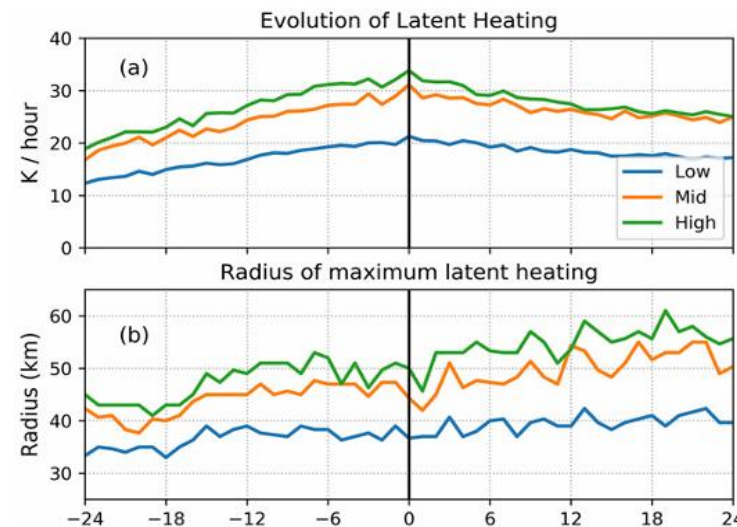
TCs intensification

WRF outputs indicated that latent heating is strongly related to the amount of ice water content which can serve as an observable proxy for latent heating in the mid-to-upper troposphere. (Wu et al. 2021)

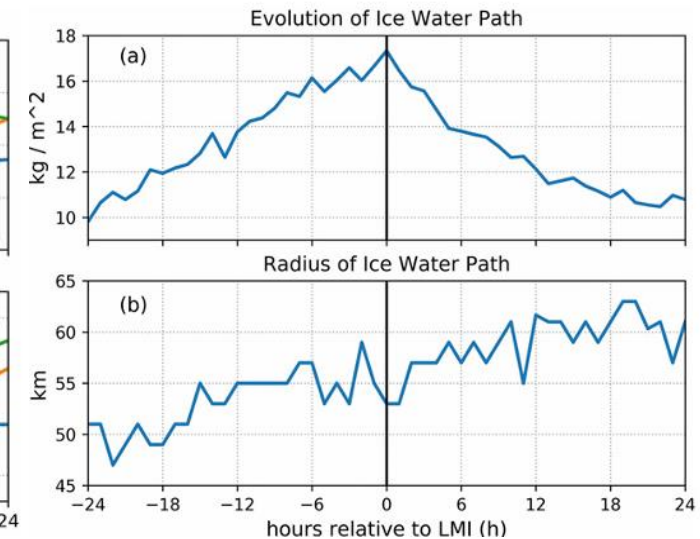
Intensity



Latent Heating



Ice Water Path



(Wu et al. 2021)

Observe

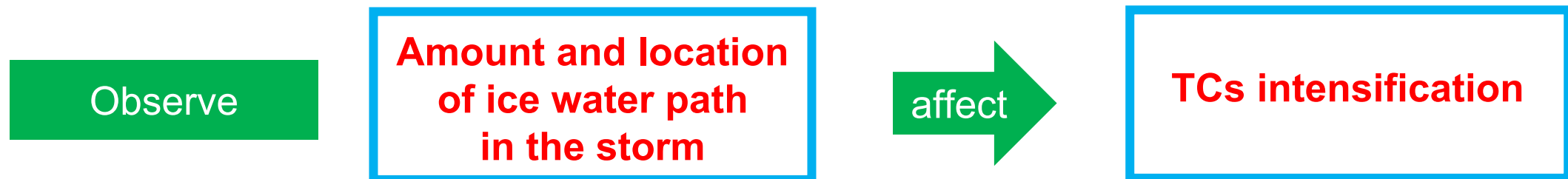
**Amount and Location
of ice water path
in the storm**

affect

TC intensification

WRF outputs indicated that latent heating is strongly related to the amount of ice water content which can serve as an observable proxy for latent heating in the mid-to-upper troposphere. (Wu et al. 2021)

Different precipitation types play different roles in TC intensification. Some studies emphasize the contribution of inner-core **convective bursts** to vortex intensification (Guimond et al. 2010; Rogers et al. 2013), while others highlight the importance of **stratiform precipitation** (Fritz et al. 2016; Tao et al. 2017).



Following the approach of 黃與楊 (2023; 大氣科學), this study aims to:

- Compare the structural evolution of RI and SI TCs using satellite observations.
- Investigate the RI and SI processes using the high-resolution WRF simulations.

To understand the structural differences between rapidly intensifying (RI) and slowly intensifying (SI) tropical cyclones.

a. Satellite observation

- Ice Water Path (IWP) and Rain Water Path (RWP) from GPM SSMIS on DMSP F16, F17 and F18.
- IR Brightness Temperature (T_b) Data provided by NCEP and NOAA.

Variable	IWP, RWP	T_b
Dataset	GPM SSMIS DMSP F16/F17/F18	Global IR (GOES, METEOSAT, Himawari)
Spatial Resolution	12 km	4 km
Temporal Resolution	1.5 h	30 min
Coverage	Swath (~1700 km)	Global geostationary composite

b. Different groups – RI & SI

Different groups are based on the future 24-h change in the maximum-sustained wind ($\Delta V_{\max}$).

(Kaplan and DeMaria2003)

1. Rapidly Intensifying (RI) : $\Delta V_{\max} \geq 30$ kts in 24 hours,
2. Slowly Intensifying (SI) : $10 \text{ kt} \leq \Delta V_{\max} < 30$ kts in 24 hours.

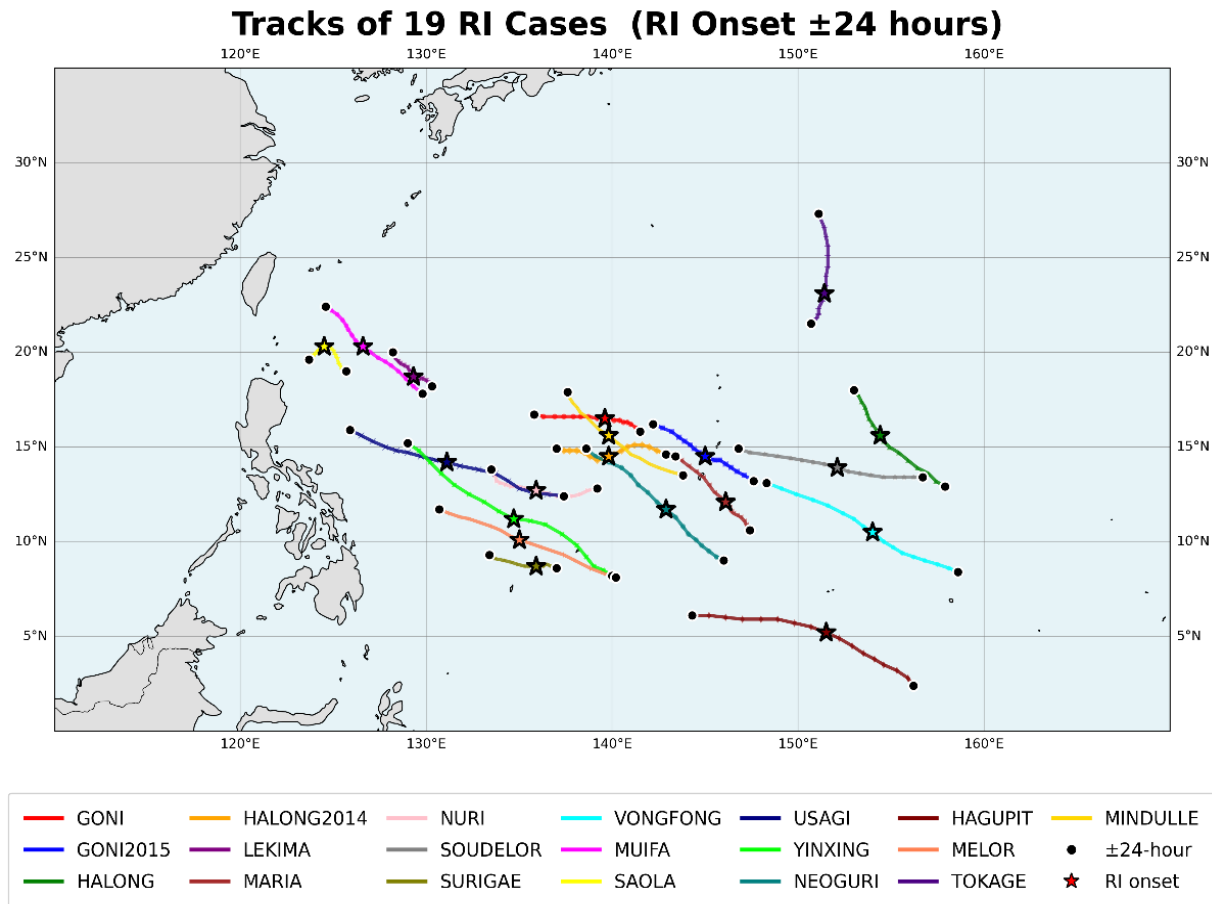
BUT the cases that confront the issues mentioned below are excluded.

1. TC makes landfall while it is under RI or SI.
2. TC locates over 30°N while it is under RI or SI.
3. Lifetime of the TCs that are less than 3 days.
4. Second time of RI or SI.



b. Different groups – RI & SI

At five different data times for RI TCs (RI onset, ± 12 h, ± 24 h) from 2012 to 2024, 14 out of 19 TC cases with satellite scans are selected for the composite analysis.

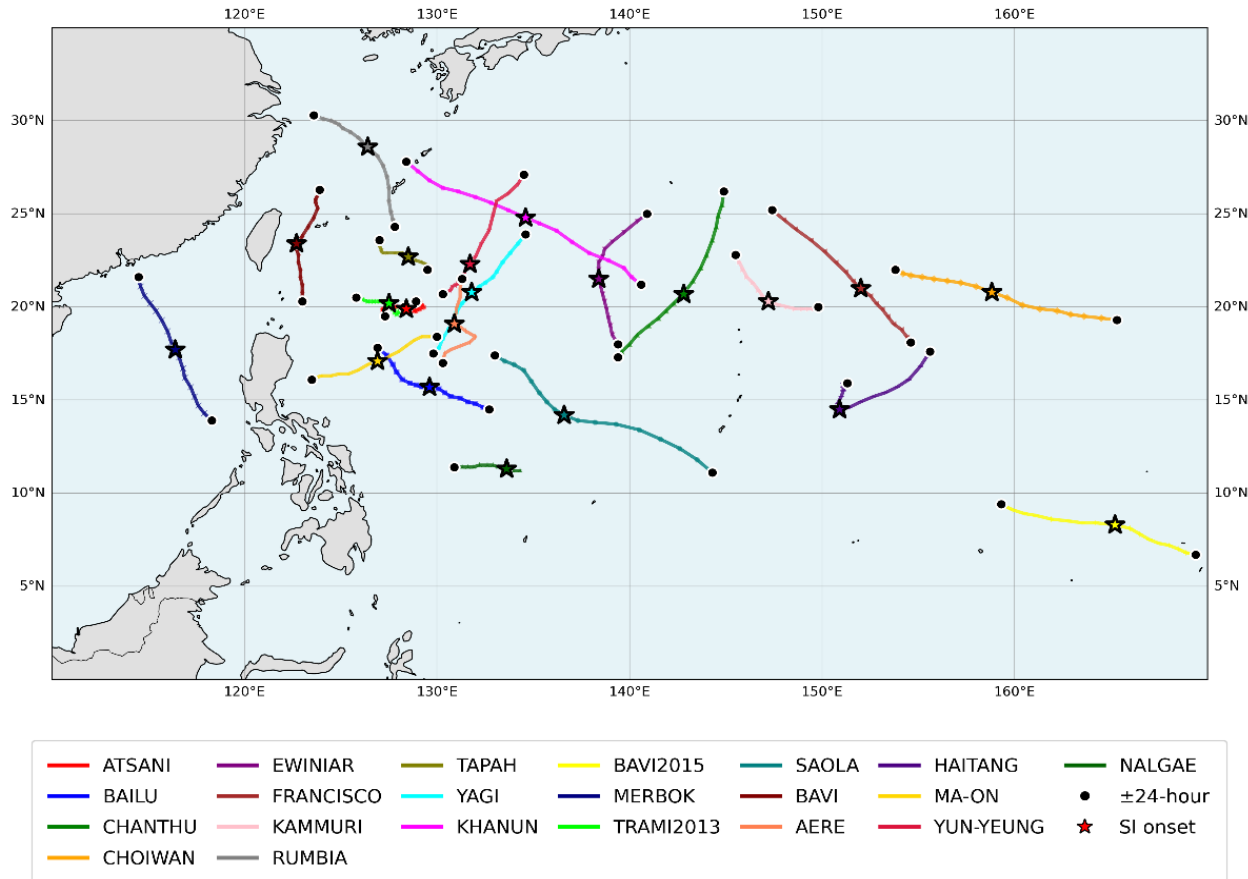


	RI cases (19)	-24h	-12h	0h	+12h	+24h
黃蜂	VONGFONG(2014)	V	V	V	V	V
哈隆	HALONG(2014)	V		V		V
浣熊	NEOGURI(2014)	V				
哈格比	HAGUPIT(2014)	V	V		V	
鸚鵡	NURI(2014)		V	V	V	
蘇迪勒	SOUDELOR(2015)			V	V	V
天鵝	GONI(2015)		V	V	V	V
茉莉	MELOR(2015)	V	V			V
瑪麗亞	MARIA(2018)	V	V	V	V	V
哈隆	HALONG(2019)	V		V	V	V
利奇馬	LEKIMA(2019)	V	V	V	V	V
天鵝	GONI(2020)	V	V	V	V	
蒲公英	MINDULLE(2021)		V			V
蘇力基	SURIGAE(2021)	V	V	V	V	V
蝎虎	TOKAGE(2022)		V	V	V	V
梅花	MUIFA(2022)	V	V			V
蘇拉	SAOLA(2023)	V	V	V	V	V
銀杏	YINXING(2024)	V	V	V	V	
天兔	USAGI(2024)	V		V	V	V

b. Different groups – RI & SI

At five different data times for SI TCs (RI onset, $\pm 12\text{h}$, $\pm 24\text{h}$) from 2012 to 2024, 14 out of 21 TC cases with satellite scans are selected for the composite analysis.

Tracks of 21 SI Cases (SI Onset ± 24 hours)



SI cases (21)		-24h	-12h	0h	+12h	+24h
艾維尼	EWINIAR(2012)			V		V
卡努	KHANUN(2012)	V				
潭美	TRAMI(2013)		V		V	V
雅吉	YAGI(2013)	V	V	V		V
北冕	KAMMURI(2014)	V	V	V	V	
彩雲	CHOIWAN(2015)		V	V	V	V
巴威	BAVI(2015)	V			V	
燦樹	CHANTHU(2016)	V	V	V	V	V
莫柏	MERBOK(2017)	V				
蘇拉	SAOLA(2017)		V			V
棕櫚	RUMBIA (2018)	V	V	V	V	V
塔巴	TAPAH(2019)	V	V	V	V	V
白鹿	BAILU(2019)	V	V	V	V	V
范斯高	FRANCISCO(2019)			V		
巴威	BAVI(2020)				V	V
閃電	ATSANI(2020)	V	V	V	V	
艾利	AERE(2022)	V	V	V	V	V
海棠	HAITANG(2022)	V	V	V	V	V
馬鞍	MA-ON(2022)			V		V
奈格	NALGAE(2022)	V	V		V	
鴛鴦	YUN-YEUNG(2023)	V	V	V	V	V

c. TC intensity and radius of maximum wind (RMW)

The data comes from IBTrACS, provided by the JTWC. The data include TC location, maximum sustained wind speed (V_{max}), and the radius of maximum wind (RMW) with 3-h time intervals were linearly interpolated to the exact times of satellite observations.

d. Environmental vertical wind shear

Use the Reanalysis Data based on ERA5 from ECMWF.

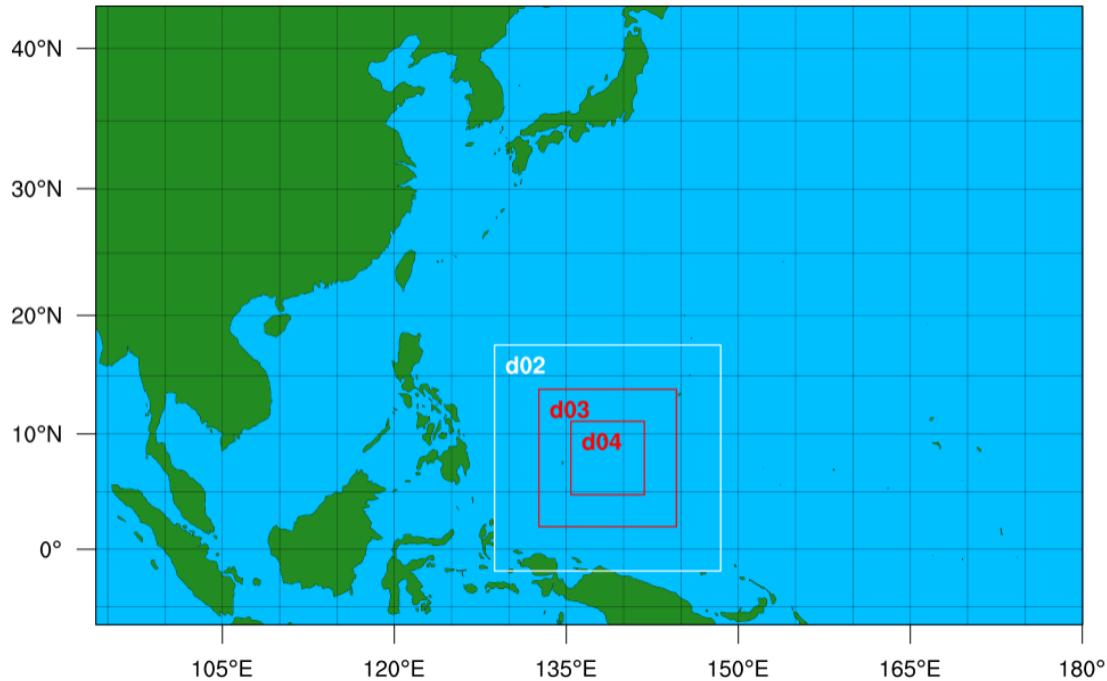
To compute the difference between the 200-hPa averaged wind field and the 850-hPa averaged wind field, within a radius of 200 km to 800 km from the TC center.

We use the shear-relative coordinate for the ease of comparing different TCs. All variables for each TC case were rotated to align with the southerly wind shear.



e. WRF model simulation (WRF v4.6.1)

RI case – SURIGAE 蘇力基 (2021)



	Setting
Simulation Period	2021/04/13 00 UTC – 2021/04/17 00UTC (96 hours)
Interval_Seconds	21600
Nested Domains	27 / 9 / 3 / 1 km
P_TOP	35 hPa
Vortex Following	Yes
SST Update	Yes

RA_LW_PHYSICS: RRTMG (Iacono et al., 2008)

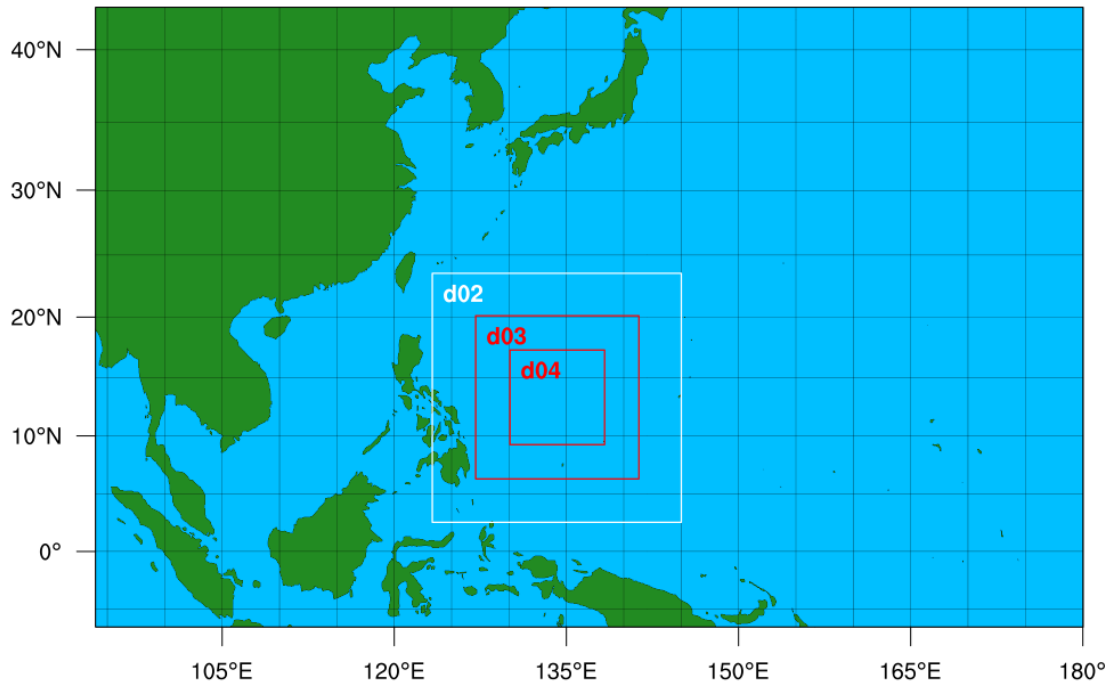
RA_SW_PHYSICS: RRTMG (Iacono et al., 2008)

BL_PBL_PHYSICS: MYJ (Janjic, 1994 & Mesinger, 1993)

CU_PHYSICS: Multi-scale Kain-Fritsch (27km domain only)
(Zheng et al., 2016; Glotfelty et al., 2019)

e. WRF model simulation (WRF v4.6.1)

SI case – BAILU 白鹿 (2019)



	Setting
Simulation Period	2019/08/19 12 UTC – 2019/08/23 12UTC (96 hours)
Interval Seconds	21600
Nested Domains	27 / 9 / 3 / 1 km
P_TOP	35 hPa
Vortex Following	Yes
SST Update	Yes

RA_LW_PHYSICS: RRTMG (Iacono et al., 2008)

RA_SW_PHYSICS: RRTMG (Iacono et al., 2008)

BL_PBL_PHYSICS: MYJ (Janjic, 1994 & Mesinger, 1993)

CU_PHYSICS: Multi-scale Kain-Fritsch (27km domain only) (Zheng et al., 2016; Glotfelty et al., 2019)

f. Precipitation Regime Type

Type	Definition	Type	Definition
Convective	≥ 42 dBZ at 2 km	Deep Convection(DC)	20 dBZ echo top > 10km
		Moderate Convection(MC)	10km>20 dBZ echo top > 4km
		Shallow Convection(SC)	20 dBZ echo top < 4km
Stratiform	< 42 dBZ at 2 km	Stratiform(ST)	With radar echo > 20 dBZ
		Weak Echo(WE)	With radar echo < 20 dBZ

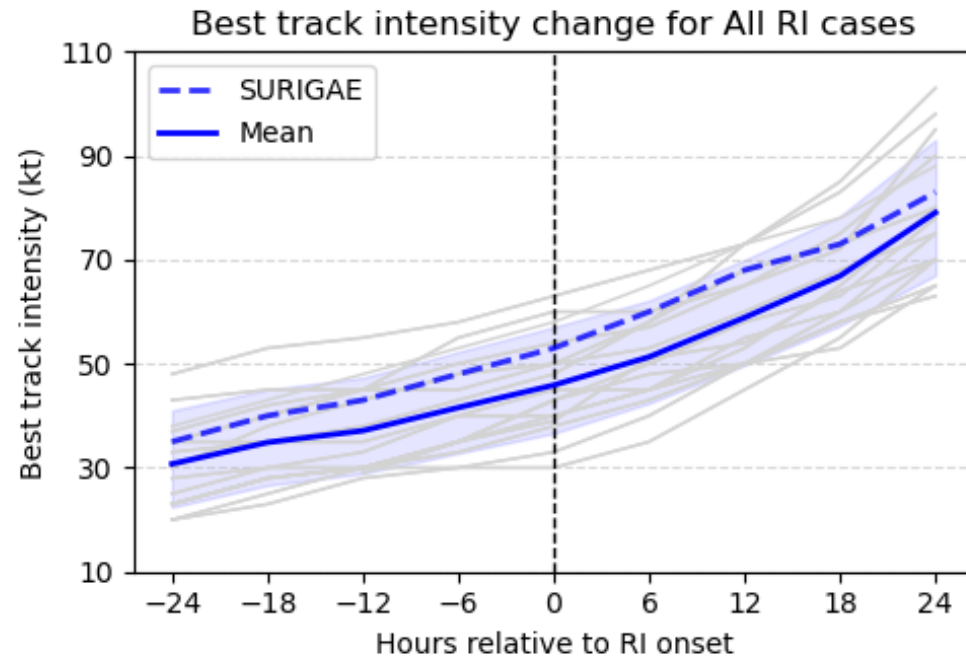
(Churchill and Houze 1984; Steiner et al. 1995)

(Tao and Jiang 2015; Fritz et al. 2016; Rogers et al. 1993, 2020; Wu et al. 2022)

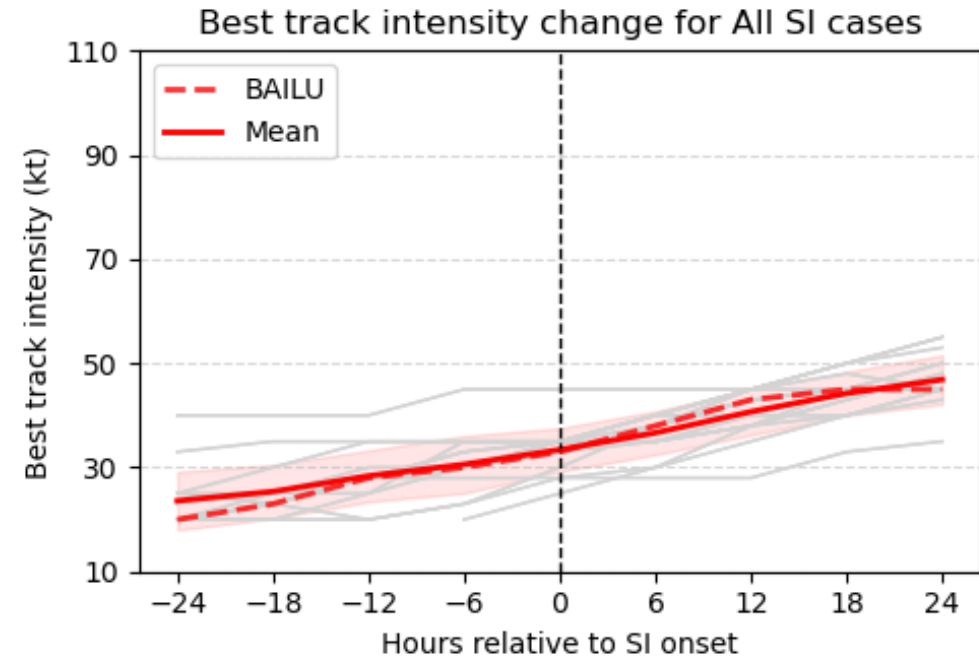
48-hour intensity evolution

Gray lines: individual ensemble members.
Colored solid lines: ensemble mean.
Colored dashed lines: selected RI and SI cases.

RI



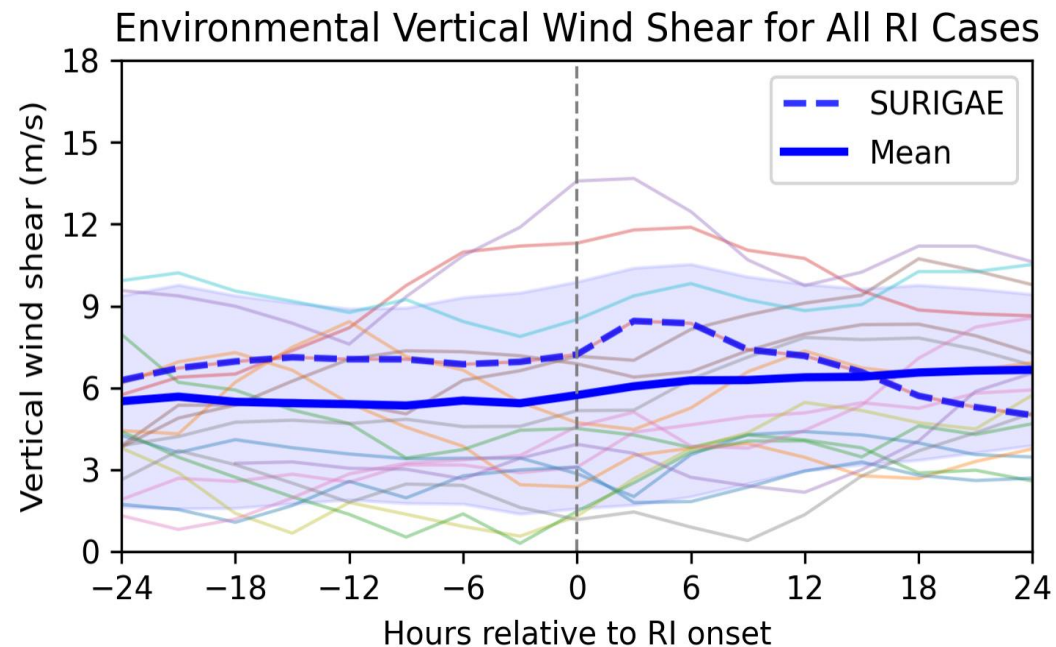
SI



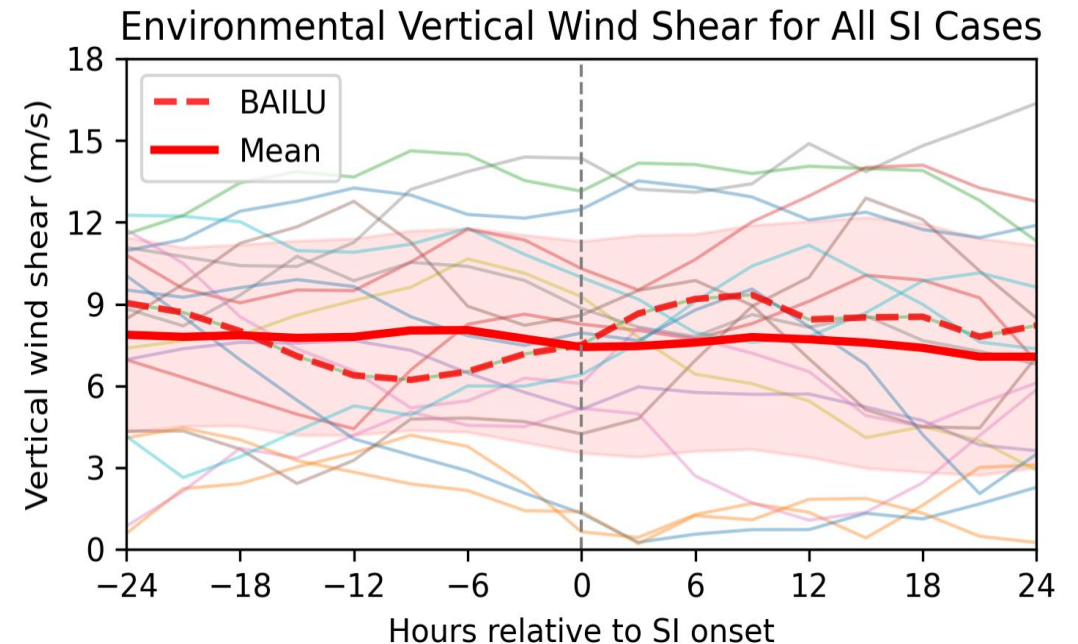
48-hour environmental VWS

Gray lines: individual ensemble members.
Colored solid lines: ensemble mean.
Colored dashed lines: selected RI and SI cases.

RI

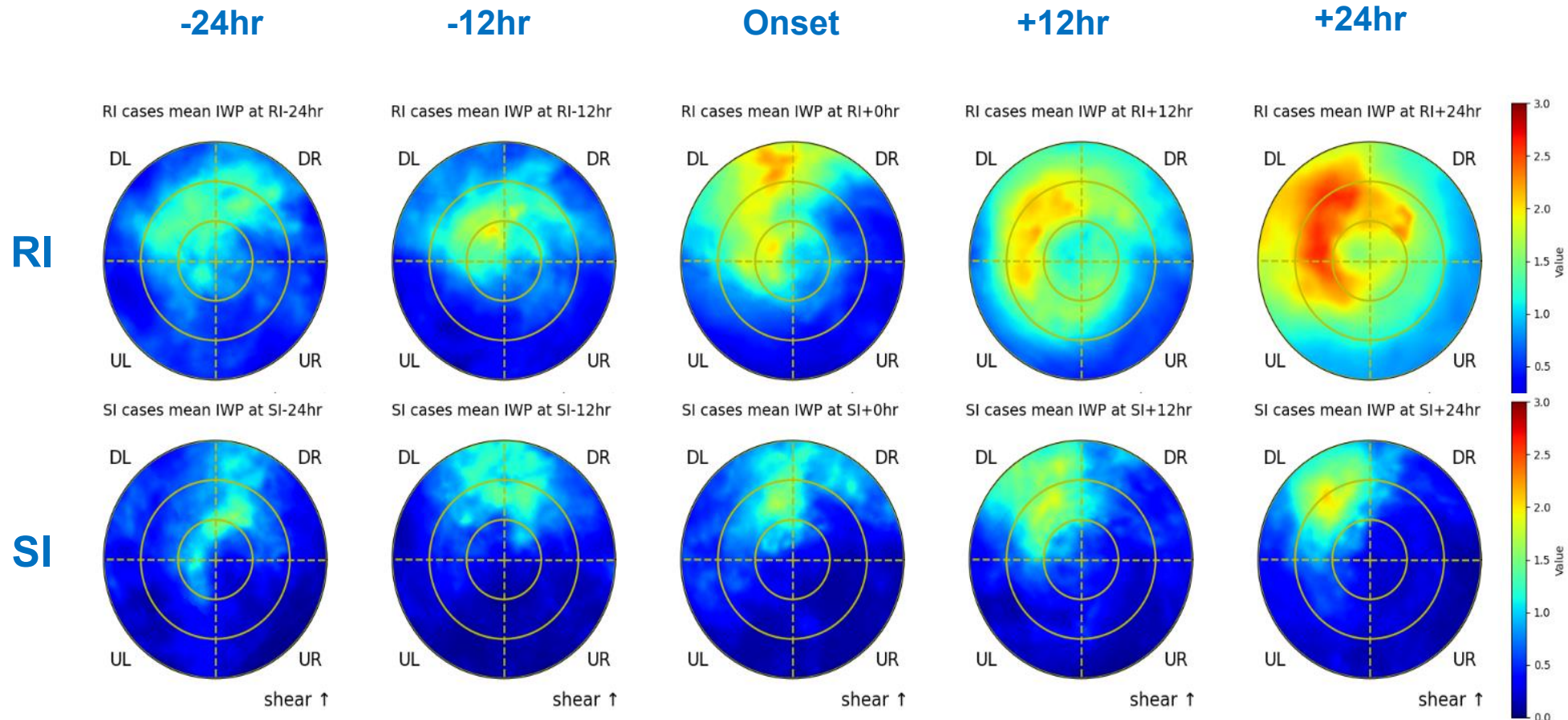
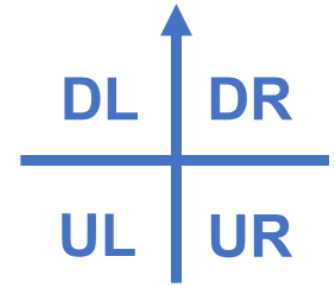


SI



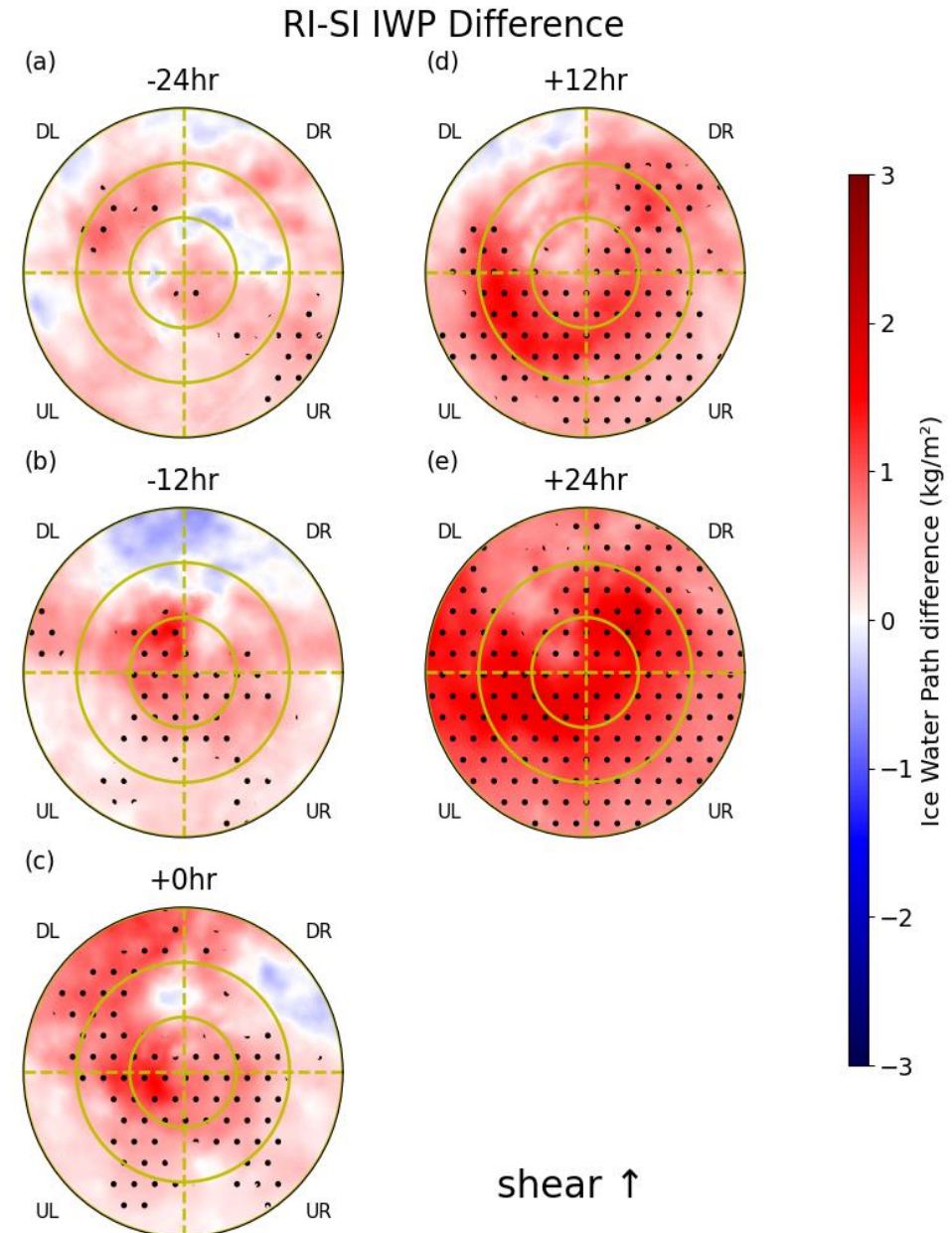
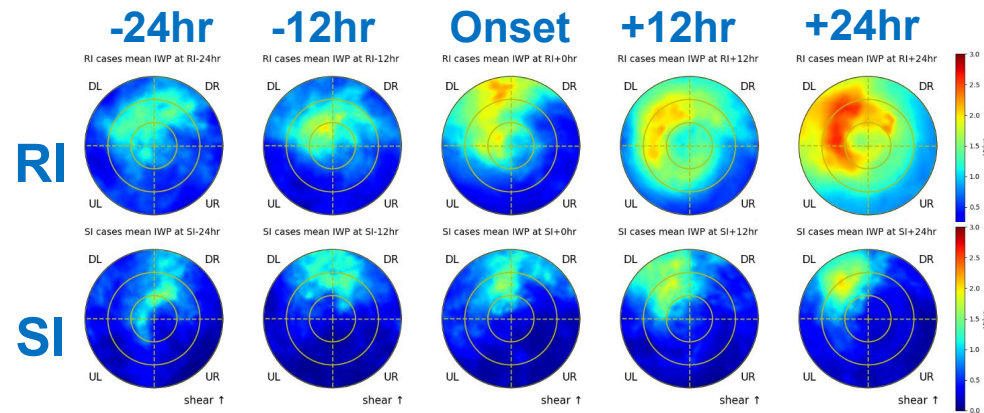
a. The difference between RI and SI ---- IWP

The difference on the **upshear side** is significant.

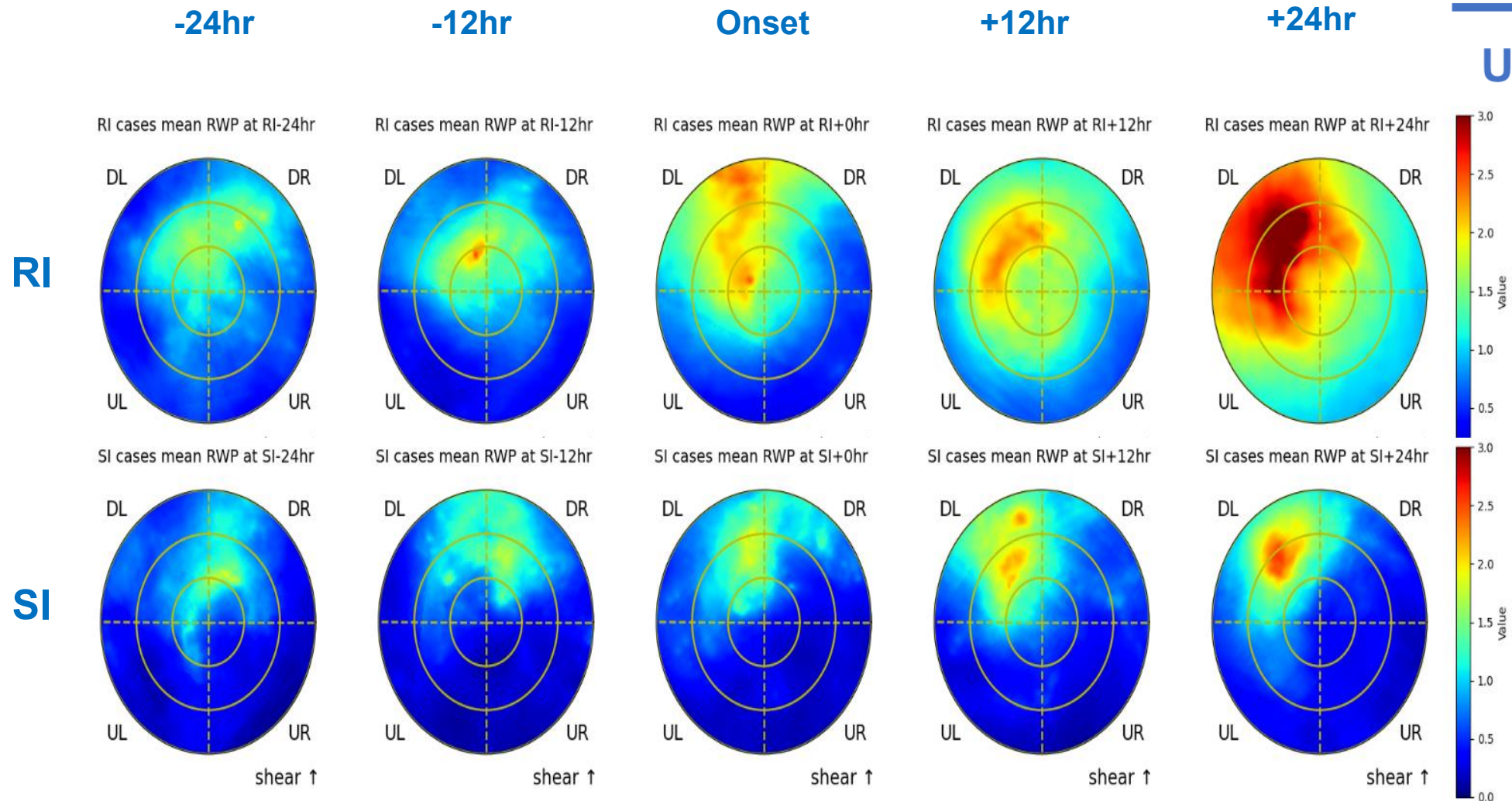


a. The difference between RI and SI ---- IWP

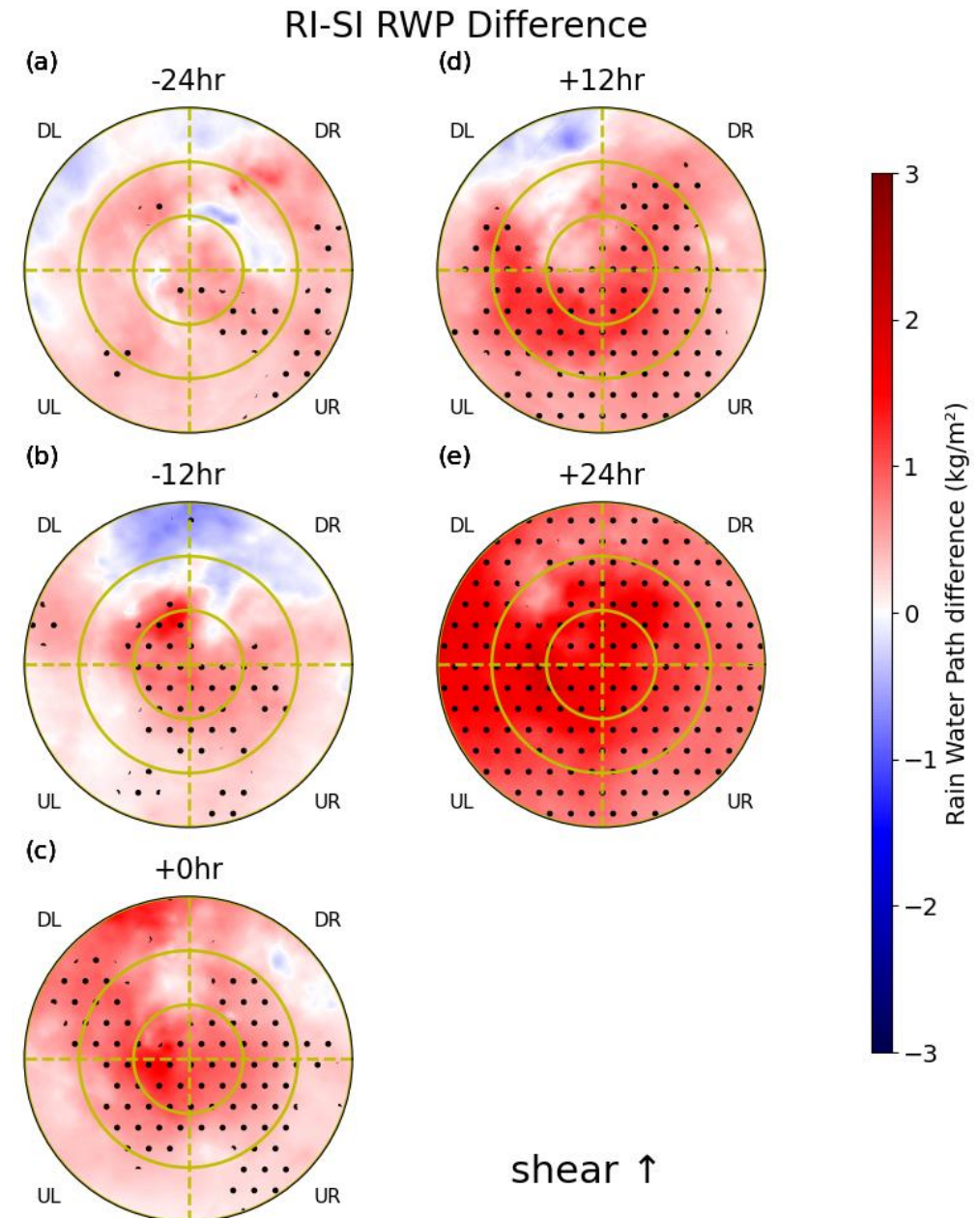
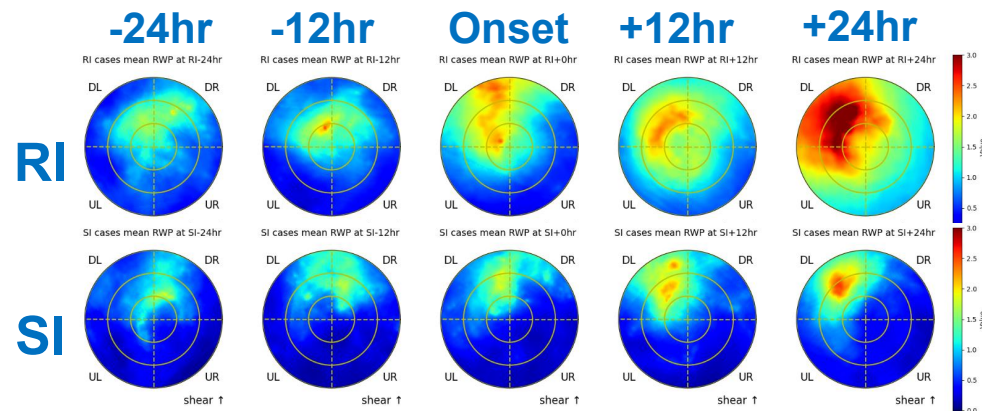
The difference on the **upshear side** is significant.



b. The difference between RI and SI ---- RWP



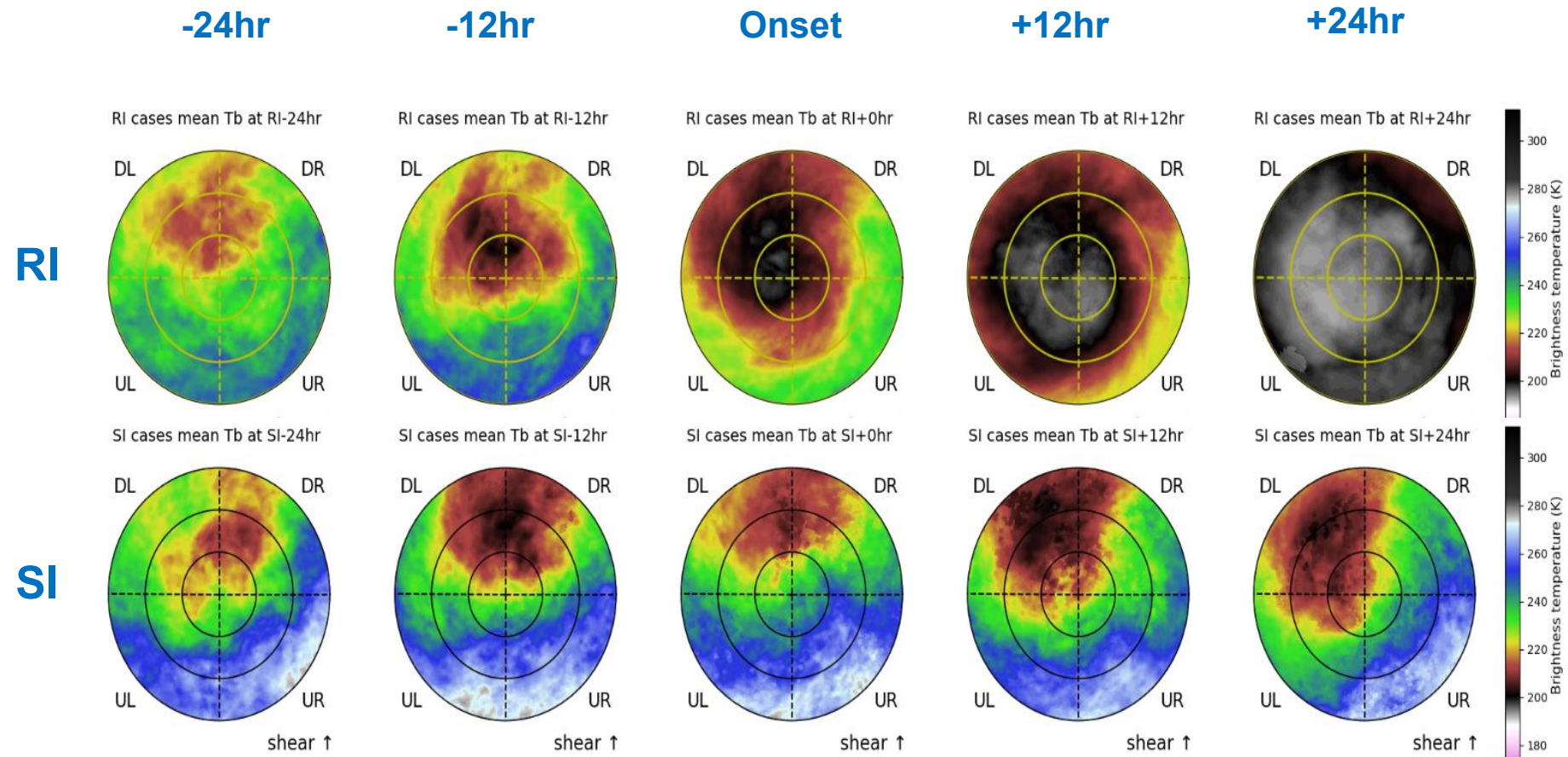
b. The difference between RI and SI ---- RWP



c. The difference between RI and SI ---- Tb

For RI cases, T_b significantly decrease in all four quadrants.

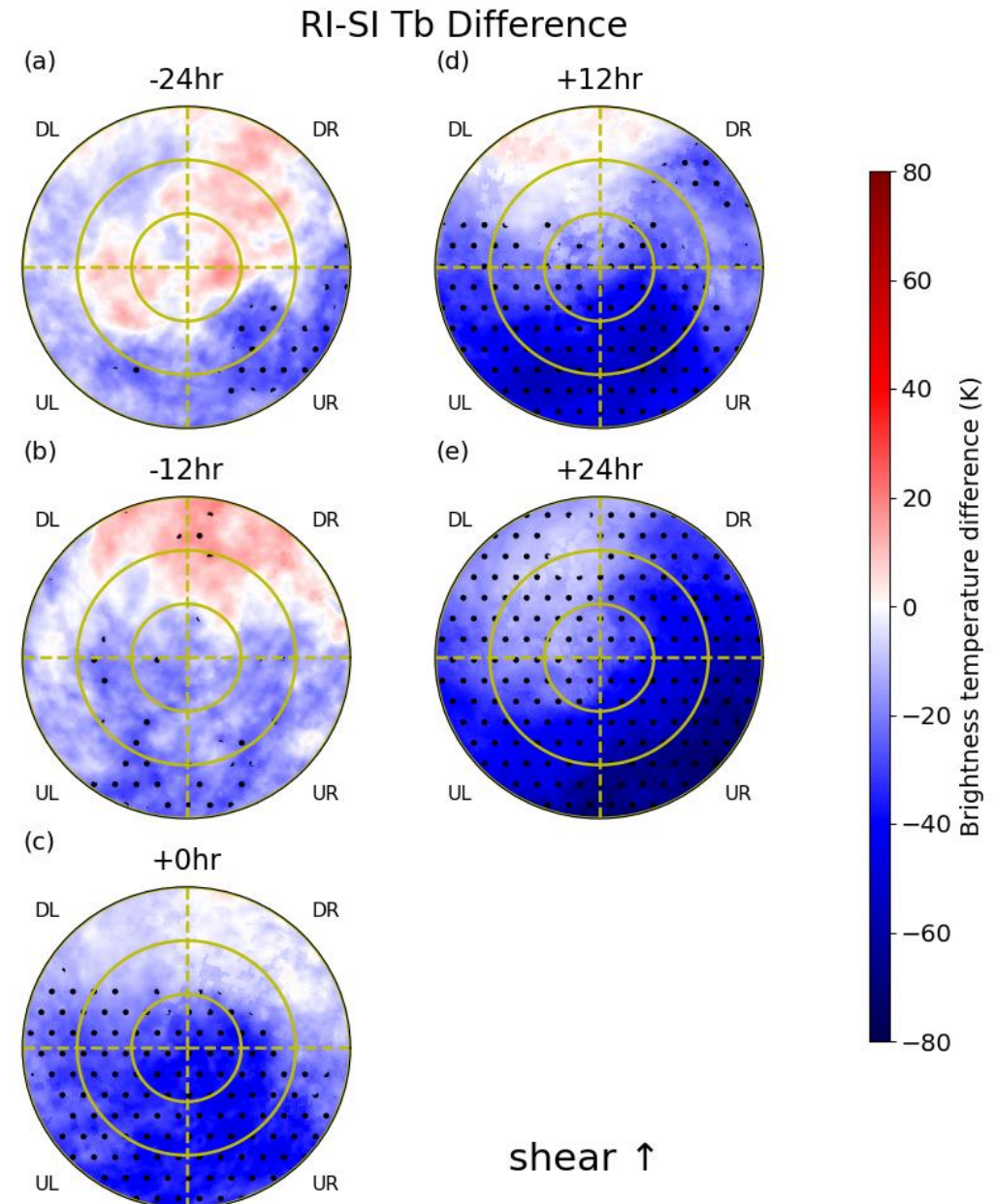
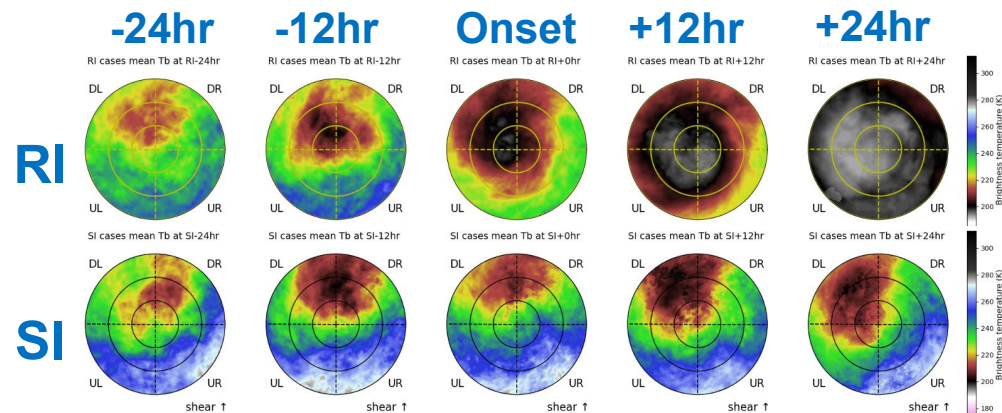
For SI cases, lower T_b appear only in the DL quadrant.



c. The difference between RI and SI ---- Tb

For RI cases, T_b significantly decrease in all four quadrants.

For SI cases, lower T_b appear only in the DL quadrant.



RAPID INTENSIFICATION (RI)

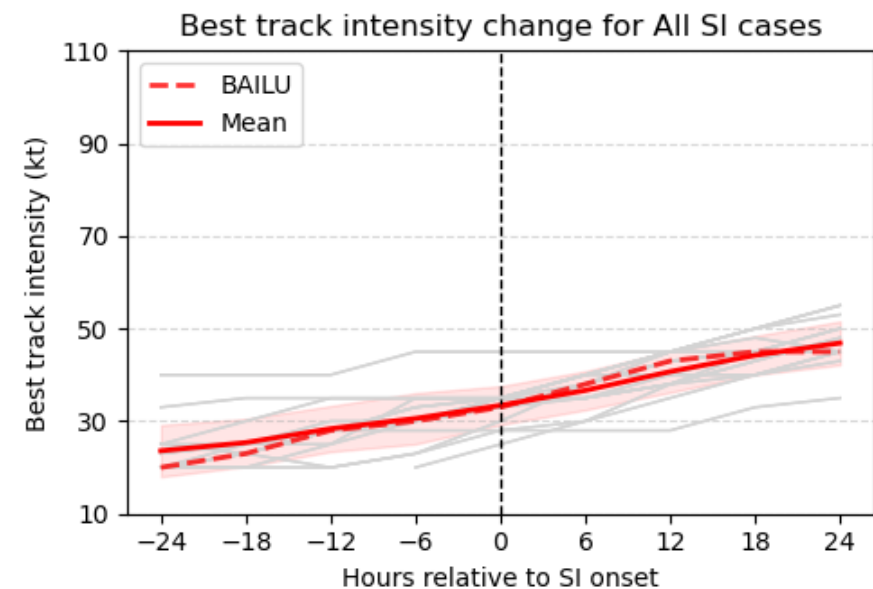
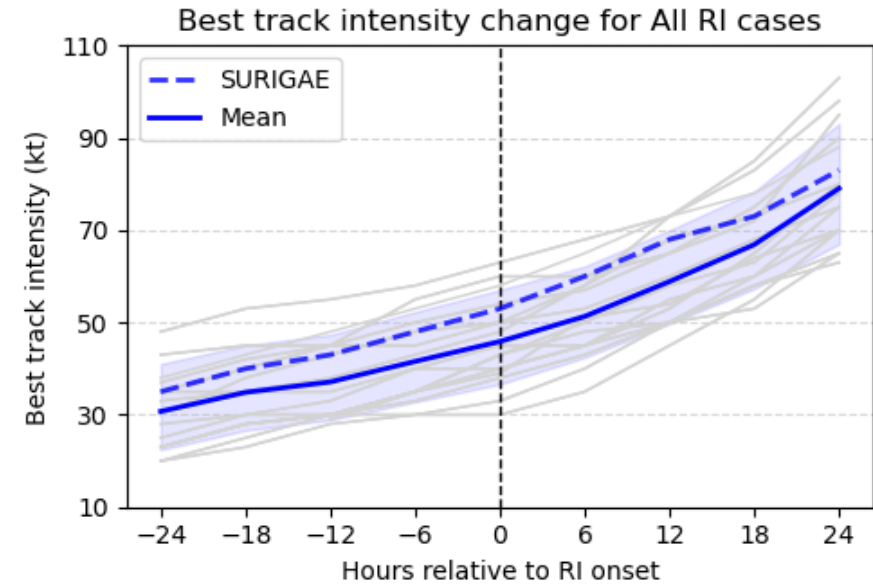
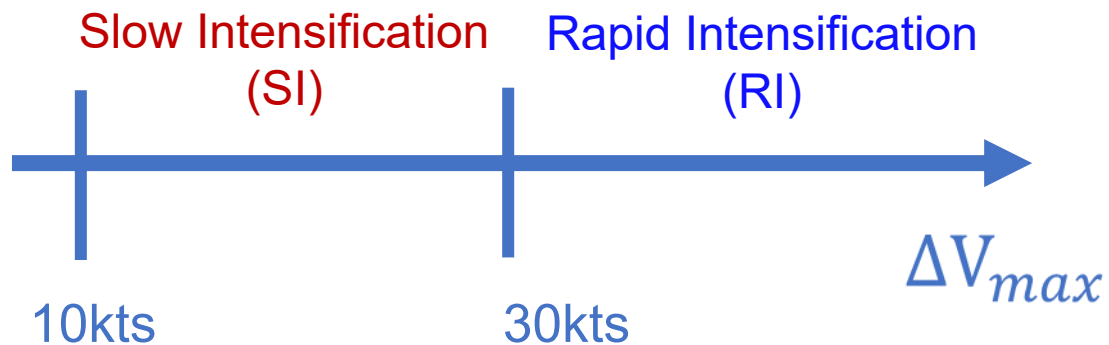
Surigae 蘇力基 (2021)

- Intensity increased from 53 kts to 83 kts

SLOW INTENSIFICATION (SI)

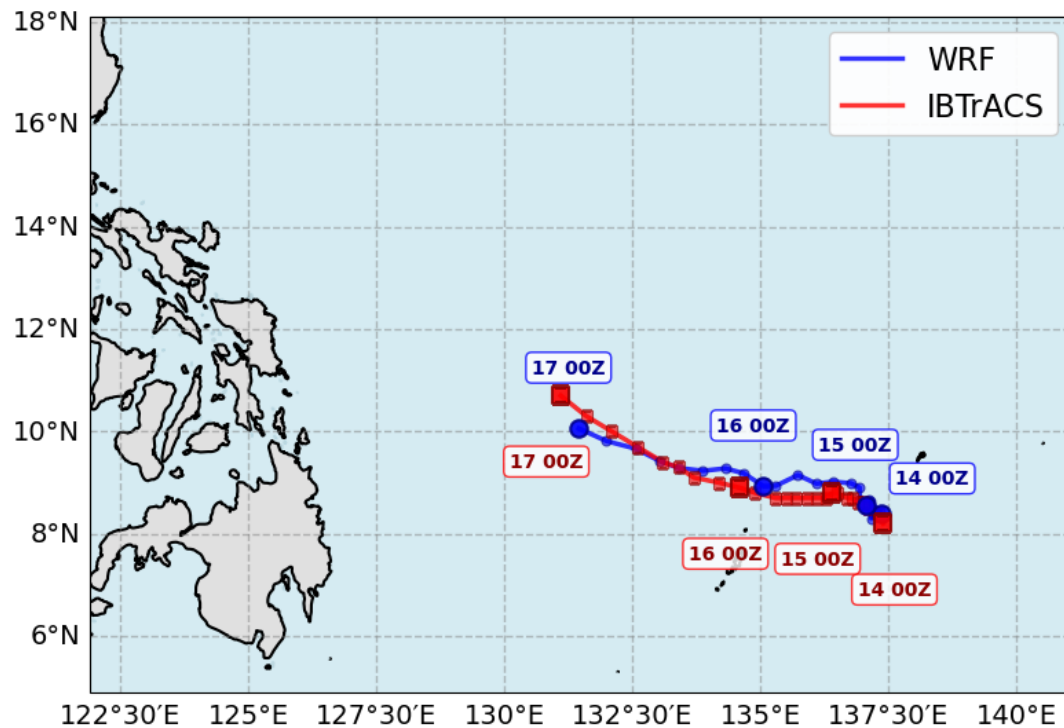
Bailu 白鹿 (2019)

- Intensity increased from 35 kts to 48 kts

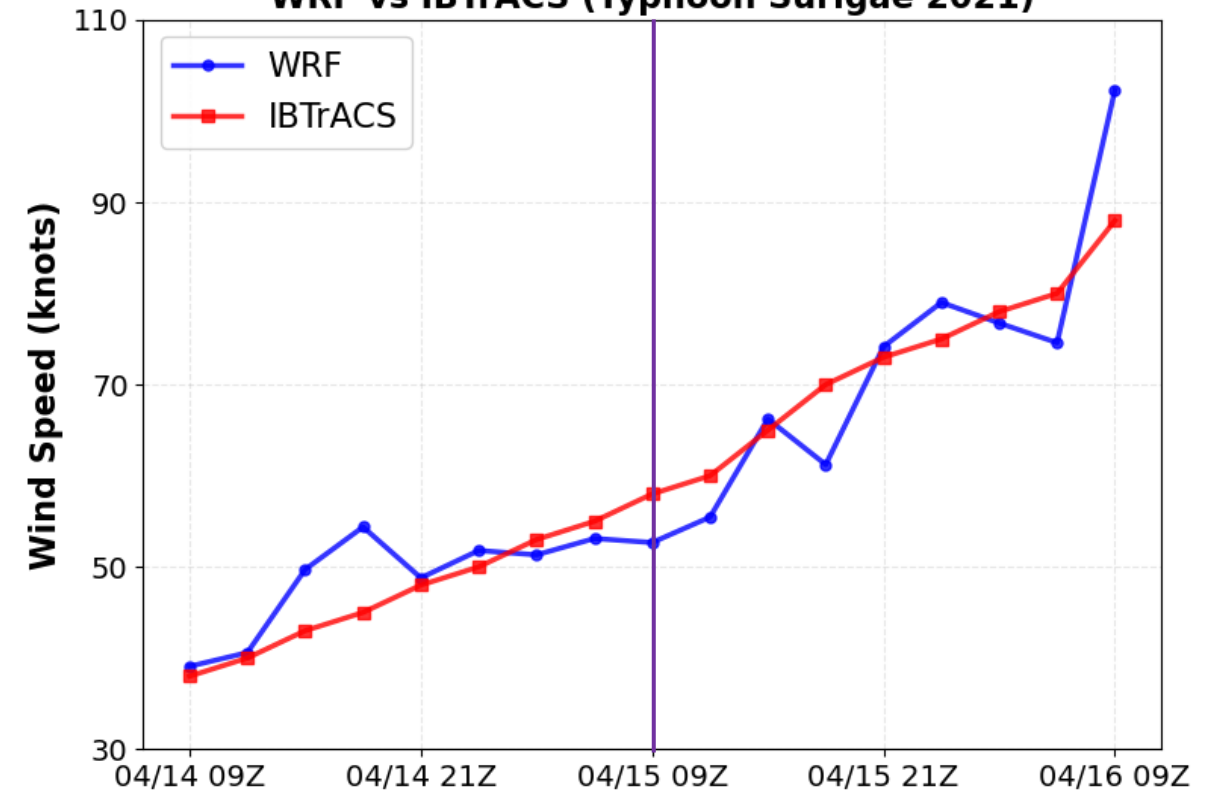


WRF vs. Observation (Surigae 2021)

Typhoon Surigae Track Comparison



Maximum 10-m Wind Speed Comparison
WRF vs IBTrACS (Typhoon Surigae 2021)



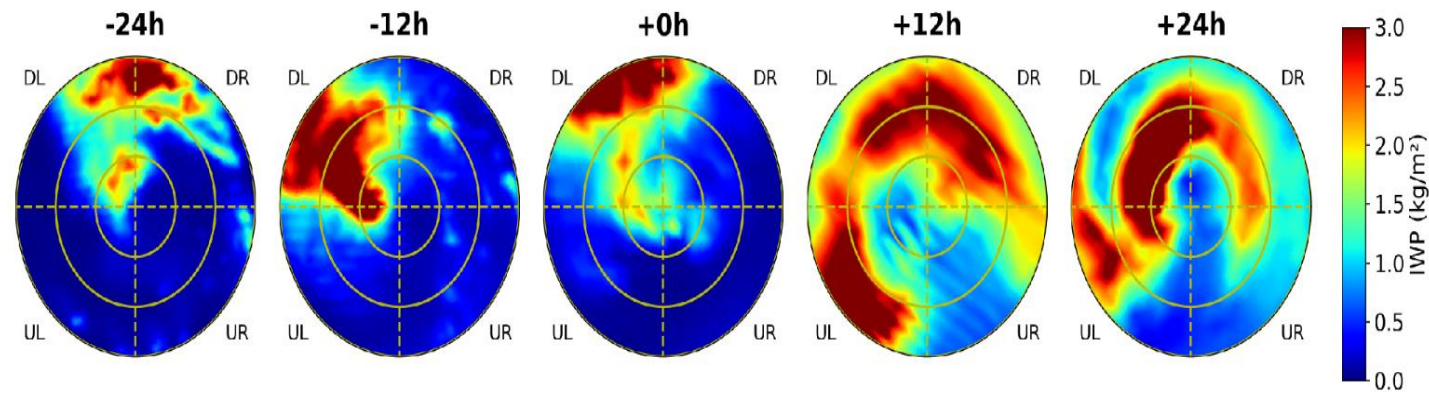
RI onset 09Z
(WRF vs. best track)

WRF vs. Observation (Surigae)

IWP

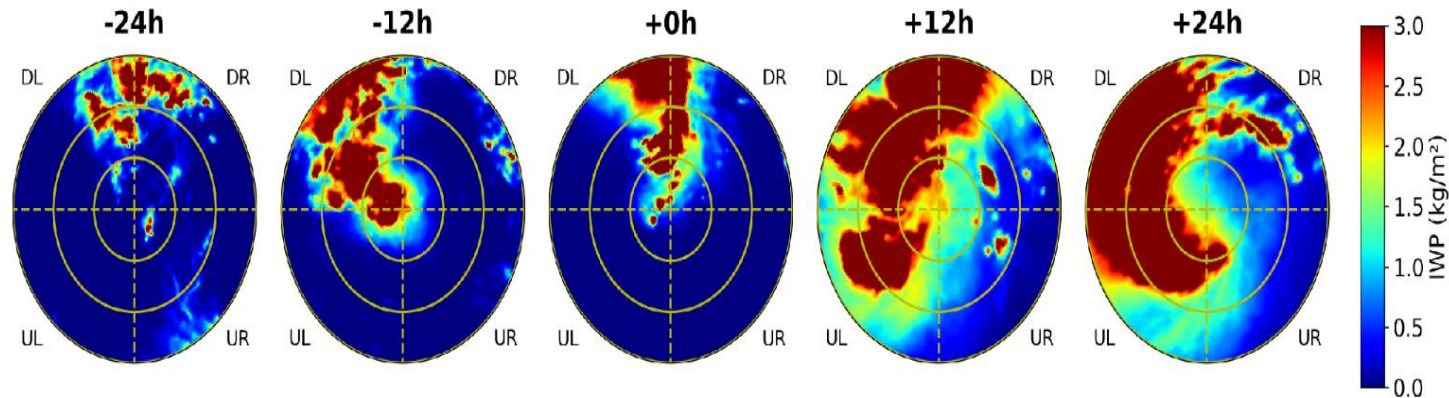
SURIGAE Observation : IWP

Observation



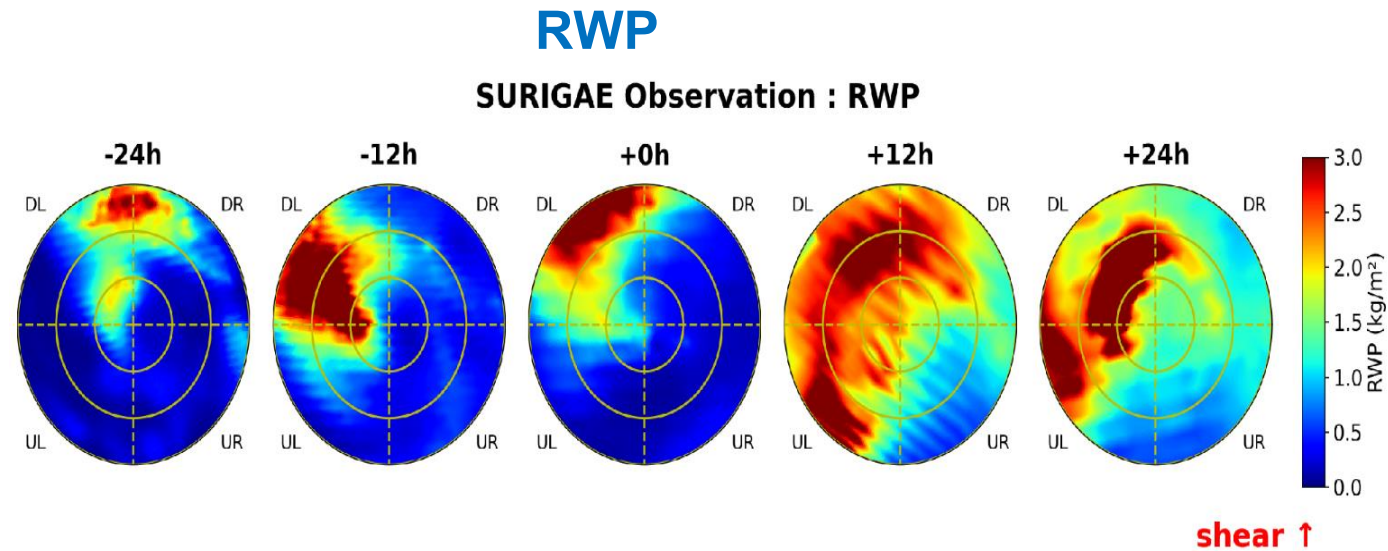
SURIGAE WRF : IWP

WRF

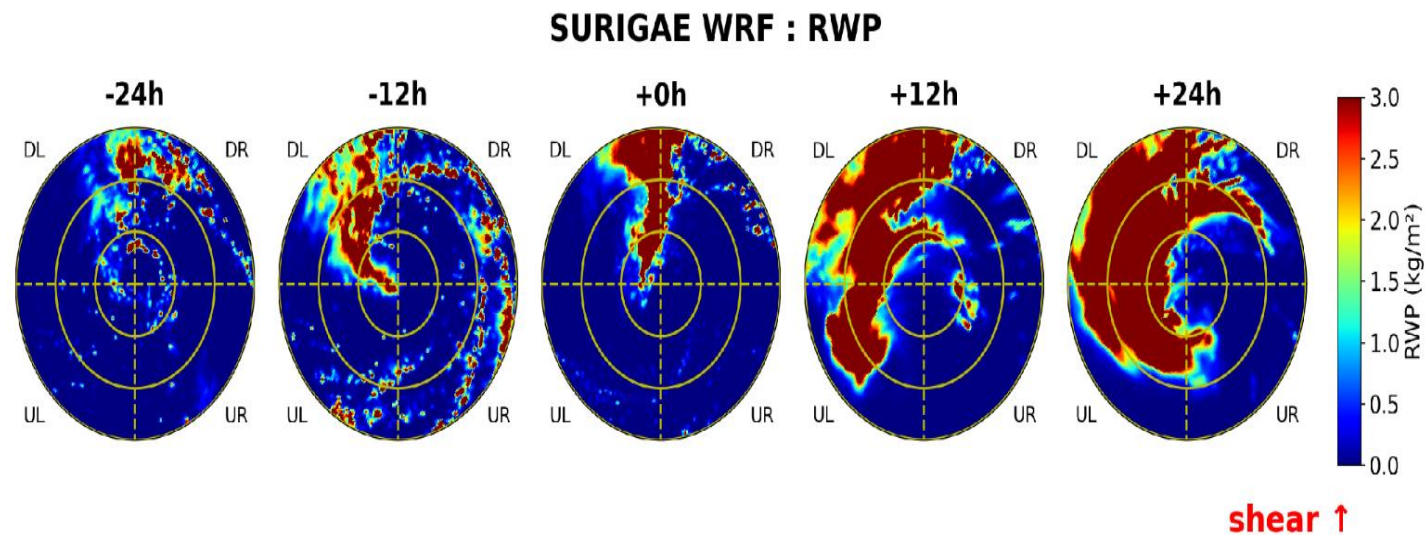


WRF vs. Observation (Surigae 2021)

Observation

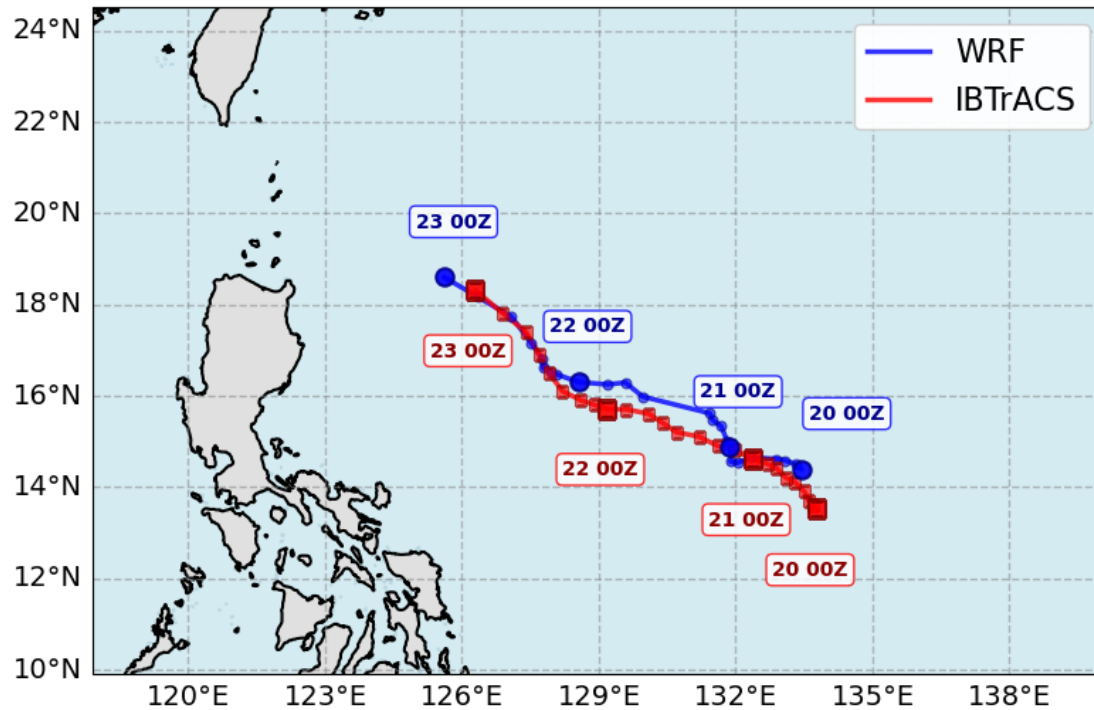
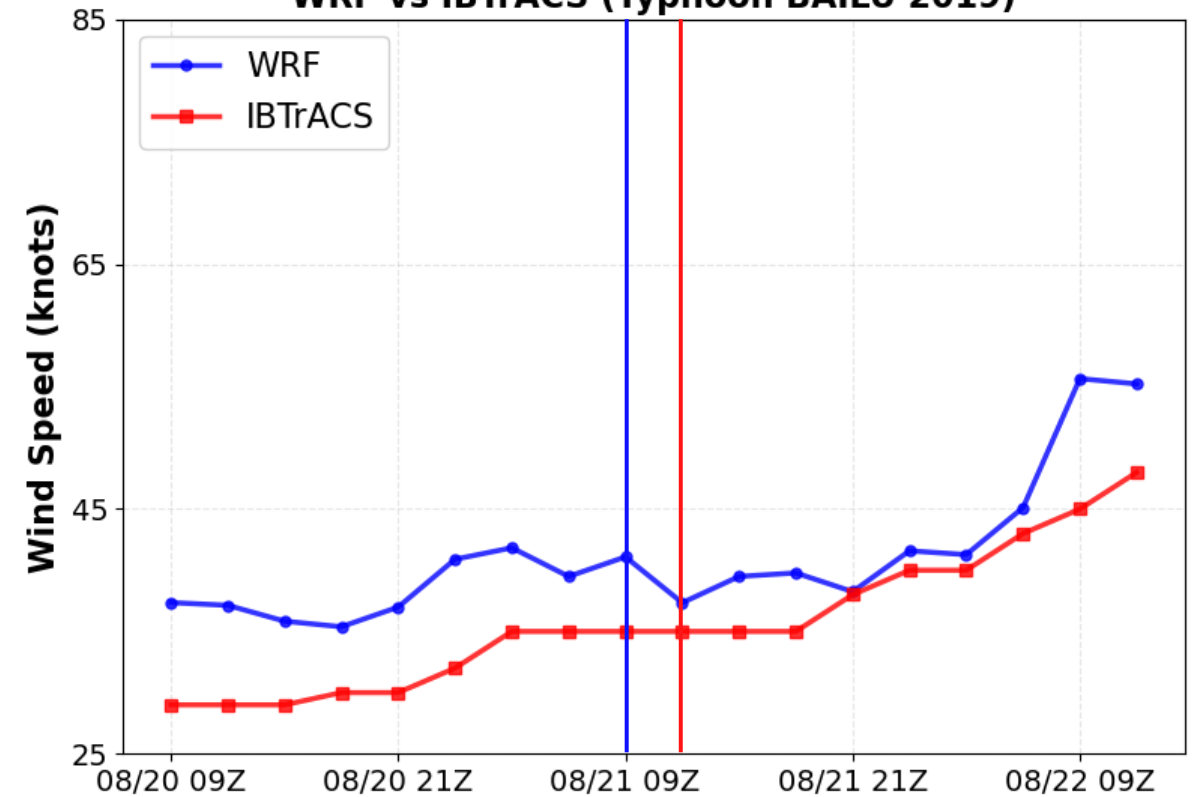


WRF



WRF vs. Observation (Bailu 2019)

Typhoon BAILU Track Comparison

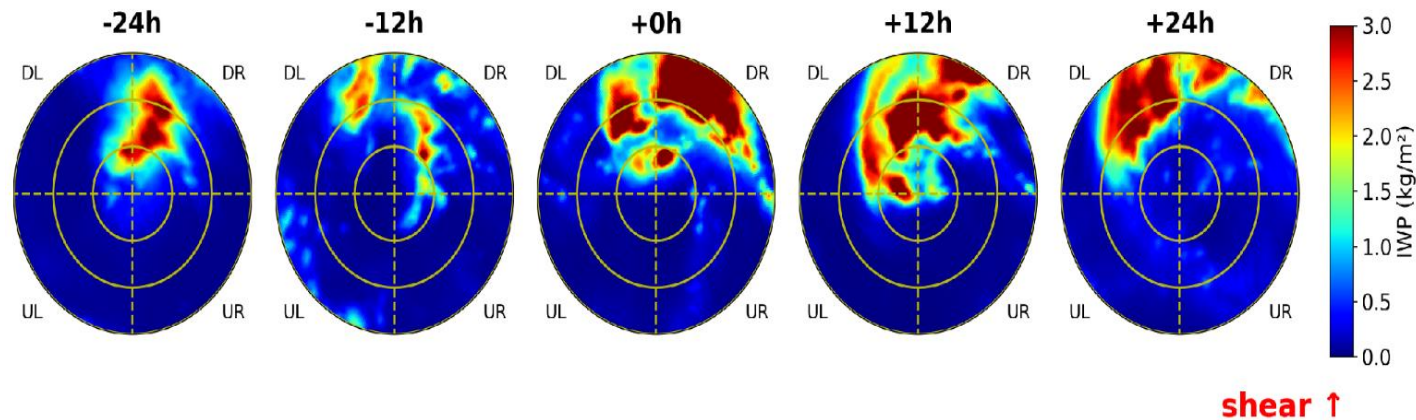
Maximum 10-m Wind Speed Comparison
WRF vs IBTrACS (Typhoon BAILU 2019)SI onset 09Z
(WRF)SI onset 12Z
(best track)

WRF vs. Observation (Bailu 2019)

IWP

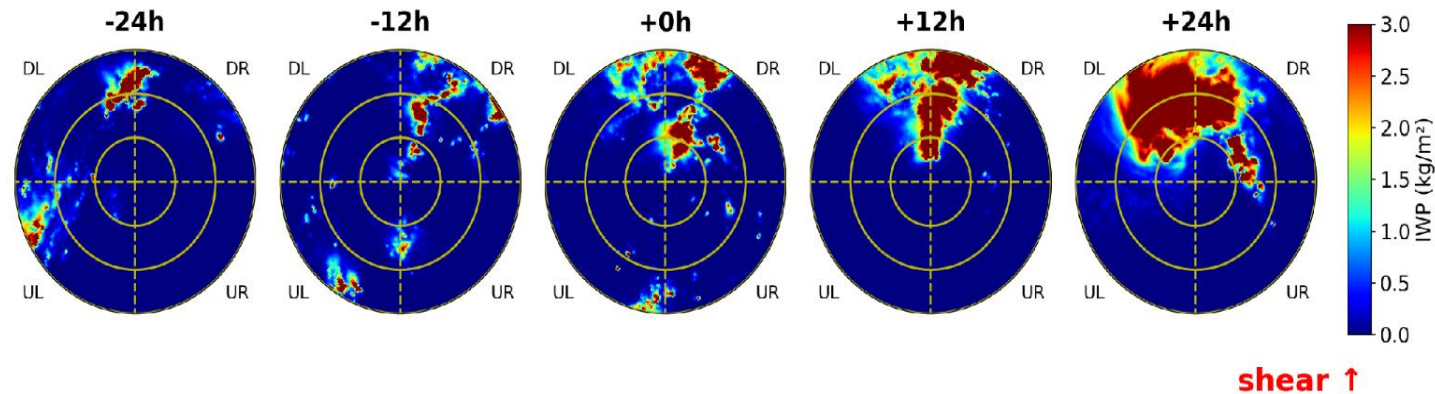
BAILU Observation : IWP

Observation



BAILU WRF : IWP

WRF

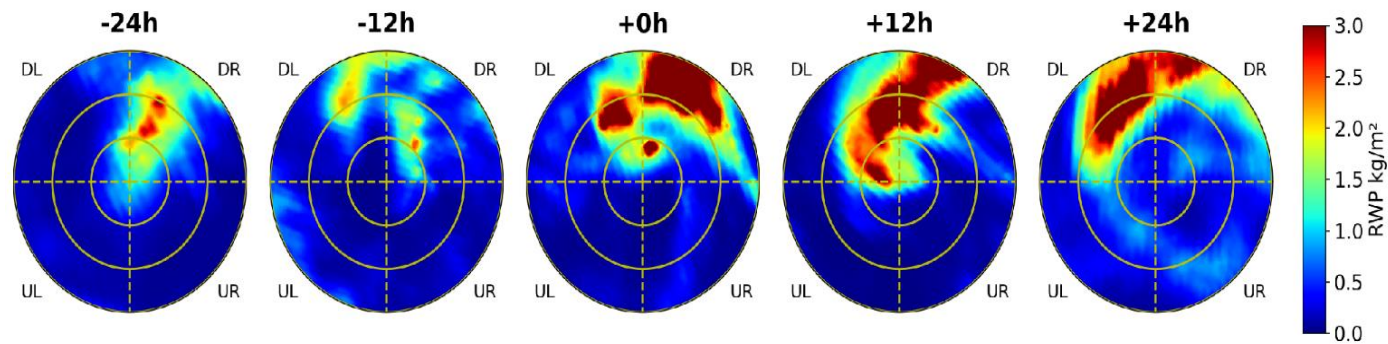


WRF vs. Observation (Bailu 2019)

RWP

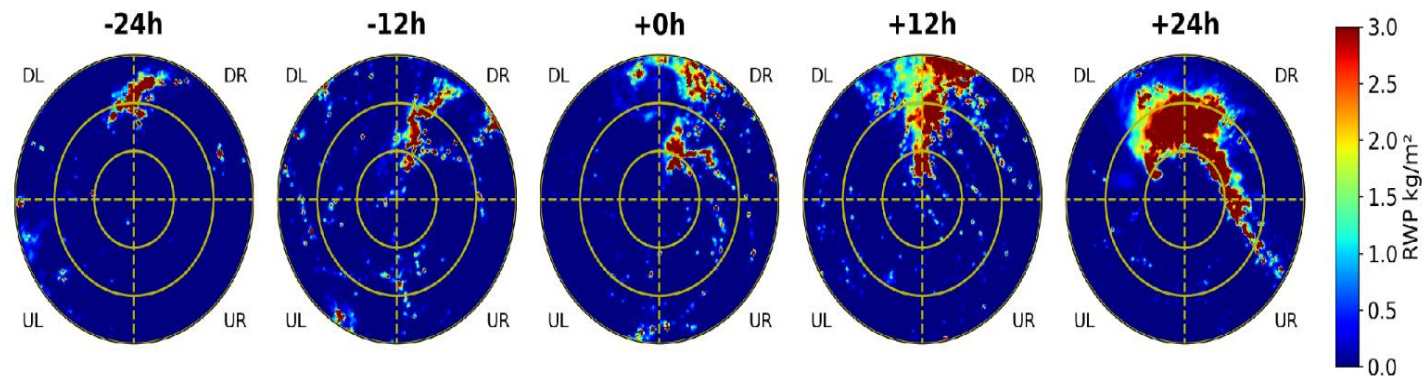
Observation

BAILU Observation : RWP



WRF

BAILU WRF : RWP

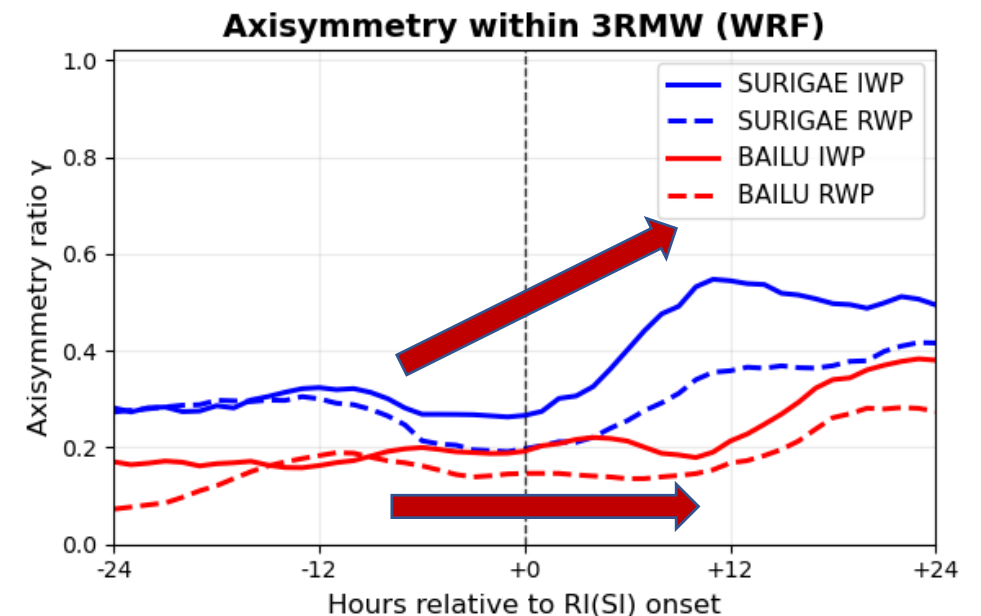
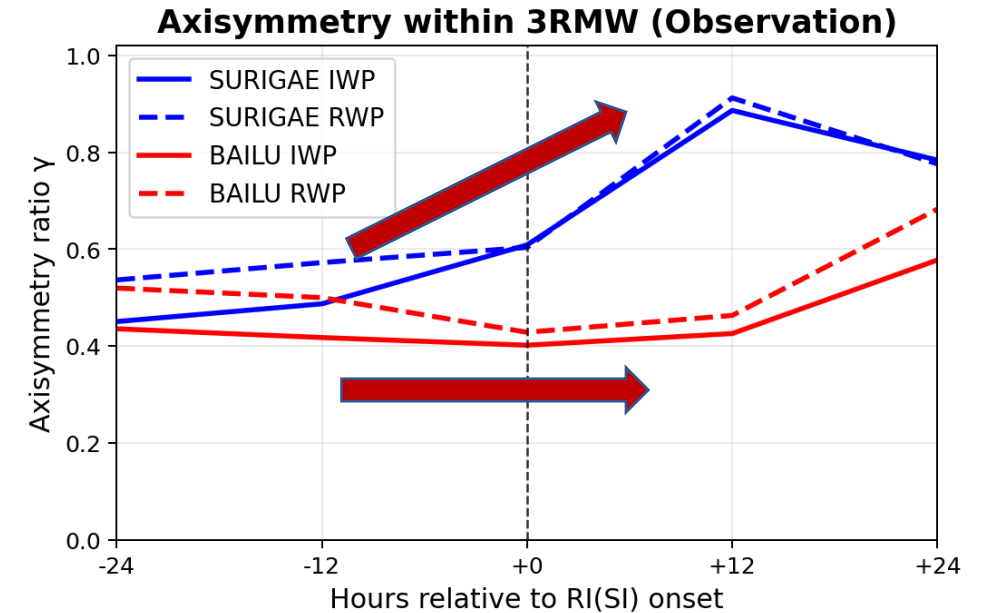


WRF vs. Observation: Axisymmetricty

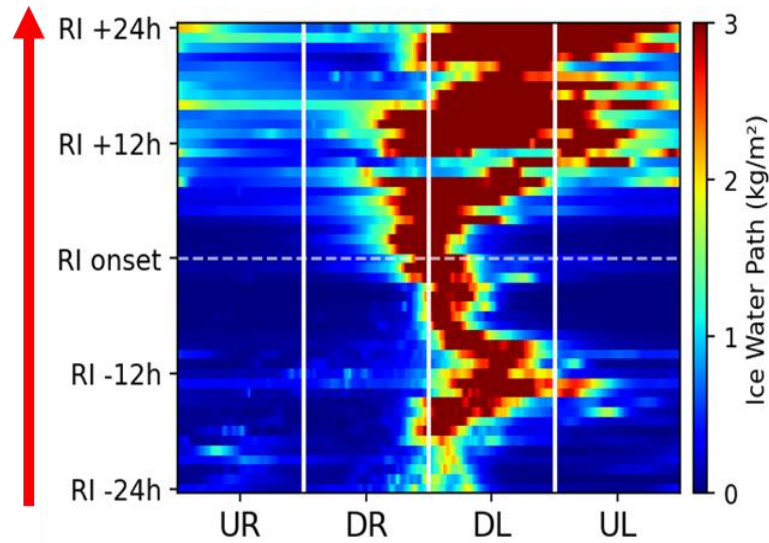
We calculated the axisymmetricty metric following Miyamoto and Takemi (2013).

$$\phi(r, \lambda, z, t) = \bar{\phi}(r, z, t) + \phi'(r, \lambda, z, t)$$

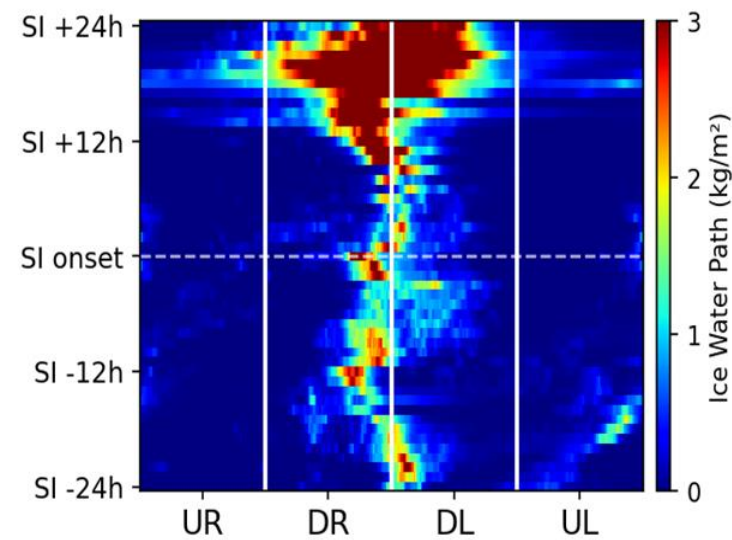
$$\gamma(r, z, t) \equiv \frac{\bar{\phi}(r, z, t)^2}{\bar{\phi}(r, z, t)^2 + \int_0^{2\pi} \phi'(r, \lambda, z, t)^2 d\lambda / 2\pi}$$



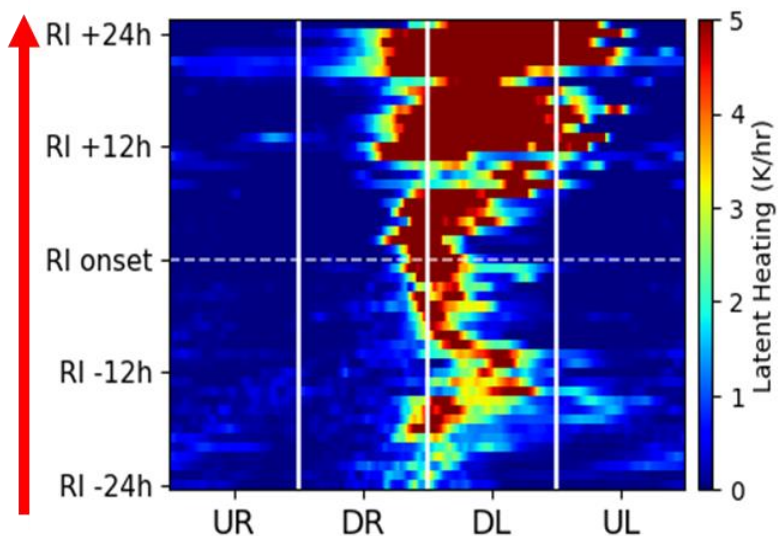
SURIGAE IWP Hovmoller diagram



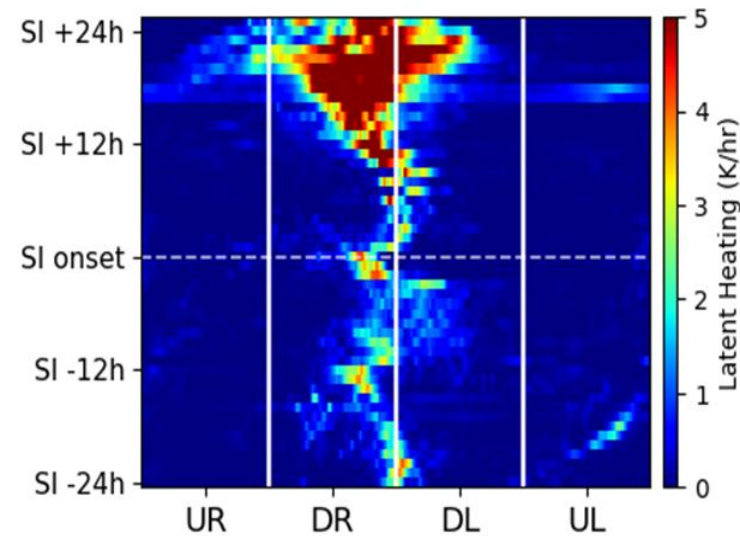
BAILU IWP Hovmoller diagram



SURIGAE Latent Heating Hovmoller diagram

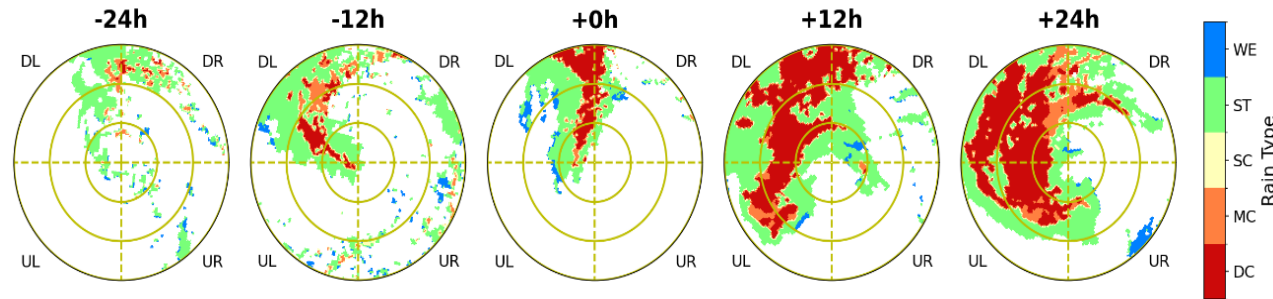


BAILU Latent Heating Hovmoller diagram



Deep Convection(DC) Moderate Convection(MC) Shallow Convection(SC) Stratiform(ST) Weak Echo(WE)

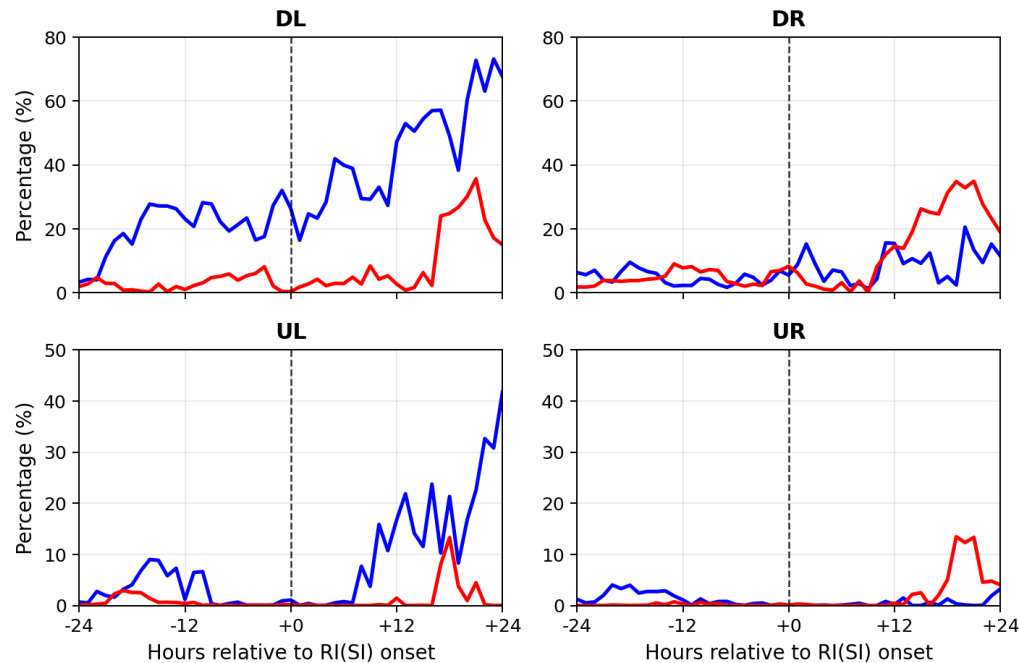
SURIGAE : Precipitation Type



Convection

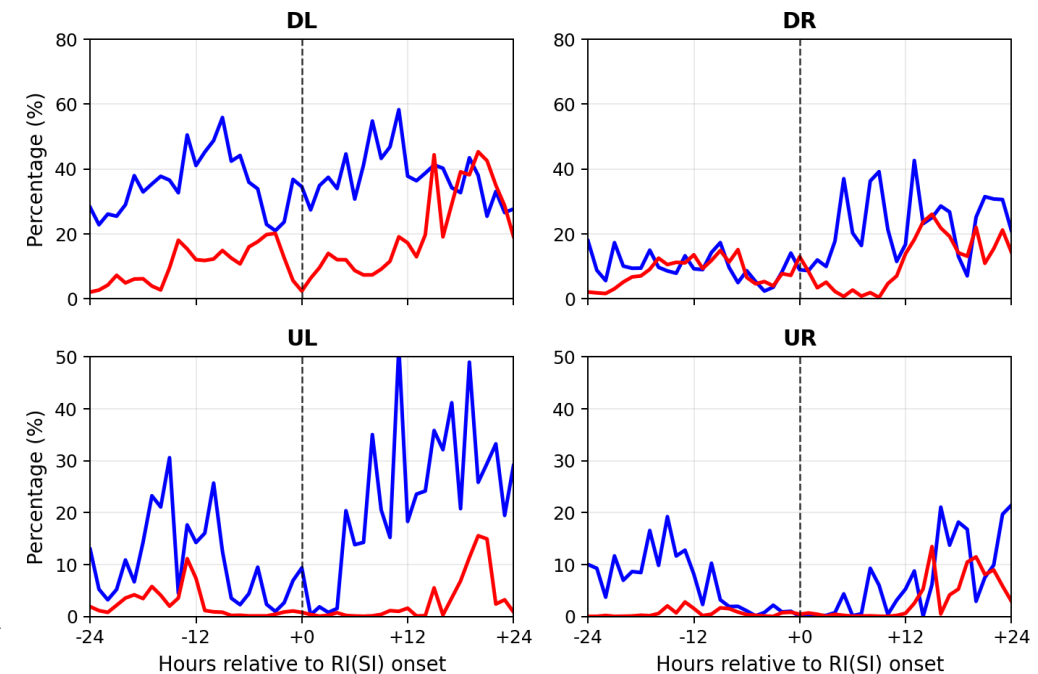
DC+MC+SC (Convective) Rain Ratio

— SURIGAE — BAILU



ST+WE (Stratiform+Weak) Rain Ratio

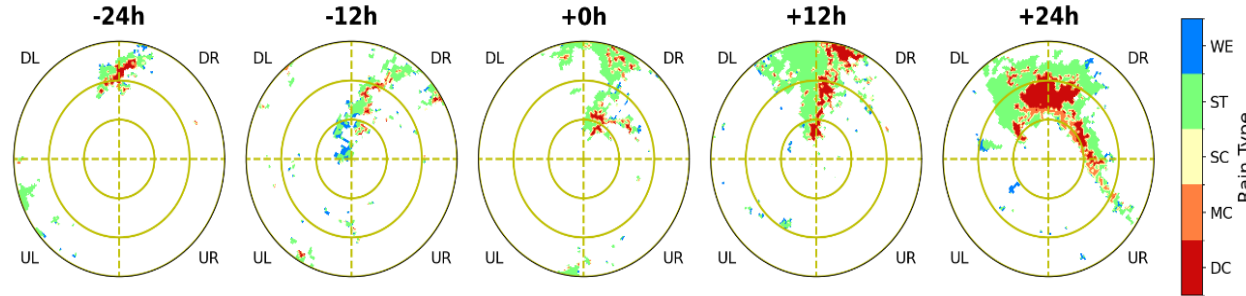
— SURIGAE — BAILU



Stratiform

Deep Convection(DC) **Moderate Convection(MC)** **Shallow Convection(SC)** **Stratiform(ST)** **Weak Echo(WE)**

BAILU : Precipitation Type

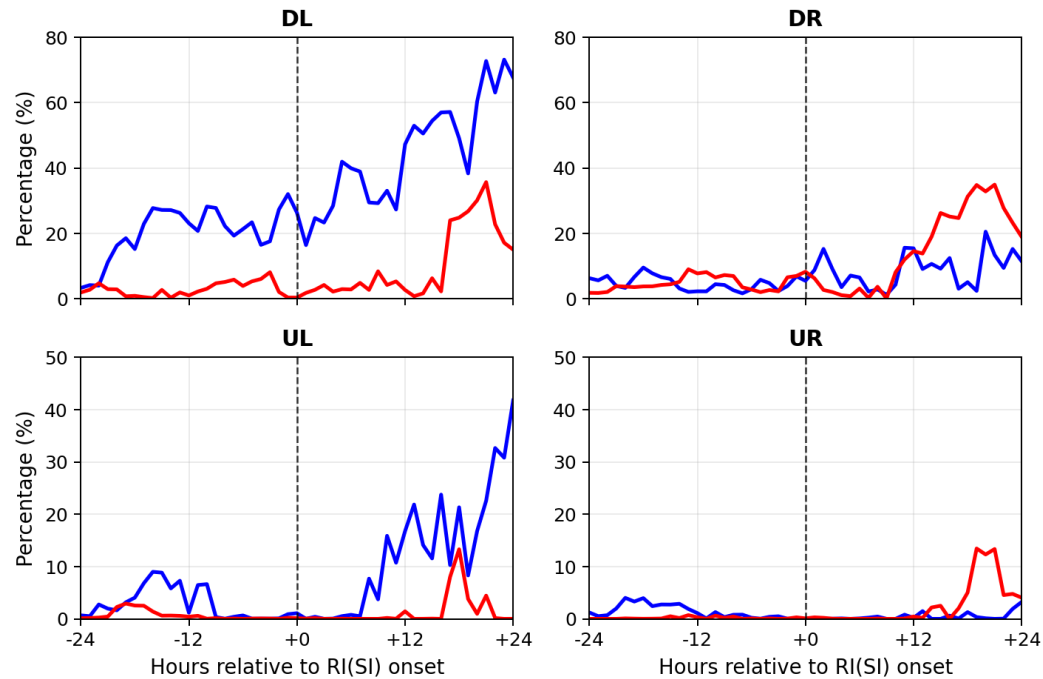


shear ↑

Convection

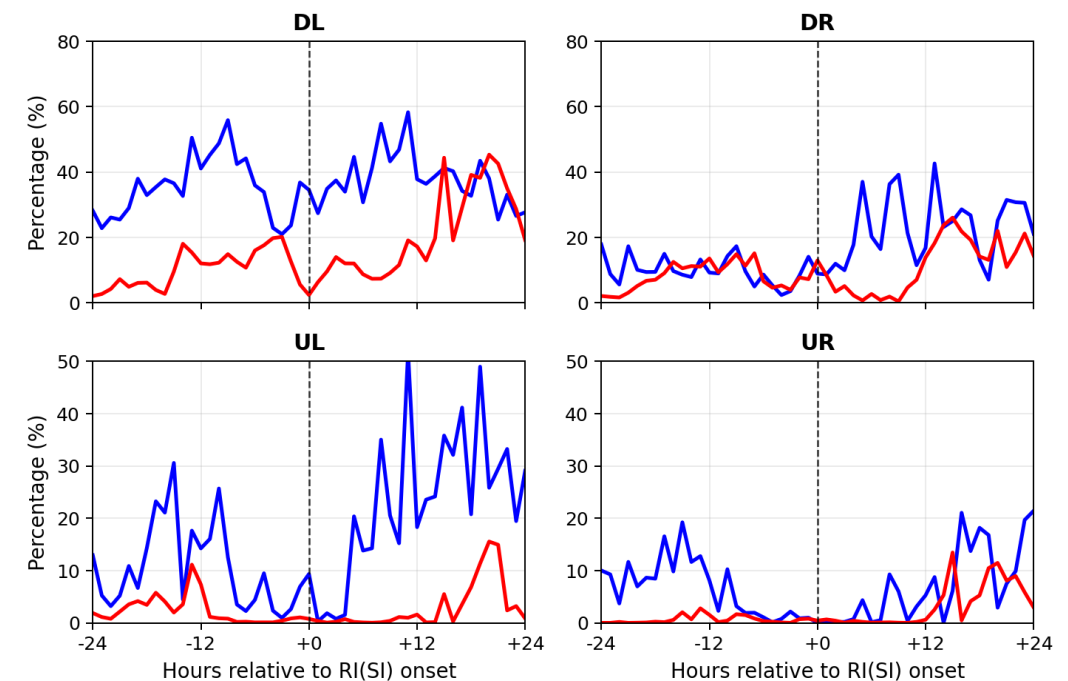
DC+MC+SC (Convective) Rain Ratio

— SURIGAE — BAILU



ST+WE (Stratiform+Weak) Rain Ratio

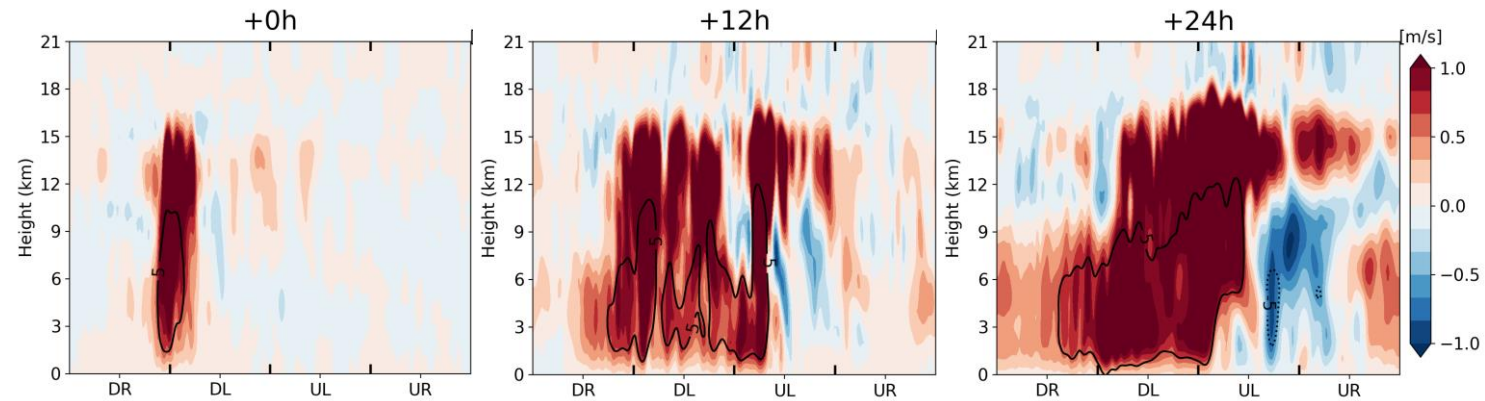
— SURIGAE — BAILU



Stratiform

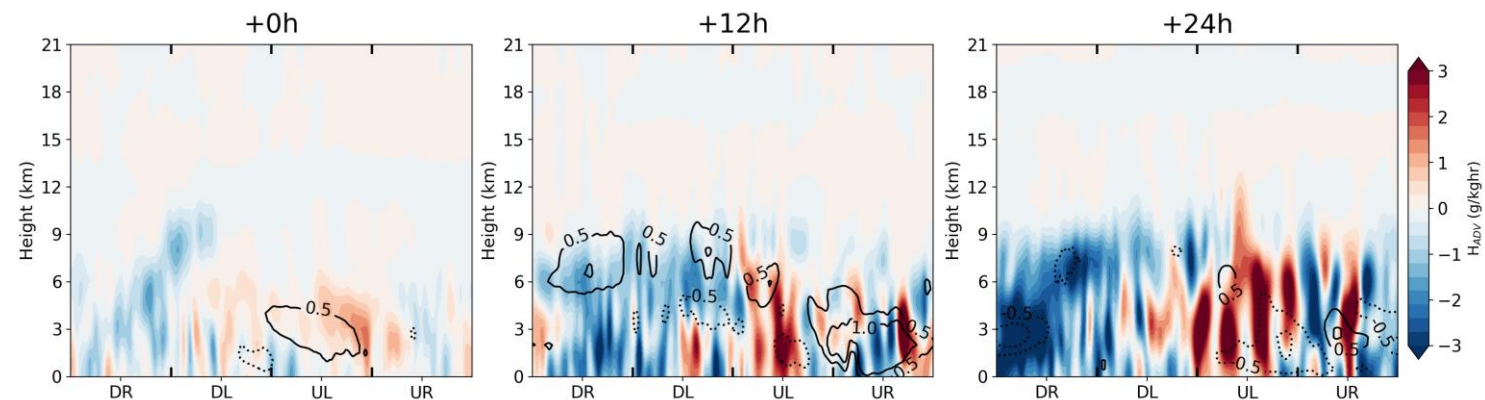
W (shading)
 qv_V_{ADV} (line contours)

Vertical advection

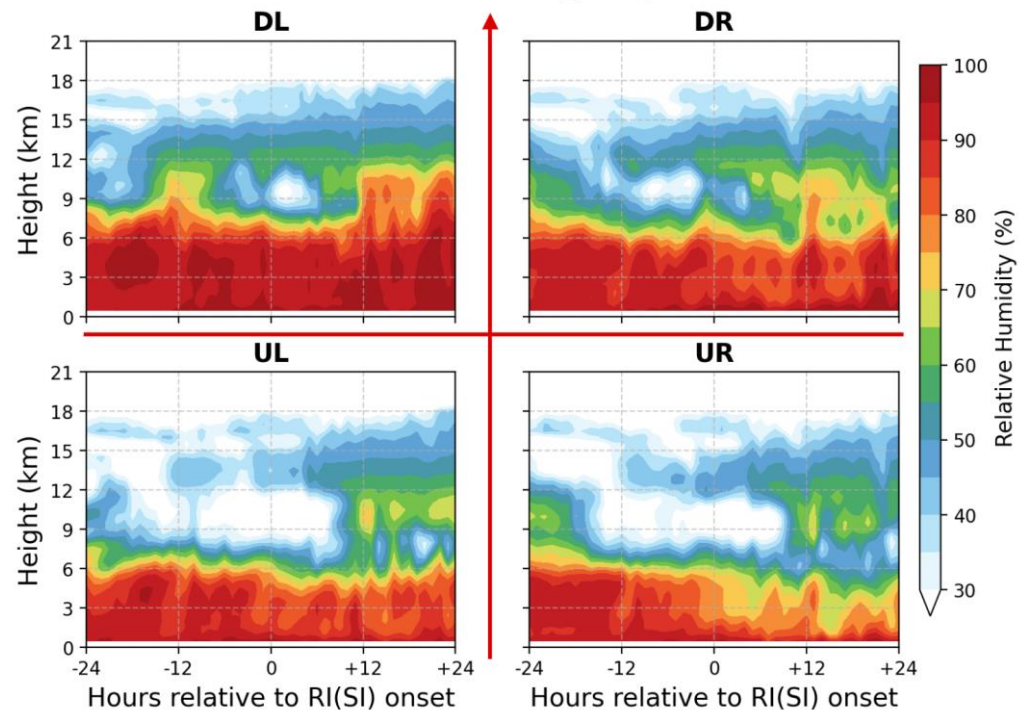


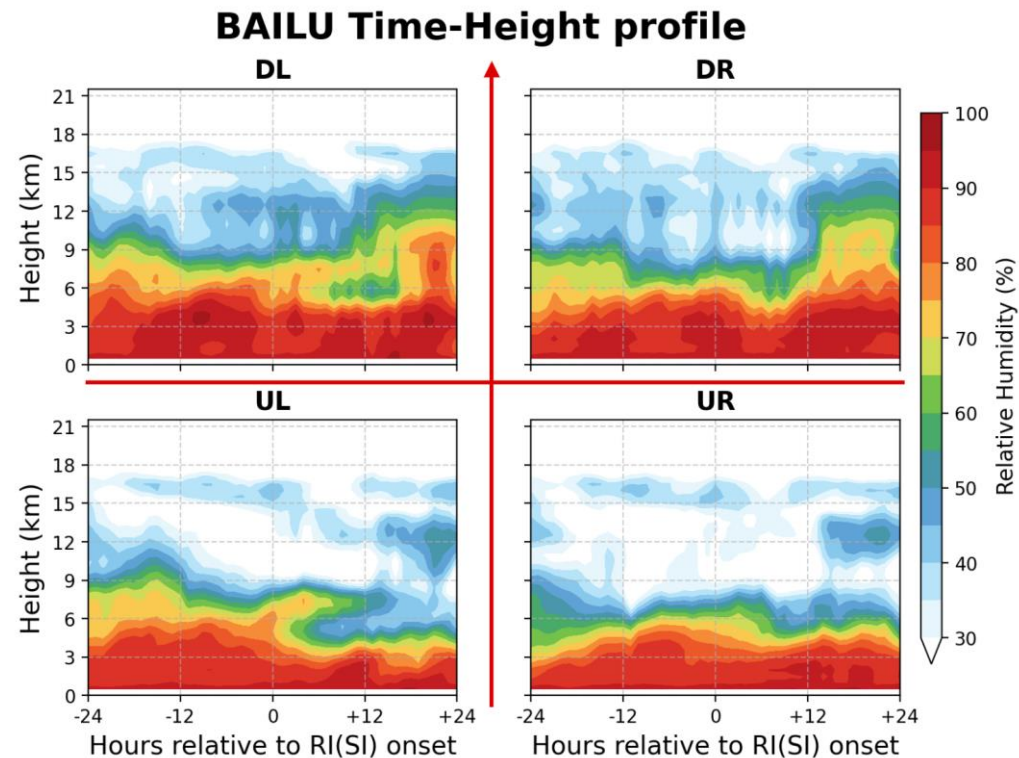
qv_H_{ADV} (shading)
 qv rate of change (line contours)

Horizontal advection



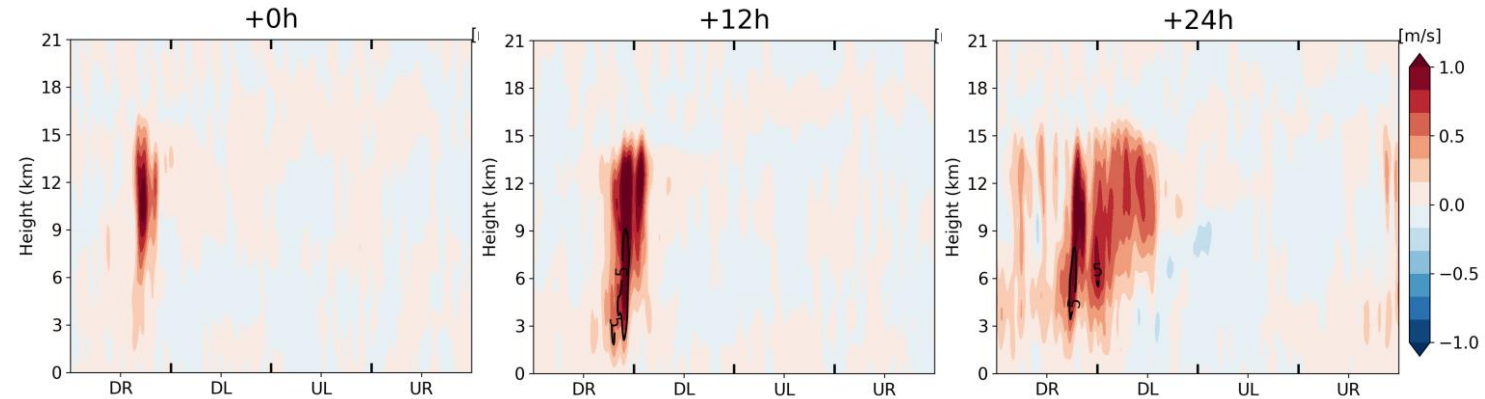
SURIGAE Time-Height profile





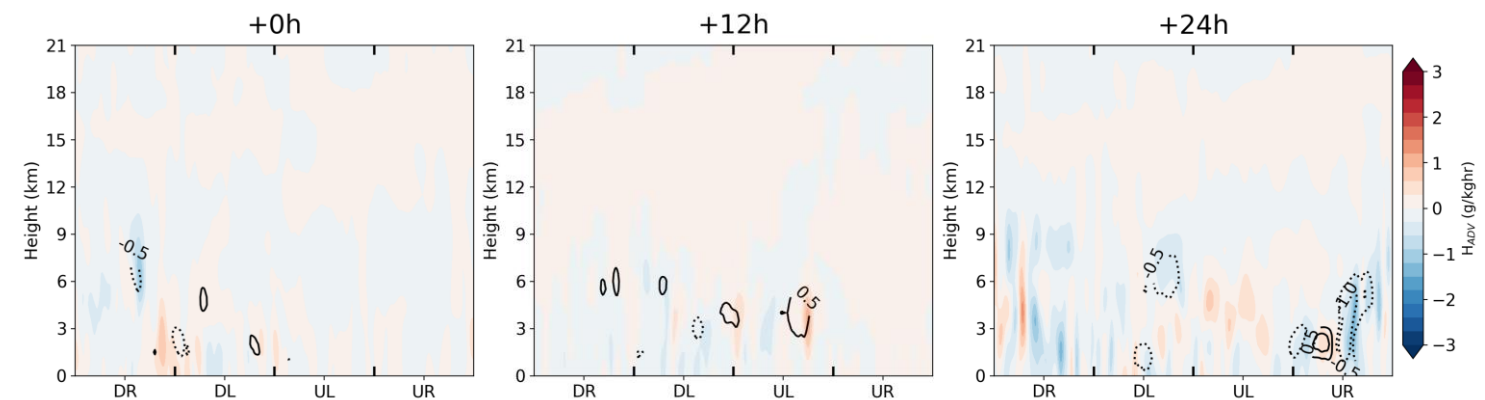
Vertical advection

W (shading)
 qv_V_{ADV} (line contours)



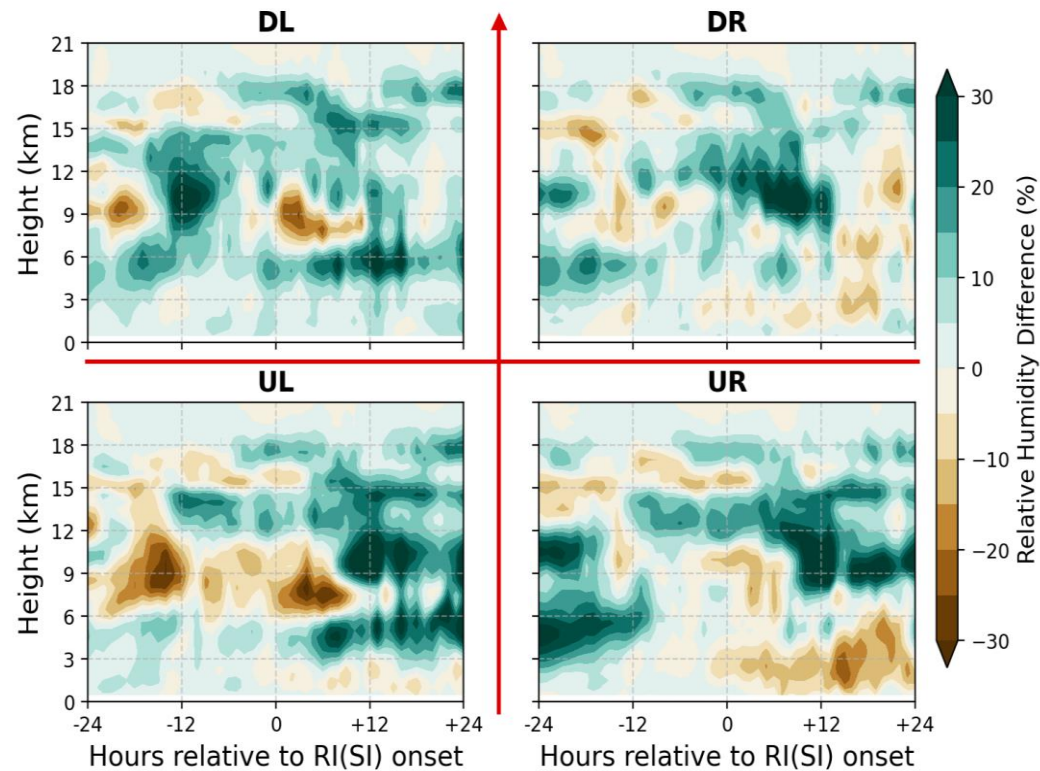
Horizontal advection

qv_H_{ADV} (shading)
 qv rate of change (line contours)



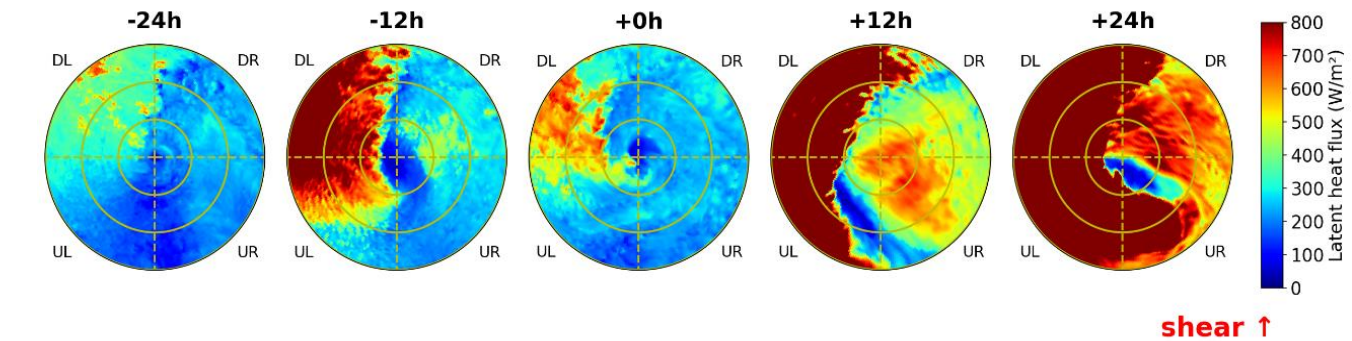
Time – Height profile

RH Difference (SURIGAE - BAILU)

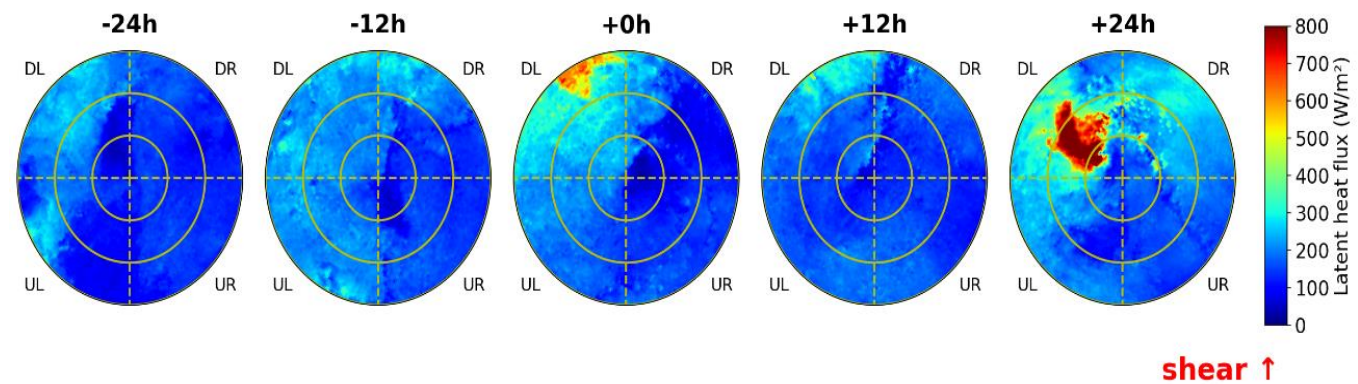


Surface Latent Heat Flux

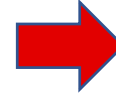
SURIGA : Latent Heat Flux



BAILU : Latent Heat Flux



Simulated
latent heating



Observed
Ice water path
Rain water path

- The SSMIS composite analysis indicates that **the earliest differences in IWP/RWP within 3RMW between RI and SI TCs occur in the Upshear Region.**
- Higher IWP and RWP are mainly distributed in the **DL quadrant** before intensification. As RI/SI begins, **RI TCs have an increase in IWP and RWP in the UL quadrant.** In contrast, **SI TCs do not show upshear enhancement.**

Concluding Remarks

Surigae (RI)

Strong horizontal & vertical moisture transport

Upshear moistening

Upshear deep convection

Symmetric latent heating

Bailu (SI)

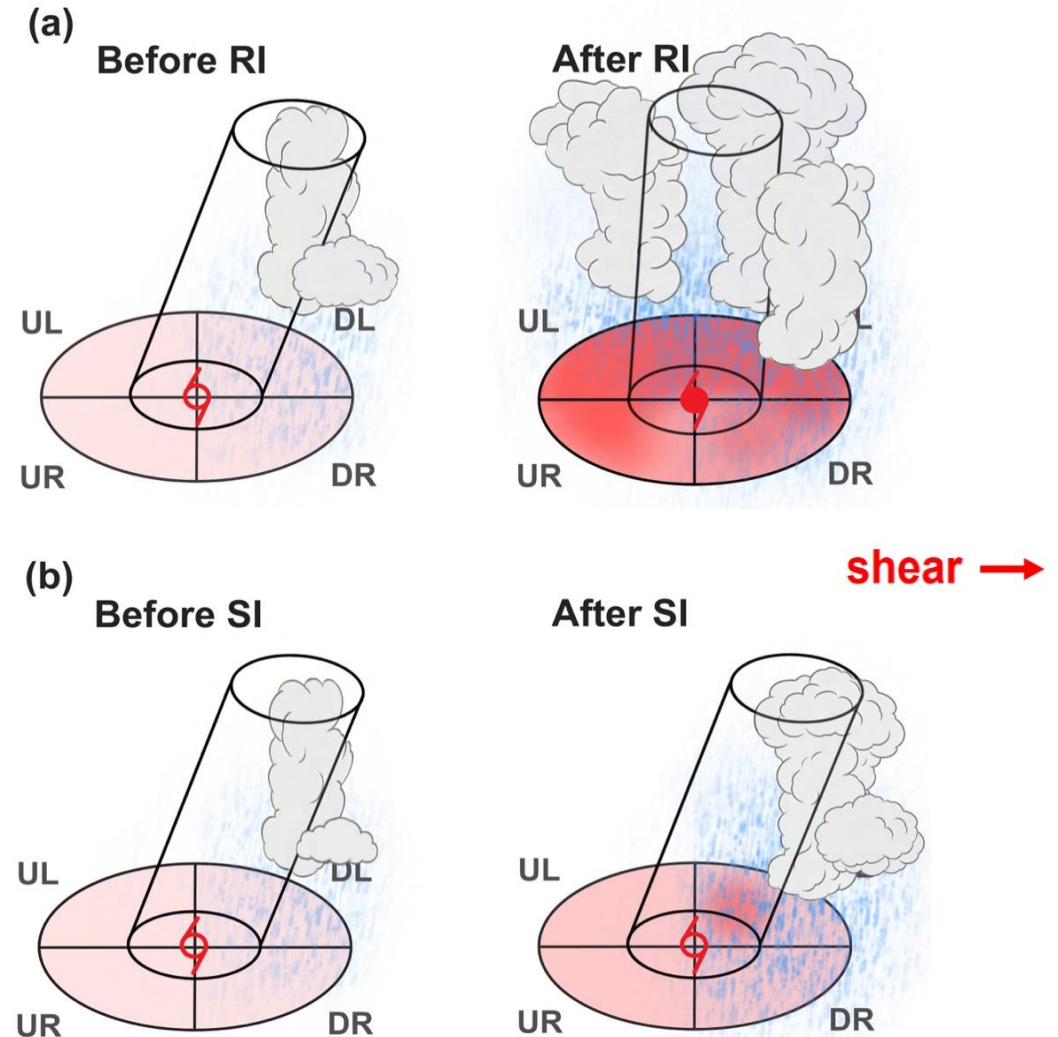
Weak moisture transport

Limited upshear moistening

Downshear-confined convection

Asymmetric latent heating

Conceptual Model



Open and filled TC symbols denote weak and moderate-to-intense typhoons.
Red shading represents the relative magnitude of surface latent heat flux.



Thanks for your attention!

Ming-Jen Yang 楊明仁
mingjenyang@ntu.edu.tw

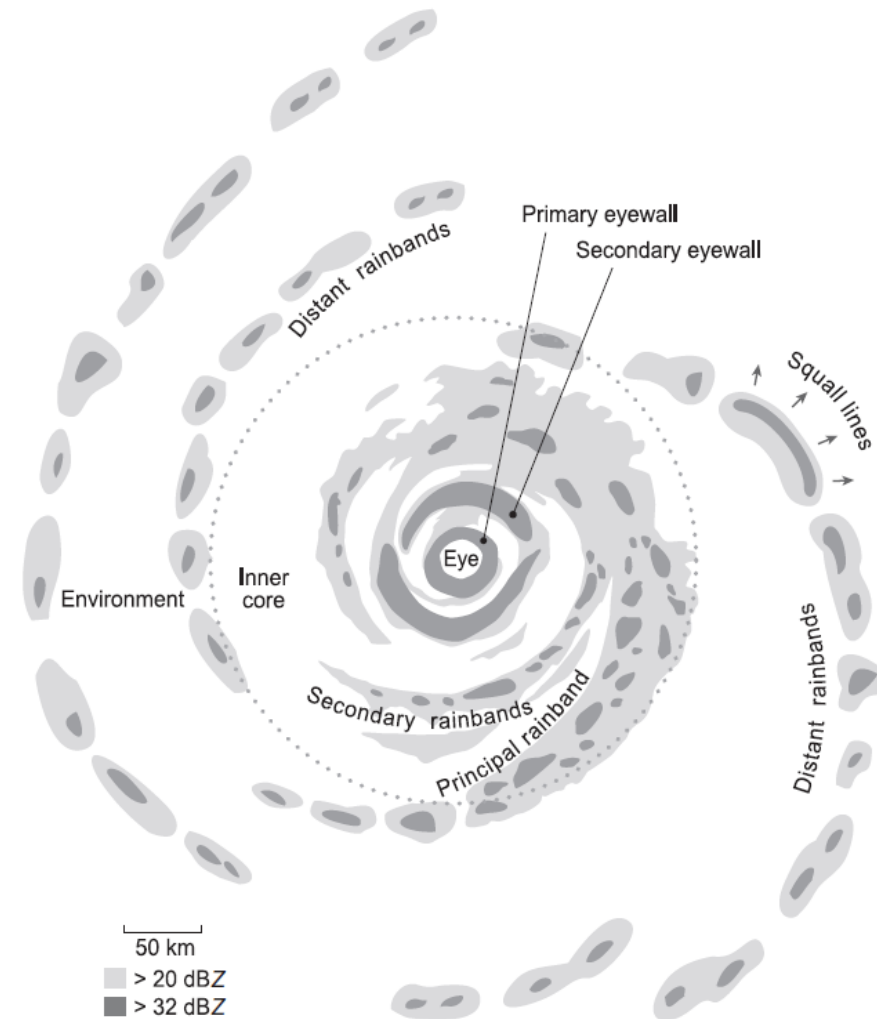


FIGURE 10.30 Schematic illustration of radar reflectivity in a Northern Hemisphere tropical cyclone with a double eyewall. From Houze (2010). Republished with permission of the American Meteorological Society.