TENTATIVE PROGRAMME FOR
ESCAP/WMO TYPHOON COMMITTEE ROVING SEMINAR 2023

Current estimation, understanding, and forecast of landfalling tropical cyclone rainfall

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Thanks for the invitation from ESCAP/WMO Typhoon Committee and the host of Viet Nam Meteorological and Hydrological Administration.

Outline

- Current estimation of tropical cyclone rainfall
- Factors impacting TC rainfall during landfall
- Forecast of landfalling TC rainfall
- Summary

Current estimation of tropical cyclone rainfall

Motivation

- **Why we care about the TC rainfall estimates**
  - **Accurate estimates of precipitation at both high temporal and spatial resolutions are required for many applications** (model verification, initialization, rainfall forecast, et al.)
  - **Though there have kinds of rain data sources, satellite rain data have high resolution, wide area-coverage and are widely used.**

→ gauge rain data (limited resolution, and only on land)

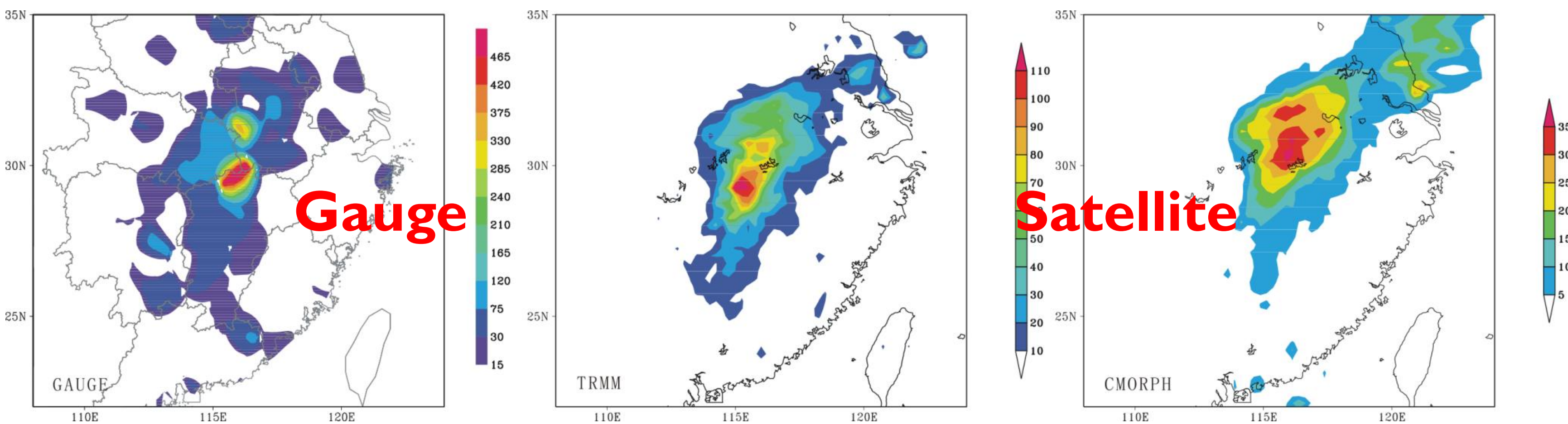
→ Radar retrieved rain data(limited space coverage)

→ Satellite-radar-gauge merged rain data (generally over land)

  - **How good are the satellite rain data performances for landfalling TCs**

Motivation

- **The issue we cares**
  - **How are satellite rain estimates doing for TC-related precipitation?**
  - **How about their performances at hourly and daily scales?**



Overview of rain data

- Satellite rain data have been used during 4 years (2003 - 2006)
  - TRMM 3B42 rain data (NOAA, 0.25º, 3h)
  - CMORPH rain data (CPC/NOAA, 0.25º, 3h)
  - GMS5 IR1 TBB retrieved rain data (GMS5-TBB data, Shanghai Typhoon Institute/CMA, 0.05º, 1h)
- Rain gauge data (Shanghai Typhoon Institute/CMA)

Yu et al., JAMC (2009)

TS, ETS, CC for 24-h rainfall

		1mm	10mm	25mm	50mm	100mm
TRMM-3B42	TS	0.59	0.33	0.13	0.03	0
	ETS	0.33	0.23	0.11	0.03	0
	CC			0.66		
CMORPH	TS	0.56	0.25	0.07	0.01	0
	ETS	0.29	0.16	0.06	0.01	0
	CC			0.60		
GMS5-TBB	TS	0.62	0.47	0.35	0.27	0.17
	ETS	0.24	0.24	0.23	0.21	0.15
	CC			0.51		

PS： Correlation Coefficient (CC)

Hits, Bias, RMSE for 24-h rainfall

	TRMM-3B42			CMORPH			GMS5-TBB		
	Hits	Bias	RMSE	Hits	Bias	RMSE	Hits	Bias	RMSE
0-1 mm	8221 (39.2%)	1.1	3.3	7720 (34.3%)	1.0	2.9	10795 (47.9%)	8.3	20.8
1-10 mm	2464 (10.9%)	-1.3	4.8	1826 (8.1%)	-1.9	4.3	6029 (26.8%)	12.3	25.9
10-25 mm	504 (2.2%)	-10.6	12.7	259 (1.2%)	-11.7	13.2	2934 (13.0%)	10.5	31.1
25-50 mm	58 (0.26%)	-25.7	27.4	14 (0.06%)	-27.7	29.0	1147 (5.1%)	3.6	35.2
> 50 mm	1 (0.004%)	-74.2	86.5	0 (0%)	-79.2	91.6	213 (0.9%)	-29.7	63.2

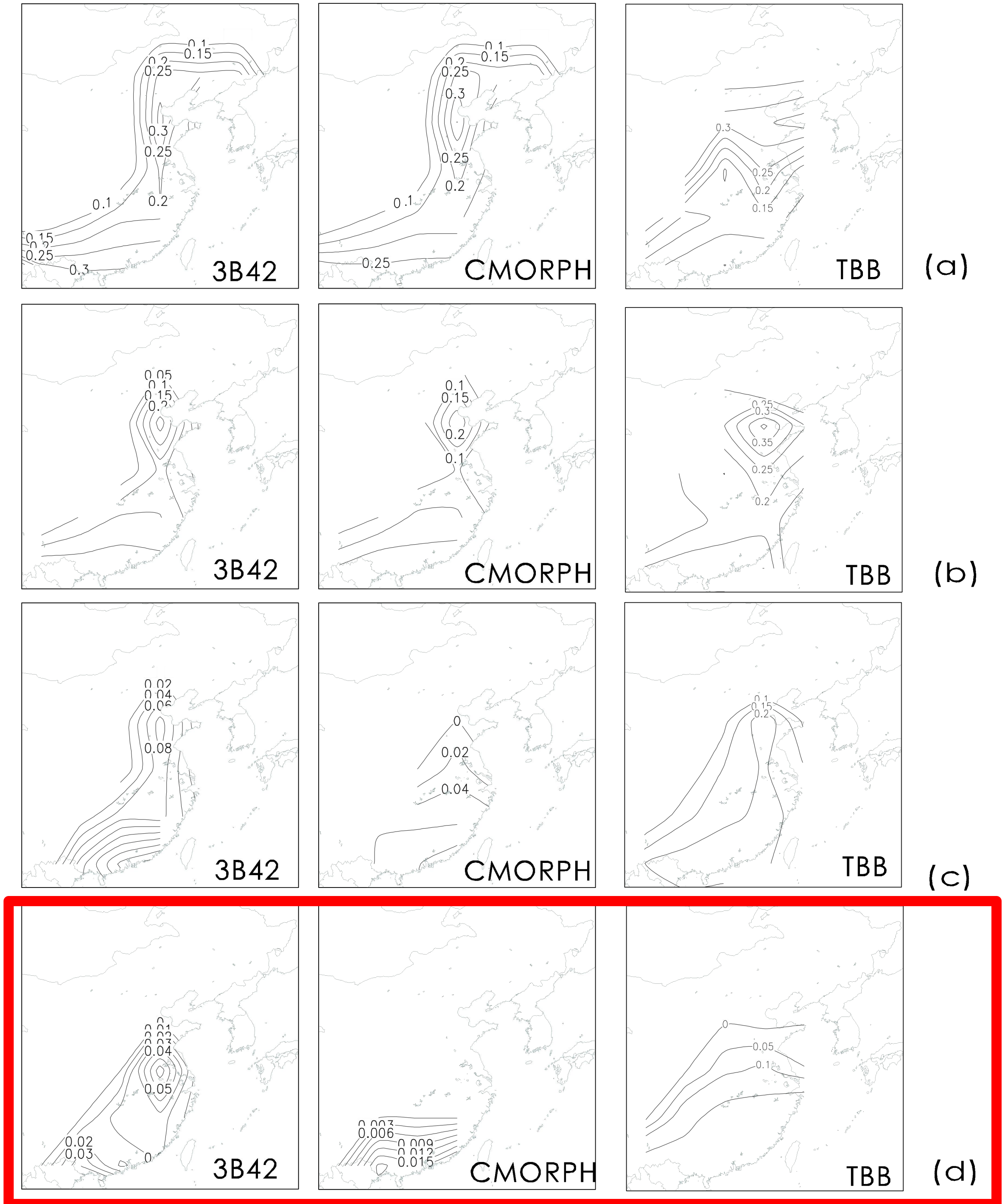


Fig. ETS for 3B42, CMORPH, and GMS5-TBB 24-h rain data for (a) 1, (b) 10, (c) 25, and (d) 50 mm.

Fig. TS for 3B42 and GMS5-TBB 24-h rain data and their TS differences (DIFF) for (a) 1, (b) 10, (c) 25, (d) 50, and (e) 100 mm.

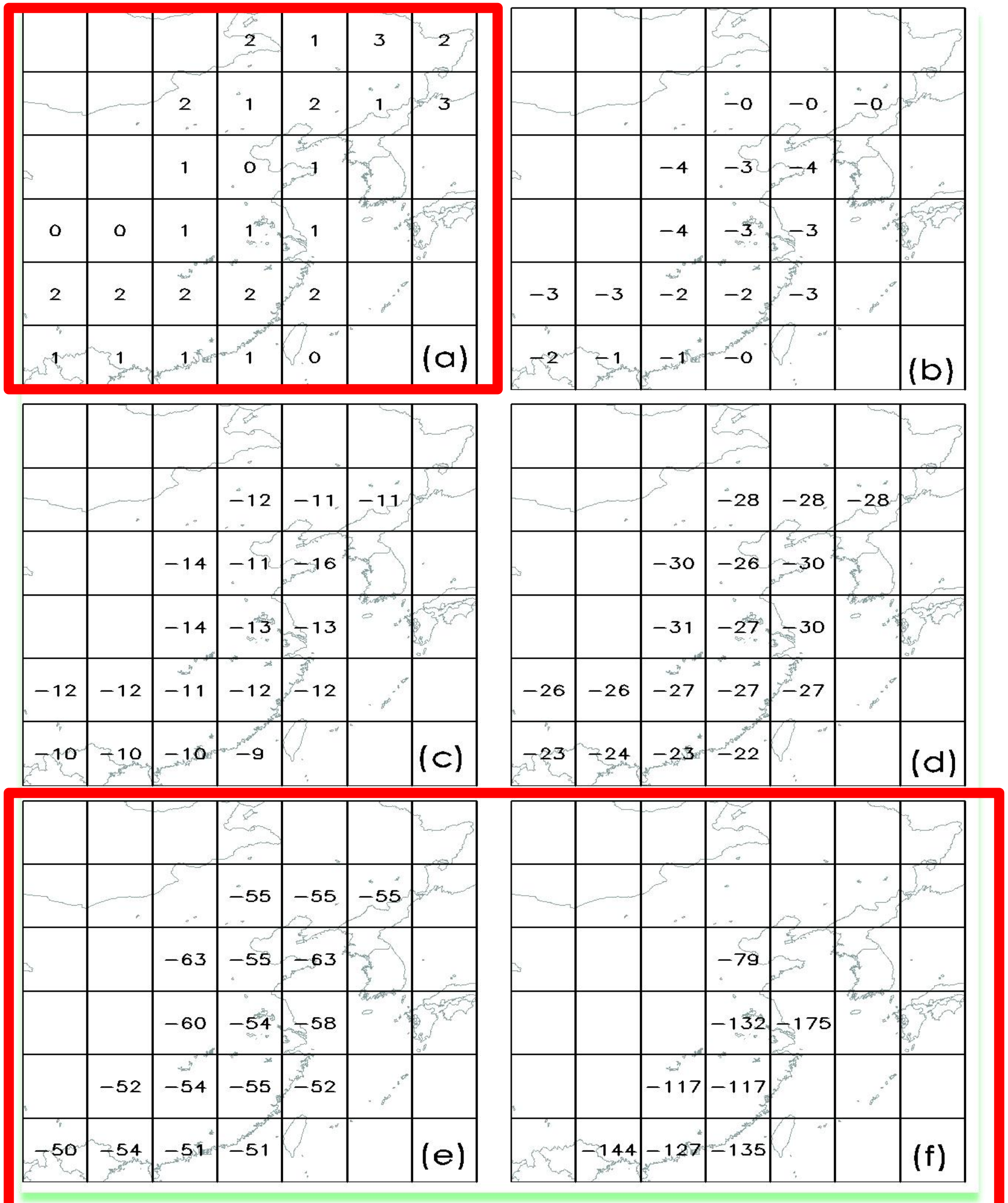
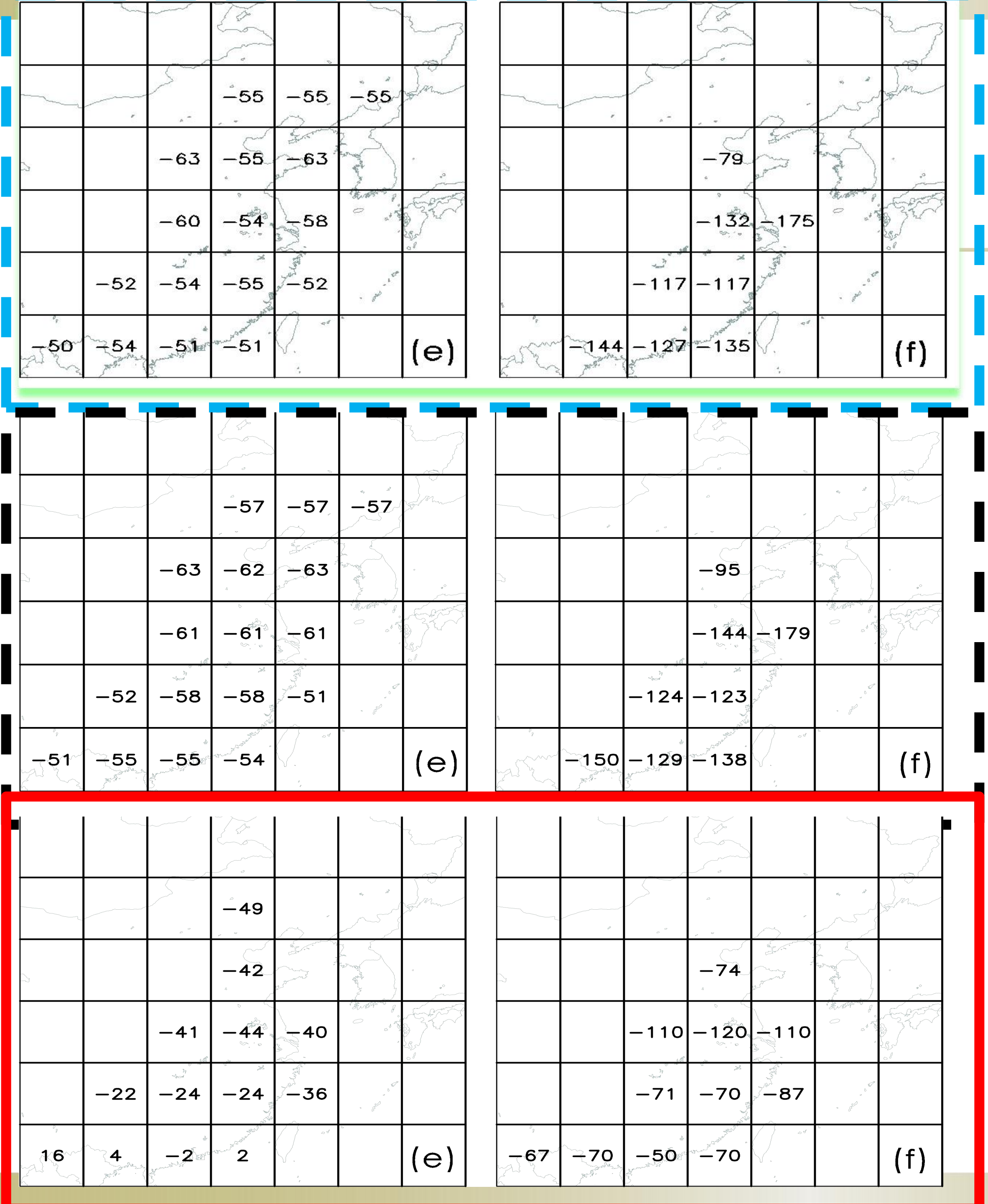


FIG. **Mean bias for 24-h 3B42 rain dataset (mm)** for (a) 0–1, (b) 1–10, (c) 10–25, (d) 25–50, (e) 50–100, and (f) >100 mm.

Mean bias for (e) 50–100, and (f) >100 mm



→ For TRMM 3B42

→ For CMORPH

→ For GMS5-TBB

TS, ETS, CC for 6-h rainfall

		1mm	10mm	25mm	50mm	100mm
TRMM-3B42	TS	0.35	0.12	0.03	0.01	0
	ETS	0.30	0.11	0.03	0.01	0
	CC	0.38				
CMORPH	TS	0.30	0.06	0.01	0	0
	ETS	0.24	0.06	0.01	0	0
	CC	0.43				
GMS5-TBB	TS	0.27	0.18	0.12	0.07	0
	ETS	0.19	0.15	0.12	0.07	0
	CC	0.37				

Conclusions

- Overall, the TRMM 3B42, CMORPH and GMS-TBB rain data give quite reasonable 6-h and 24-h rainfall distributions, but with skills decreasing with the increase in both latitude and rainfall amount.
- Both 3B42 and CMORPH considerably underestimate the moderate and heavy rainfall and overestimate the very light precipitation.
- For the heavy rainfall events, the GMS5-TBB data perform much better than the 3B42 and CMORPH with almost halved bias.
- The three satellite products evaluated in this study are more accurate for the 24-h rainfall estimates than for the 6-h rainfall estimates.
- Some newer satellite precipitation data are emerging and constantly being updated and require continued research

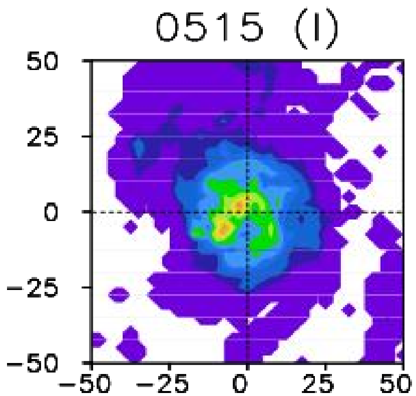
- **References:**

Yu Z., et al., 2009: Verification of Tropical Cyclones-Related Satellite Precipitation Estimates in Mainland China. *Journal of Applied Meteorology and Climatology,* 48, 2227-2241.

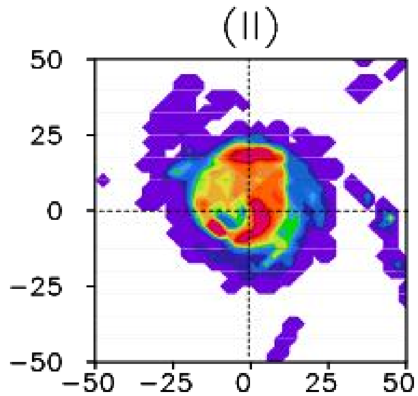
Yue C., et al., 2006: A preliminary study on method of quantitative precipitation estimation (QPE) for landfall typhoon. Scientia Meteorologica Sinica, 26, 17-23. (in Chinese)

Factors impacting TC rainfall during landfall

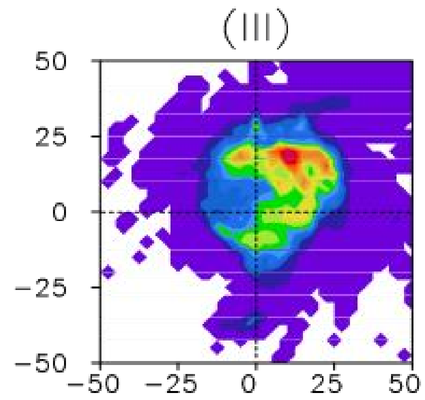
Stages of Tropical Cyclone Rainfall



Before landfall

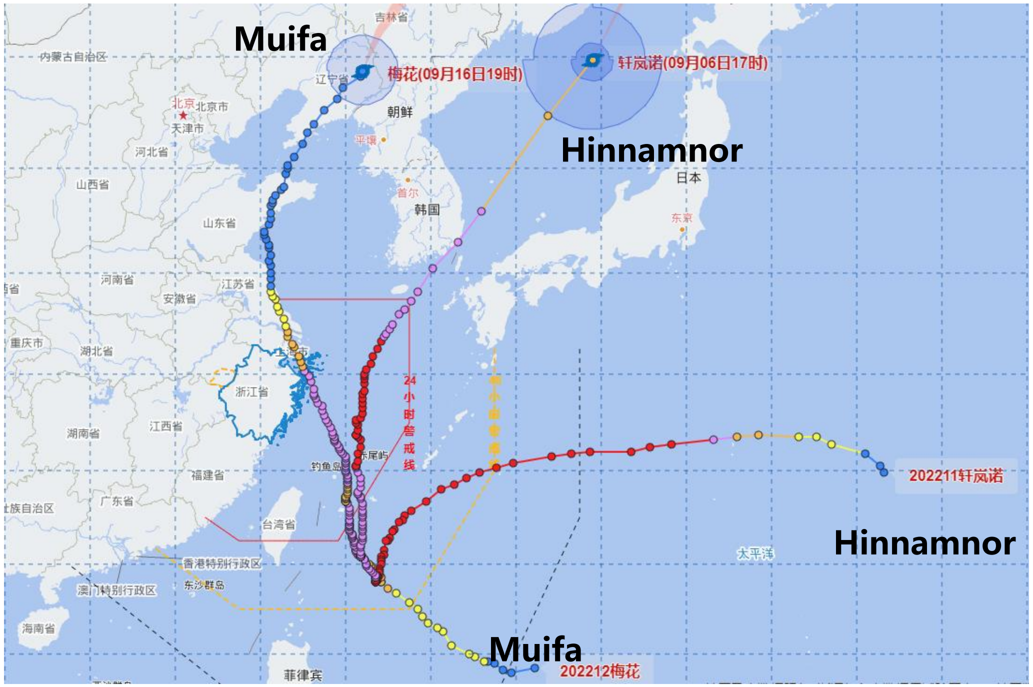


During landfall



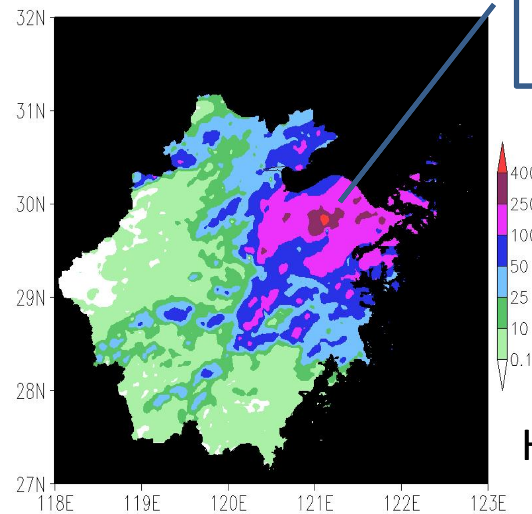
After landfall

Muifa and Hinnamnor in 2022



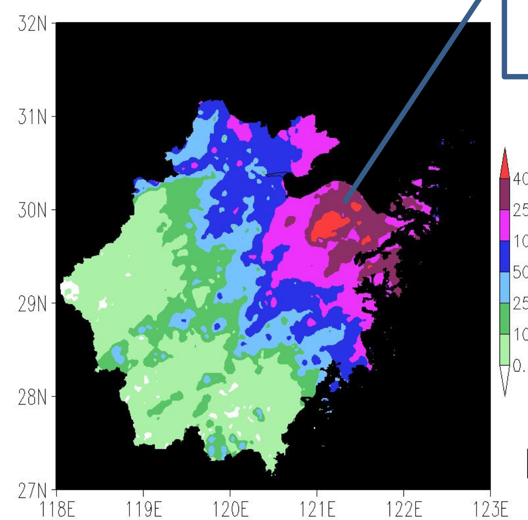
Tracks

Rainfall OBS



Max Rain 475mm

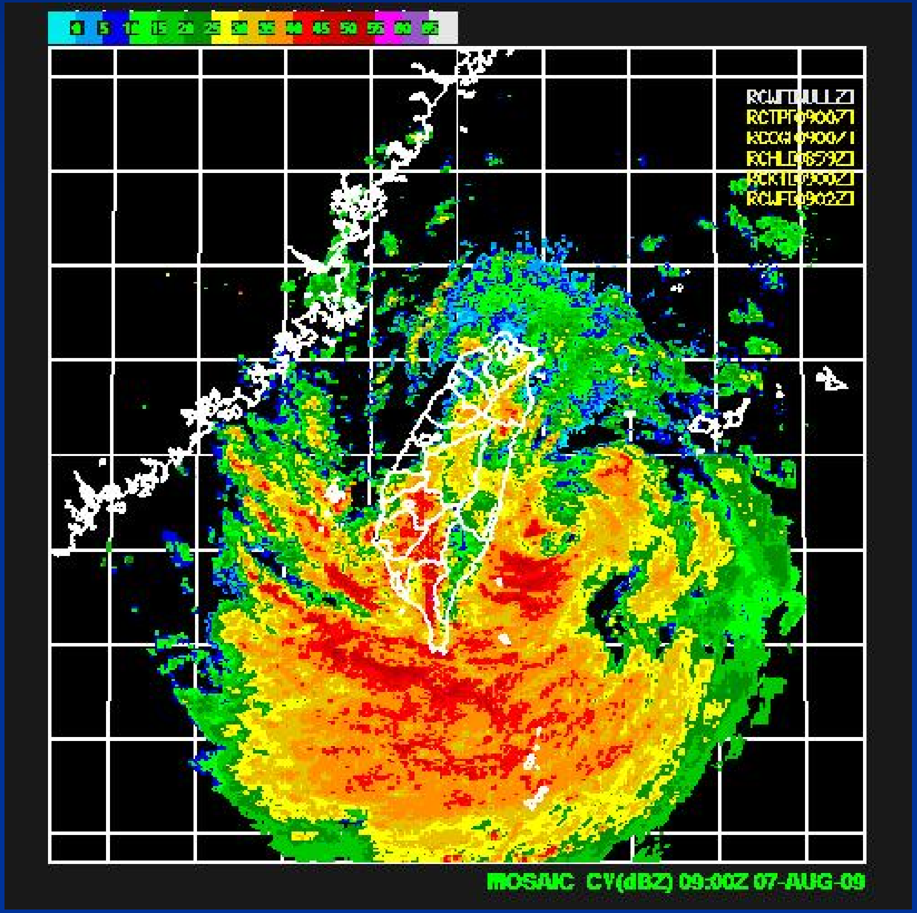
Hinnamnor



Max Rain 707mm

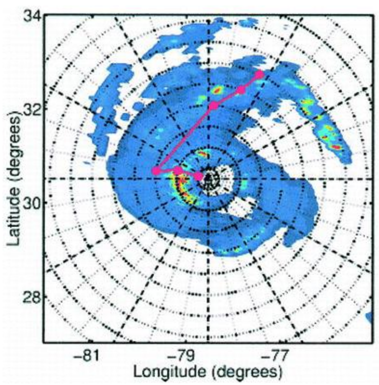
Muifa

Current basic understanding on rainfall distribution of TCs



Factors to impact TC rainfall

- Intensity
- Track (location/direction/speed)
- Large-scale environment/ET
- Vertical wind shear
- TC size
- Topography/land-sea (landfall)



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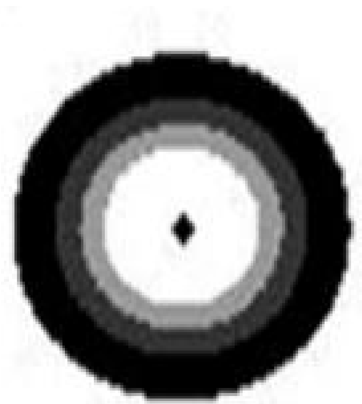

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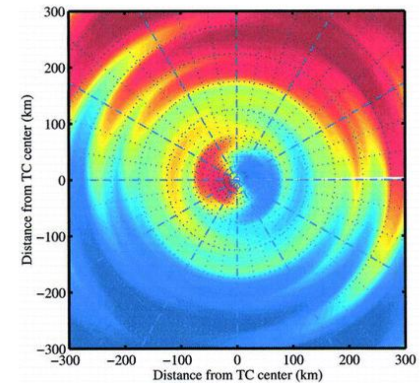


TC rainfall

Axisymmetric

（wavenumber-0）

Asymmetric

（wavenumbers-1, 2, 3, ...）

● Fourier decomposition

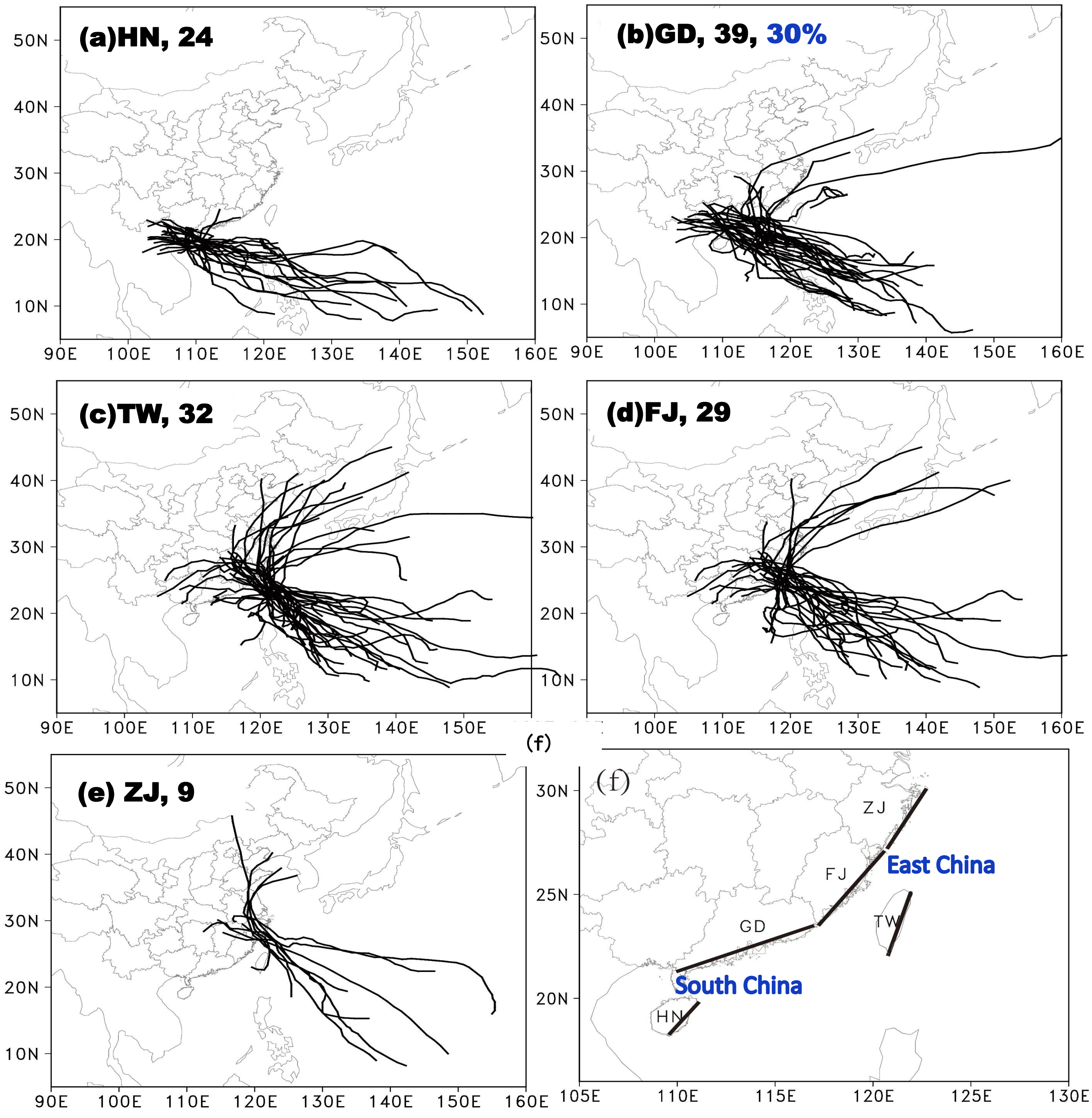
The spatial structure of the first-order asymmetry ($\mathbf{M_1}$) can be represented by

$$M_1 = [a_1 cos(\theta) + b_1 sin(\theta)]/R$$

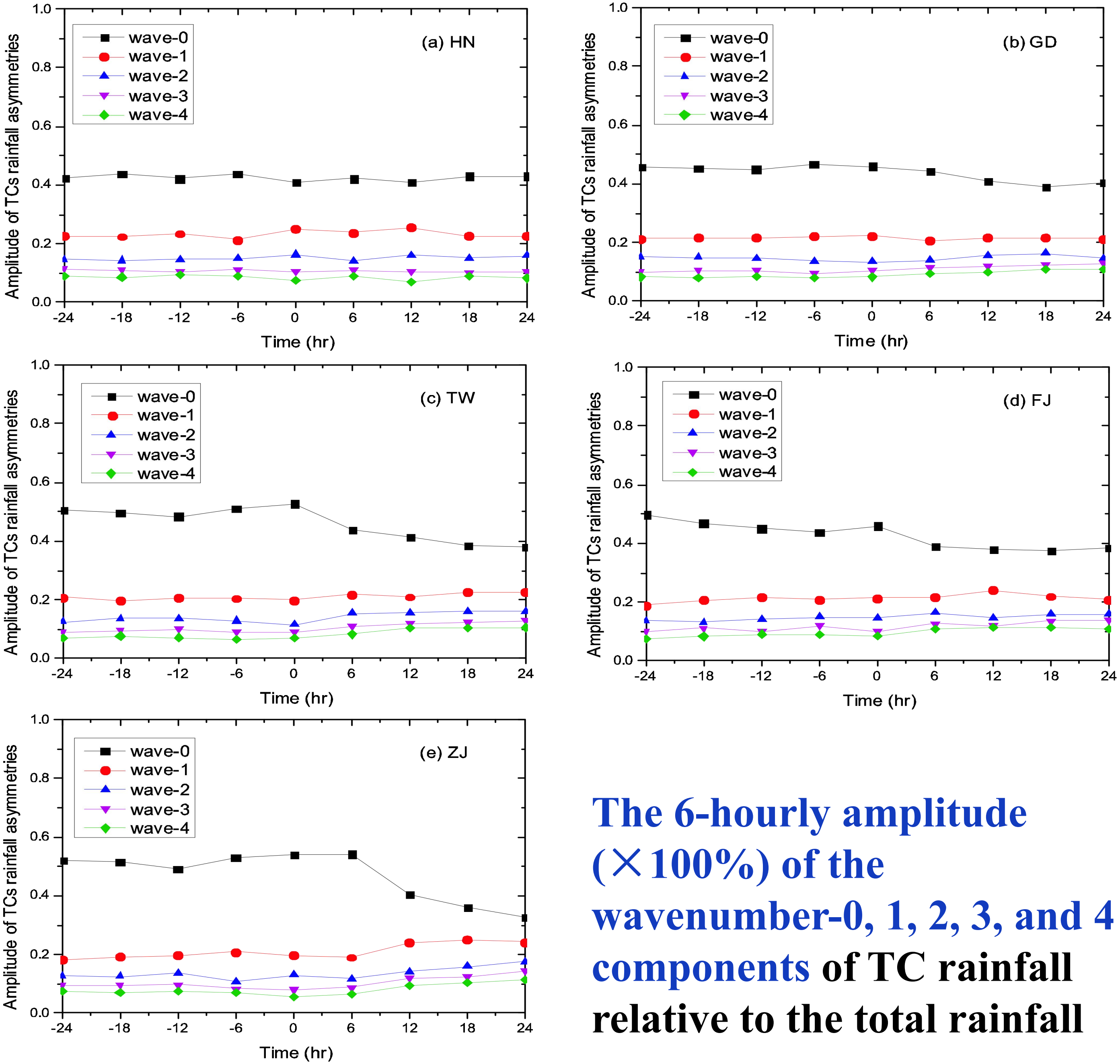
$$a_1 = \sum_i [R_i cos\,(\theta_i)]\,, \qquad b_1 = \sum_i [R_i sin\,(\theta_i)]$$

Yu et al. 2015, 2017

1) Axisymmetric LTC rainfall prior to, after landfall



- 2001-2015
- 133 TCs
- TRMM 3B42

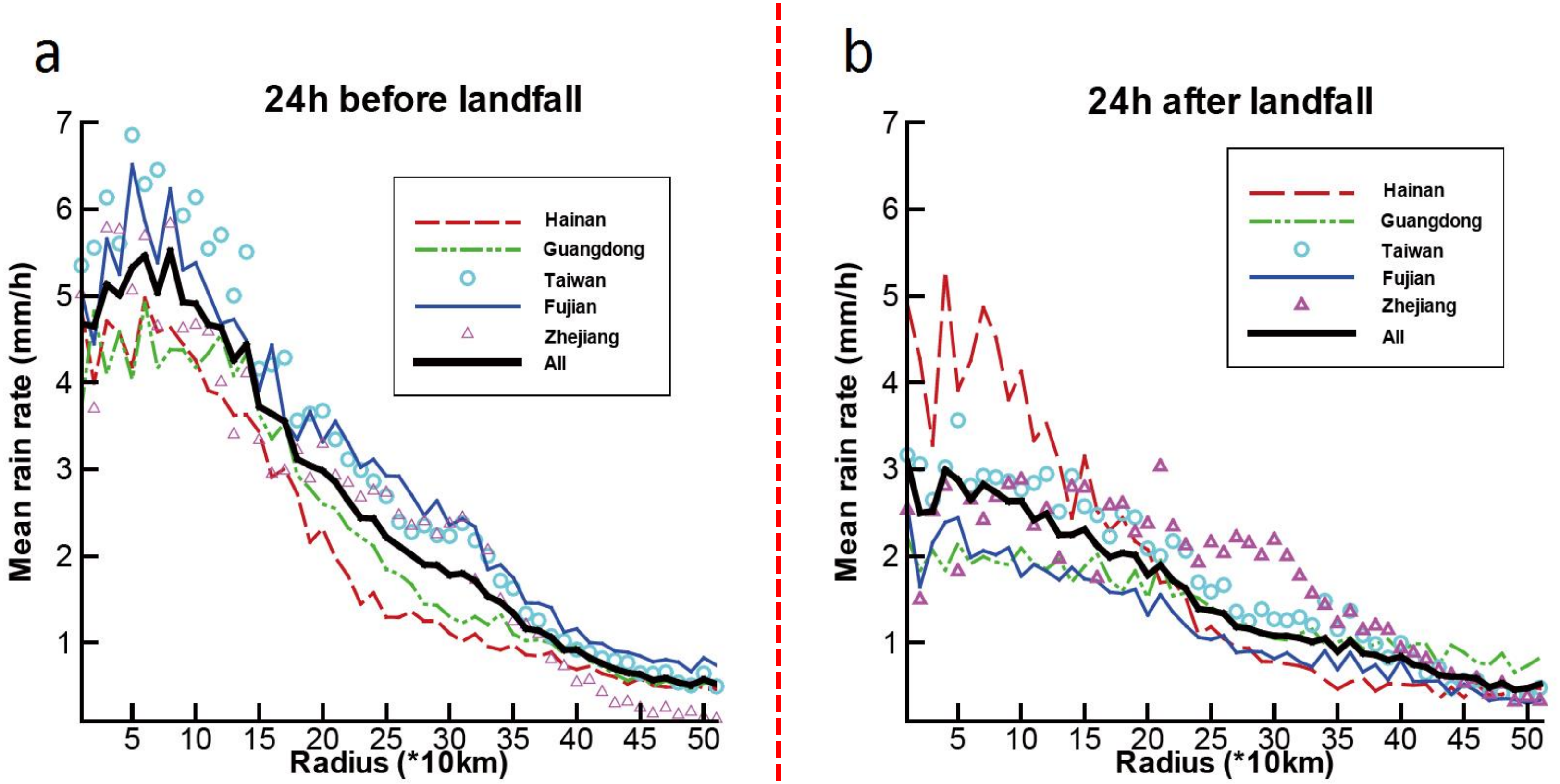


Symmetric : Asymmetric ~ 50% : 50%

WN1 asymmetry: 20%

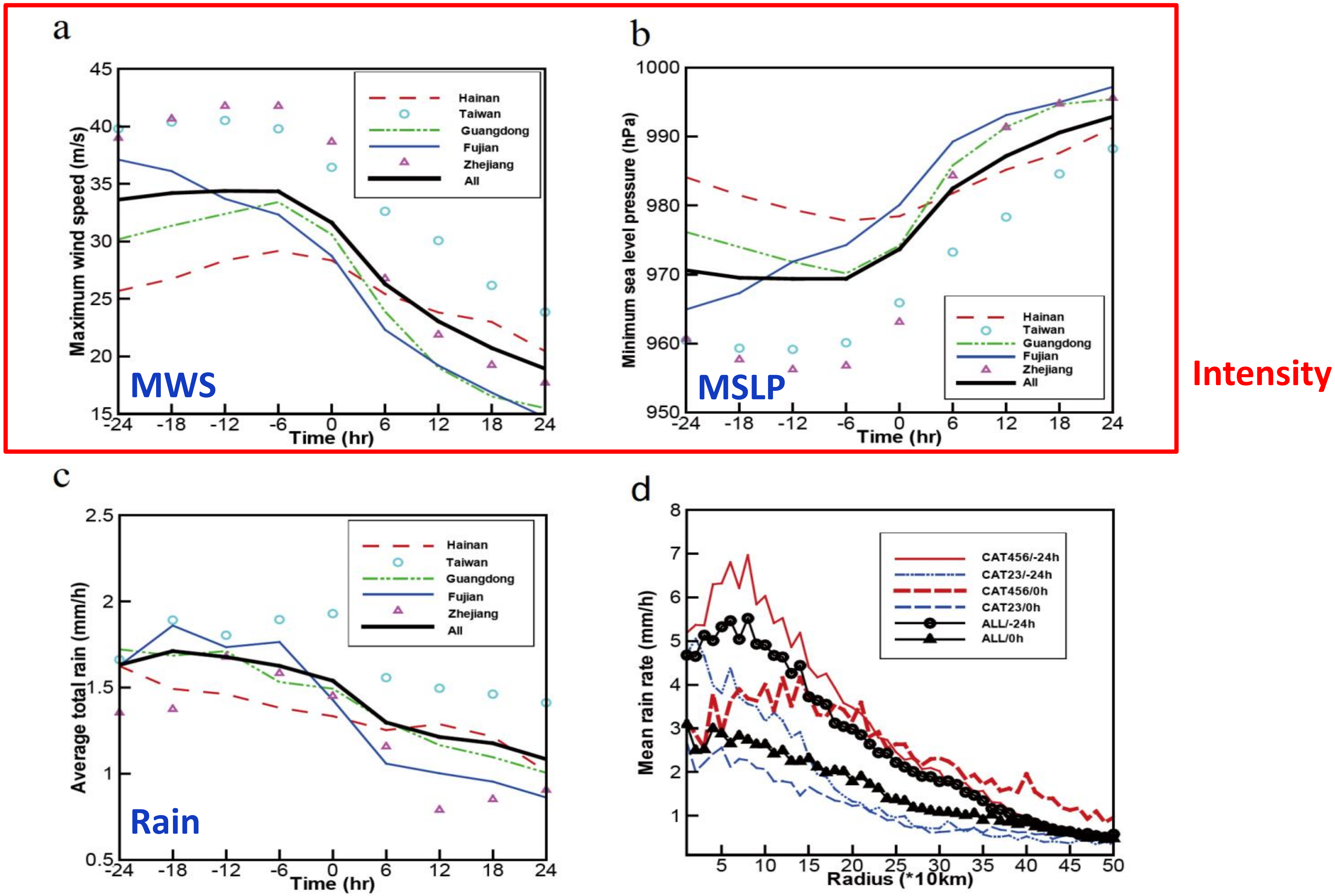
The 6-hourly amplitude (×100%) of the wavenumber-0, 1, 2, 3, and 4 components of TC rainfall relative to the total rainfall

1) Axisymmetric LTC rainfall prior to, after landfall

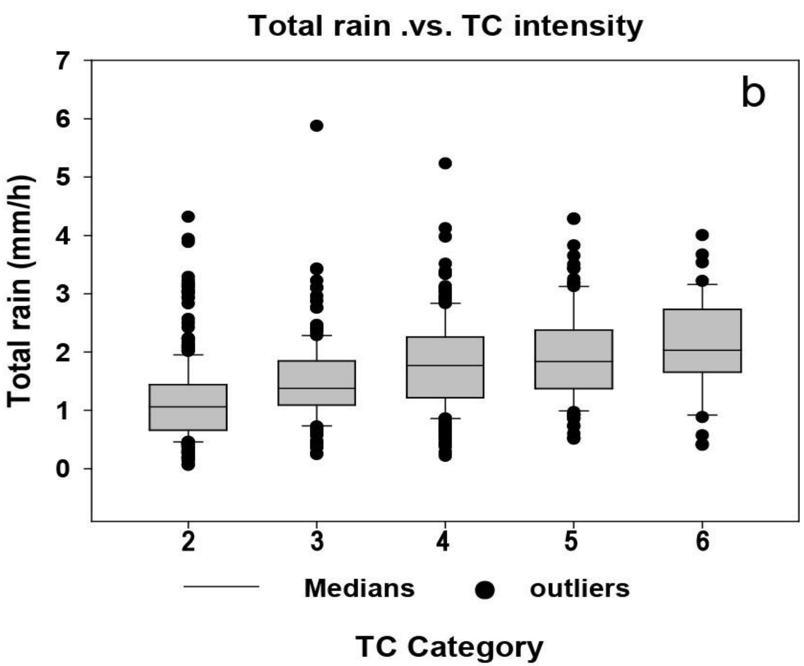


- The **peak axisymmetric rain rate mostly decreases during landfall** **but shifts inward after landfall.**
- **The radial profiles of the azimuthally-averaged rain rate are different** **for TCs making landfall in different regions over China.**

LTC intensity .vs. Rainfall



- TCs of higher intensity have higher peak azimuthal-mean rain rate.



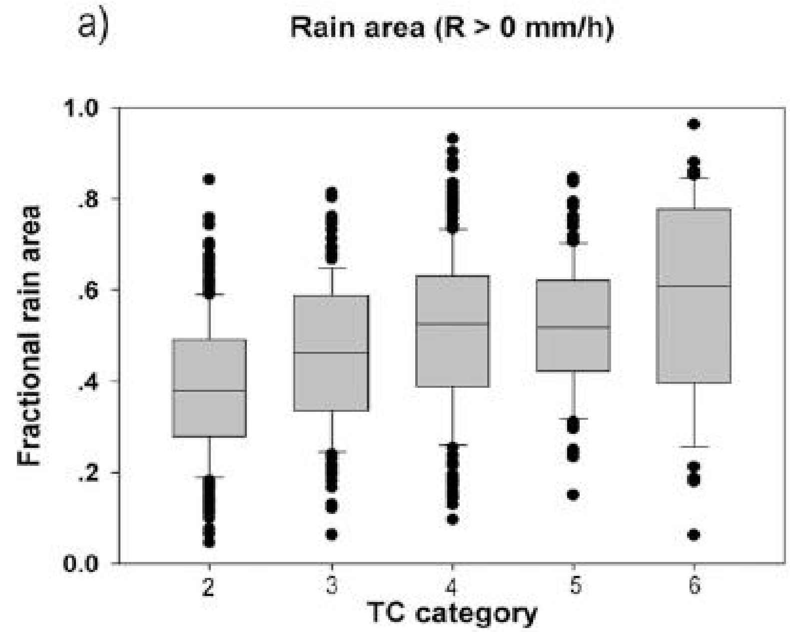
CAT2-TS

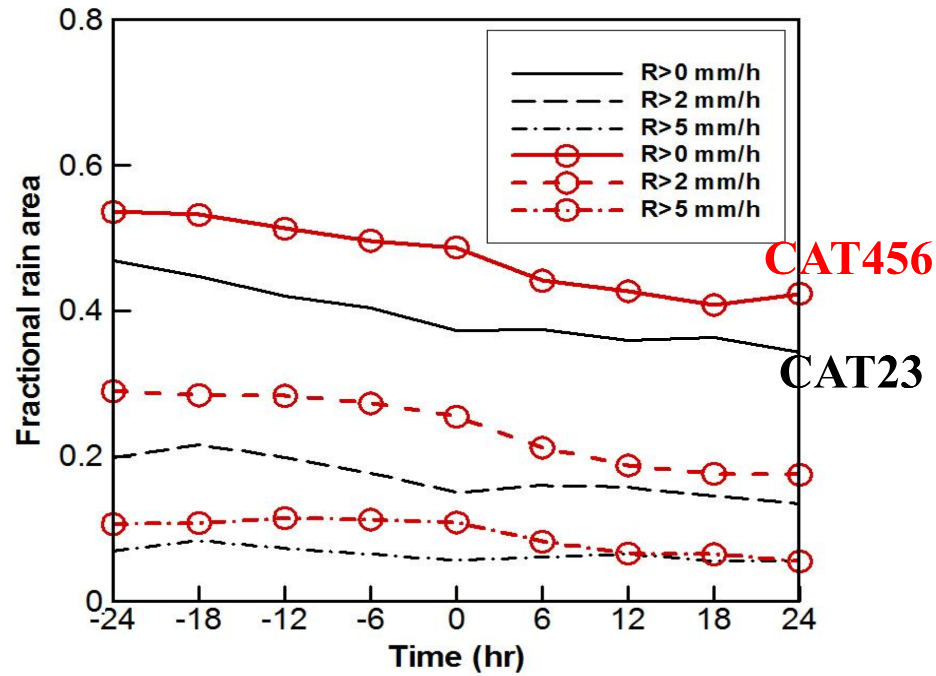
CAT3-STS

CAT4-TY

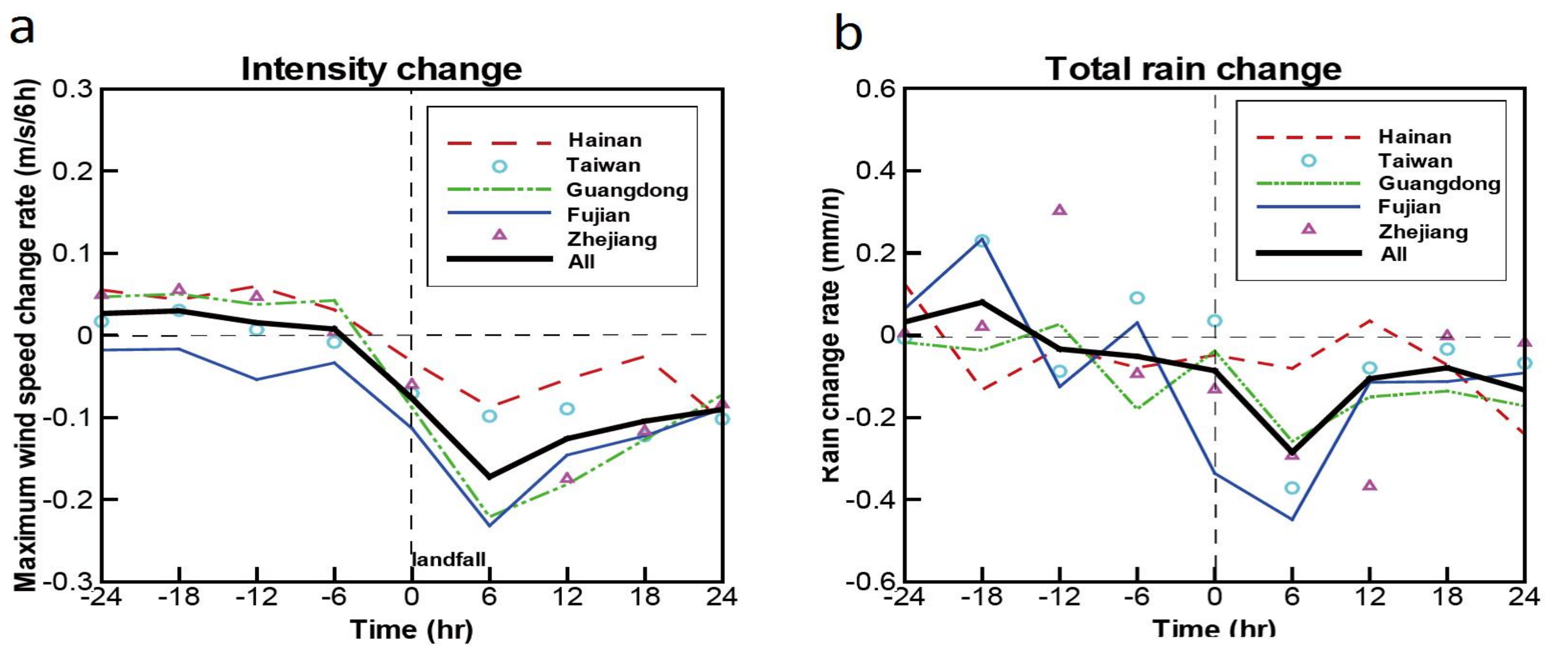
CAT5-STY

CAT6- SuperTY





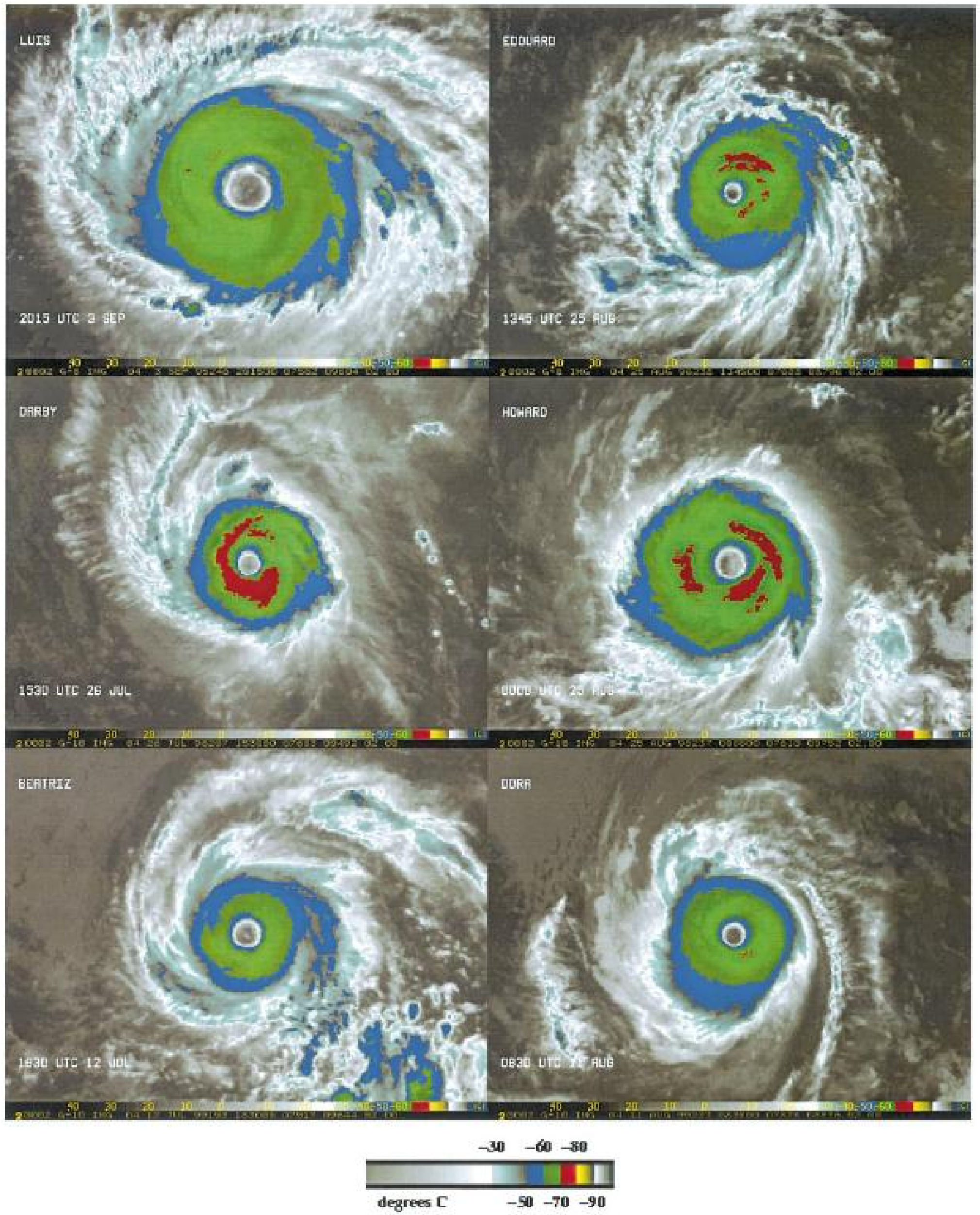
Intensity change .vs. Rain change



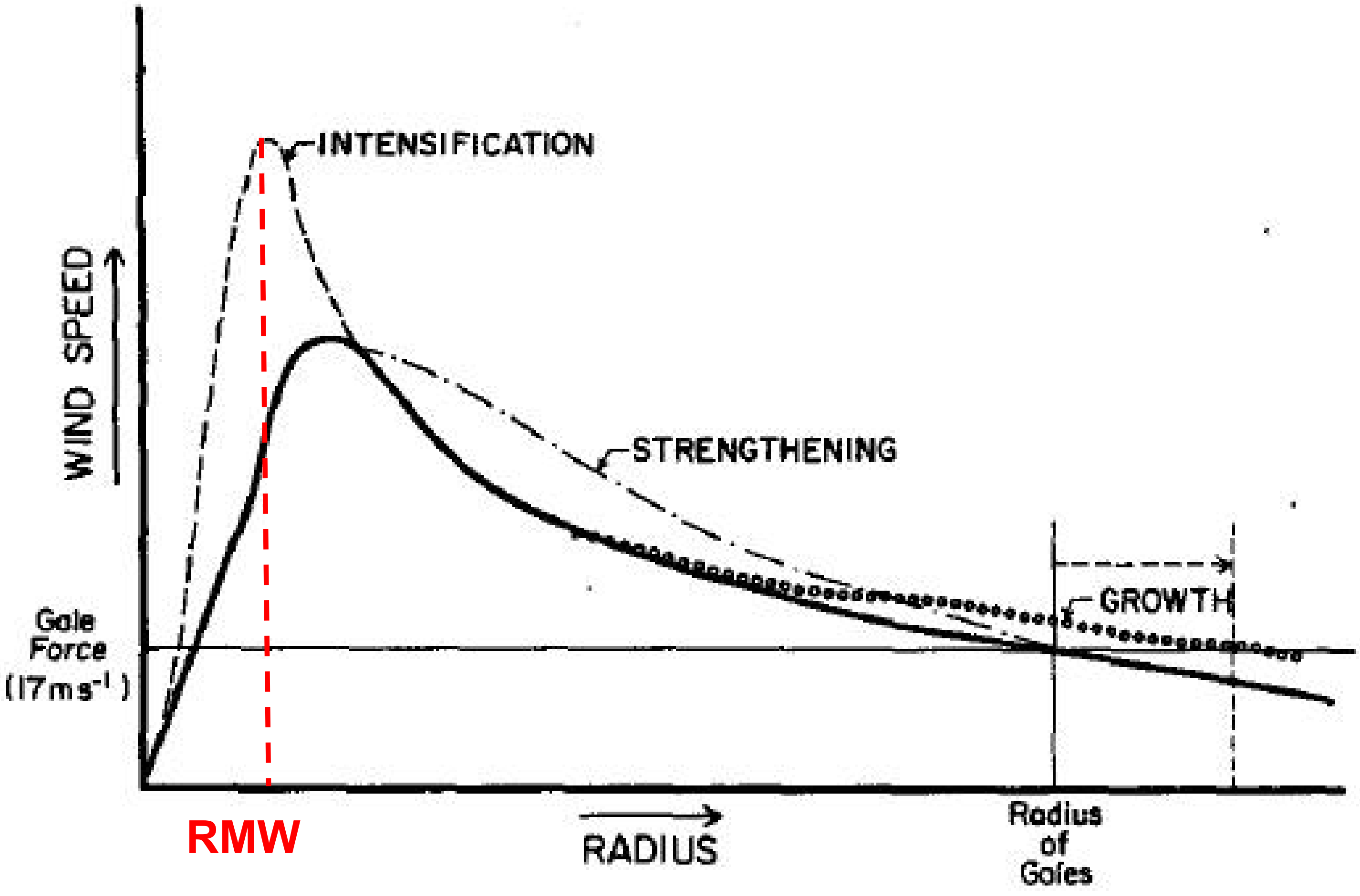
correlation coefficient : 0.77

- **The axisymmetric rainfall change is also closely related with the LTC intensity change.**

Different sized TCs



Knaff et al. 2003

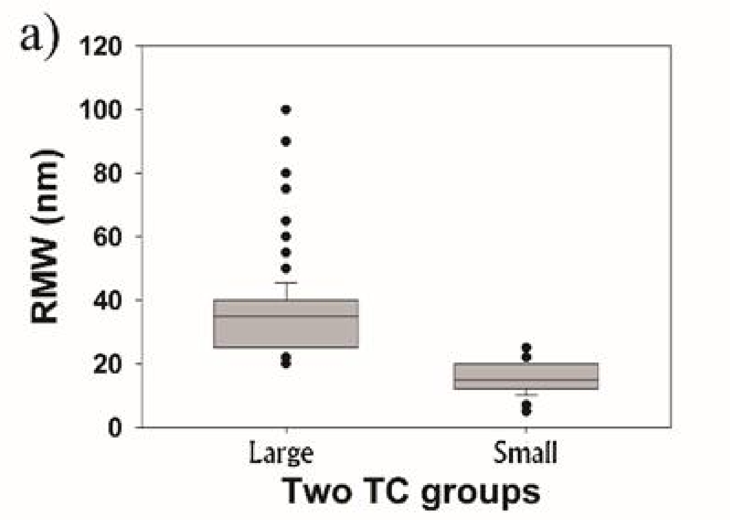


Merrill, 1984

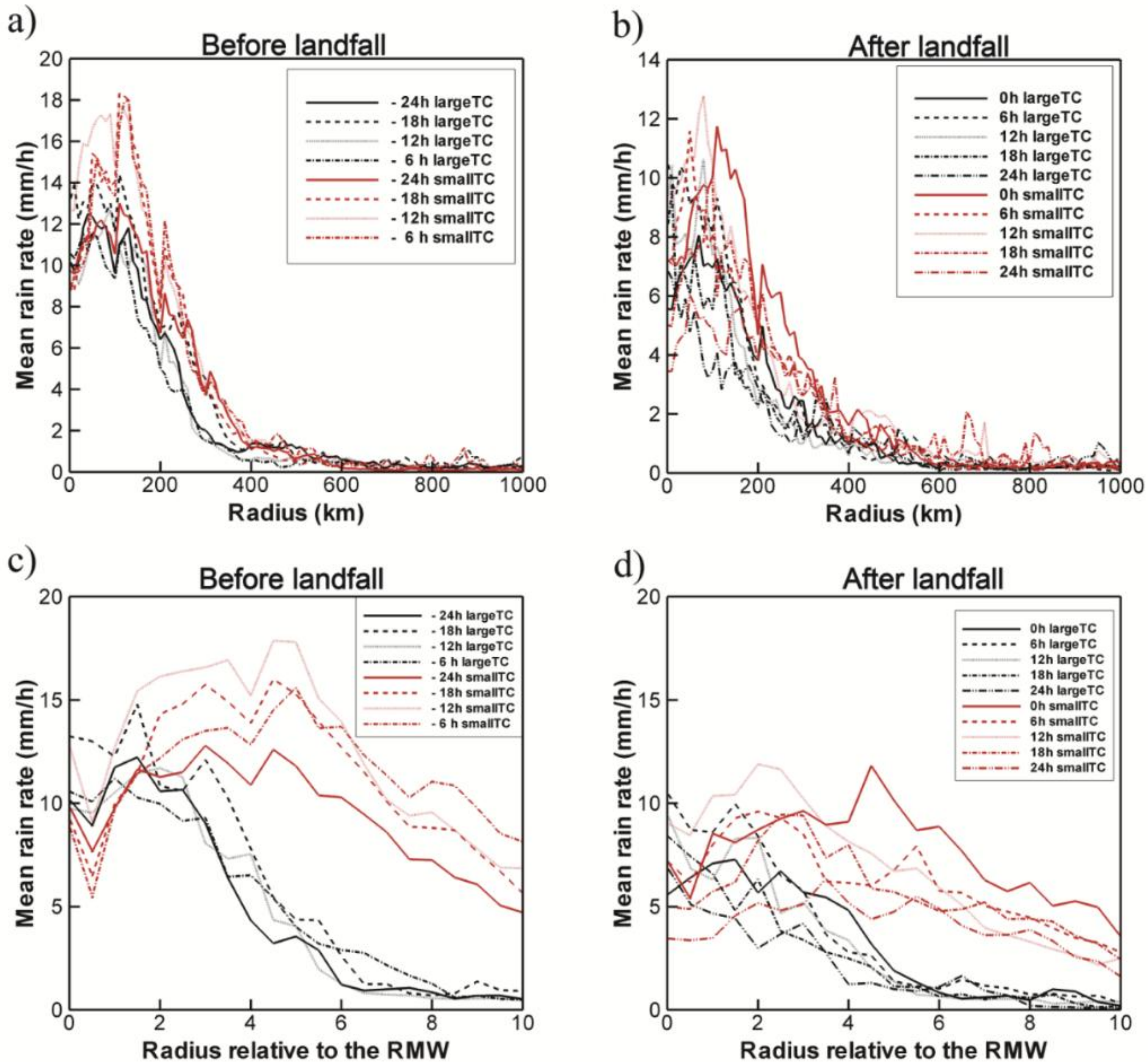
Data and method

- ✓ **Rainfall data（2001-2020）：**

  GPM（0.1° x 0.1°，hourly)
- ✓ **Best track data：6h，STI+JTWC**
- ✓ **168 landfalling TCs in China**
- ✓ **Focus -24h prior to ~ 24h after landfall**



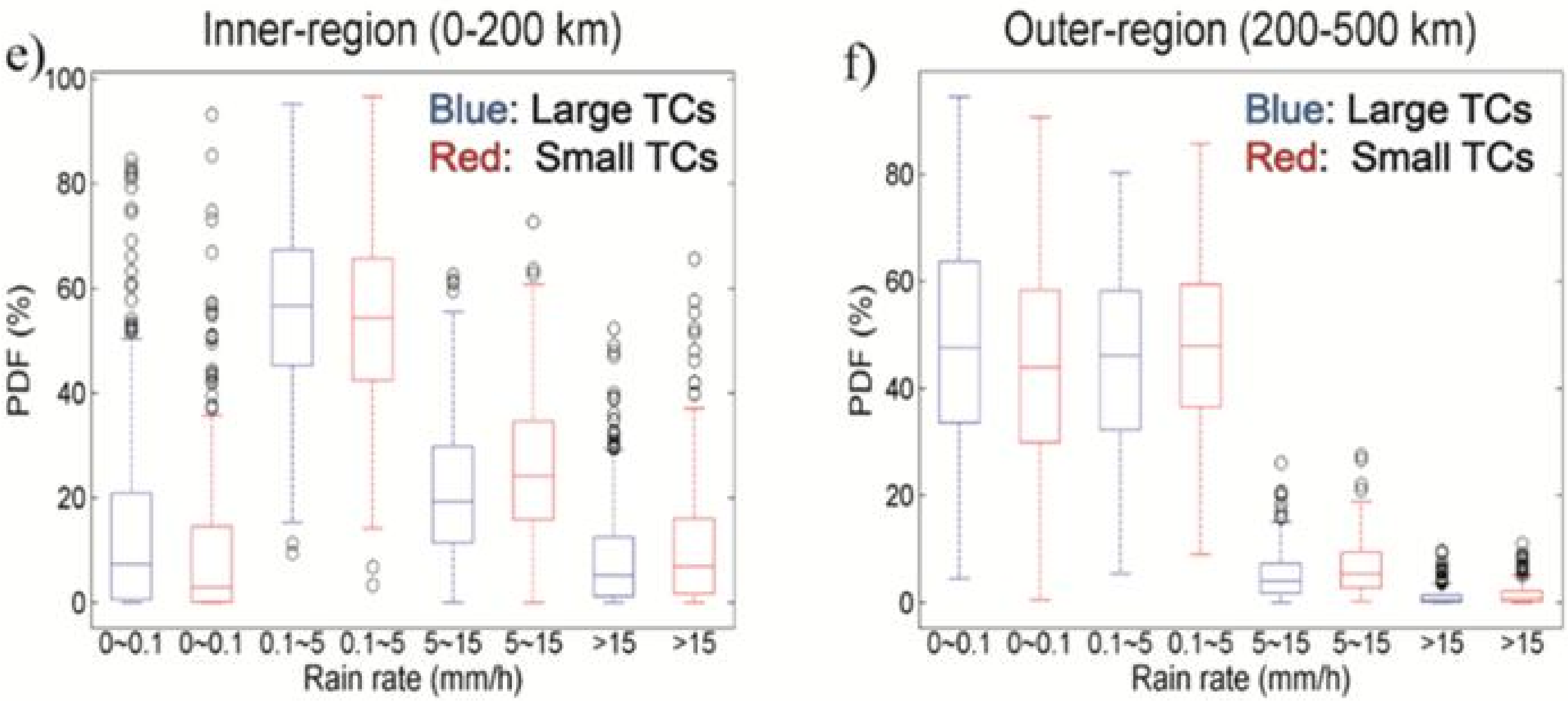
Axisymmetric rainfall evolution for large and small TCs during landfall



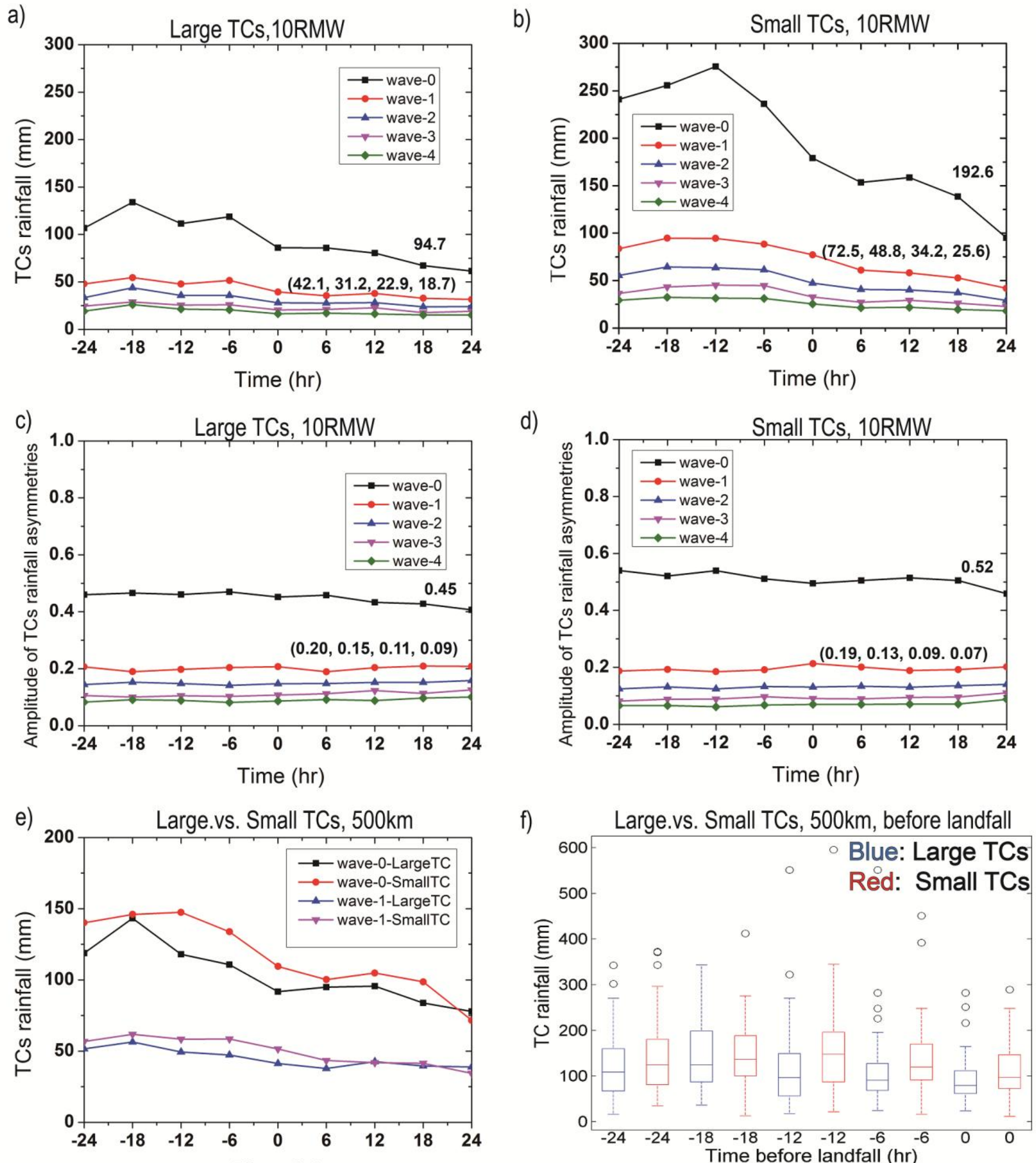
Relative to distance (km)

Relative to RMW

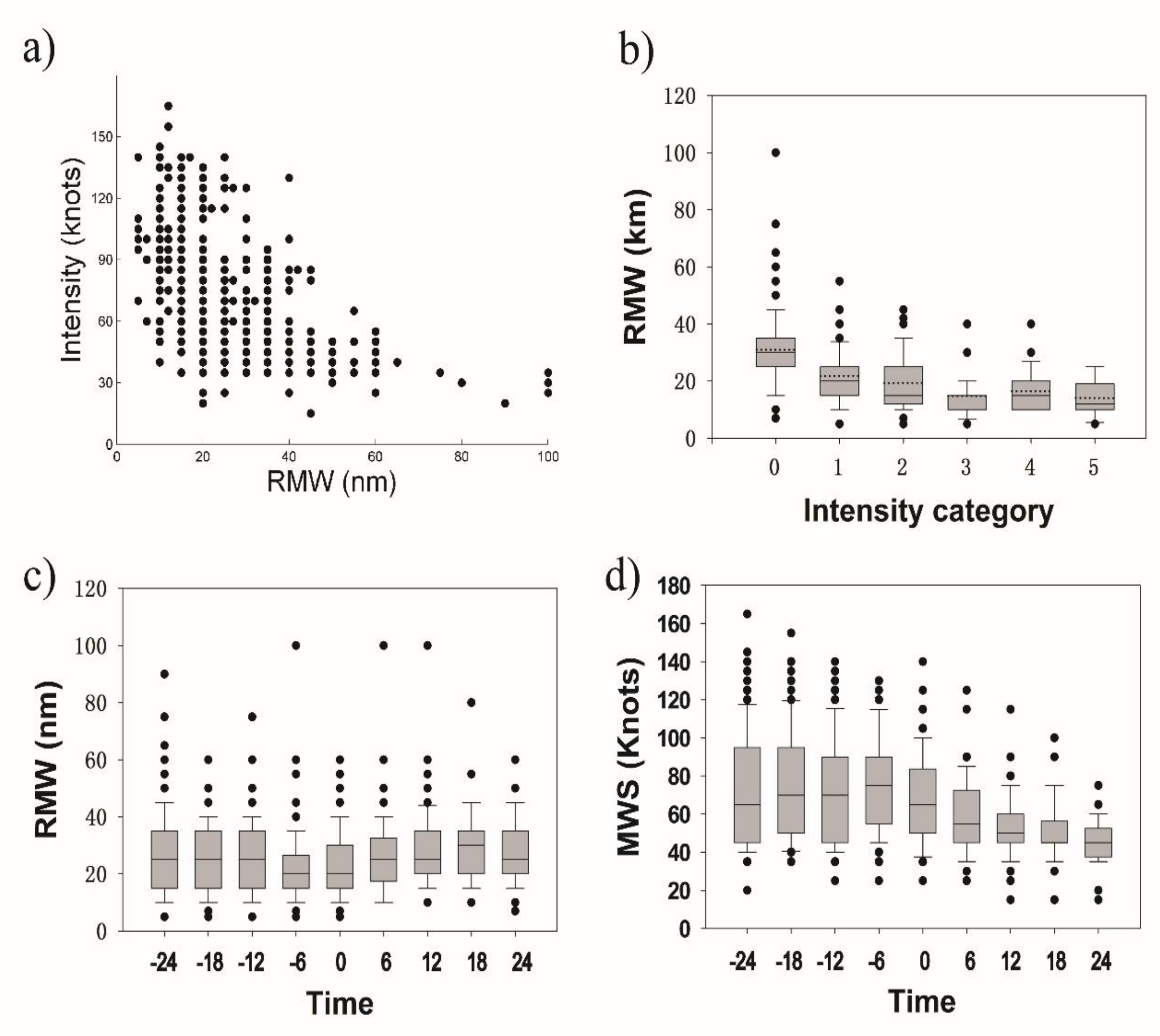
Yu et al., 2022



Inner-region (0-200 km)
e)
Blue: Large TCs
Red: Small TCs
PDF (%)
0
20
40
60
80
100
0~0.1
0~0.1
0.1~5
0.1~5
5~15
5~15
>15
>15
Rain rate (mm/h)
Outer-region (200-500 km)
f)
Blue: Large TCs
Red: Small TCs
PDF (%)
0
20
40
60
80
0~0.1
0~0.1
0.1~5
0.1~5
5~15
5~15
>15
>15
Rain rate (mm/h)

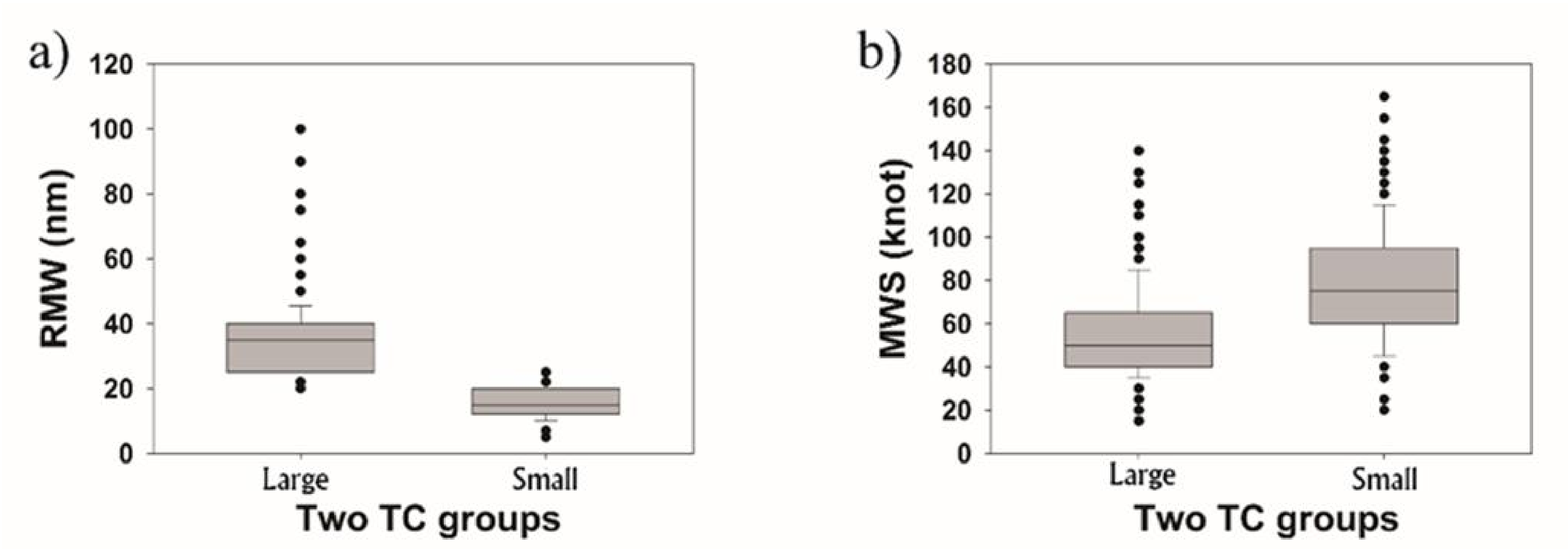

a)
Large TCs,10RMW
TCs rainfall (mm)
Time (hr)
wave-0
wave-1
wave-2
wave-3
wave-4
94.7
(42.1, 31.2, 22.9, 18.7)
b)
Small TCs, 10RMW
TCs rainfall (mm)
Time (hr)
192.6
(72.5, 48.8, 34.2, 25.6)
c)
Large TCs, 10RMW
Amplitude of TCs rainfall asymmetries
Time (hr)
0.45
(0.20, 0.15, 0.11, 0.09)
d)
Small TCs, 10RMW
Amplitude of TCs rainfall asymmetries
Time (hr)
0.52
(0.19, 0.13, 0.09. 0.07)
e)
Large.vs. Small TCs, 500km
TCs rainfall (mm)
Time (hr)
wave-0-LargeTC
wave-0-SmallTC
wave-1-LargeTC
wave-1-SmallTC
f)
Large.vs. Small TCs, 500km, before landfall
TC rainfall (mm)
Time before landfall (hr)
Blue: Large TCs
Red: Small TCs

Yu et al., 2022

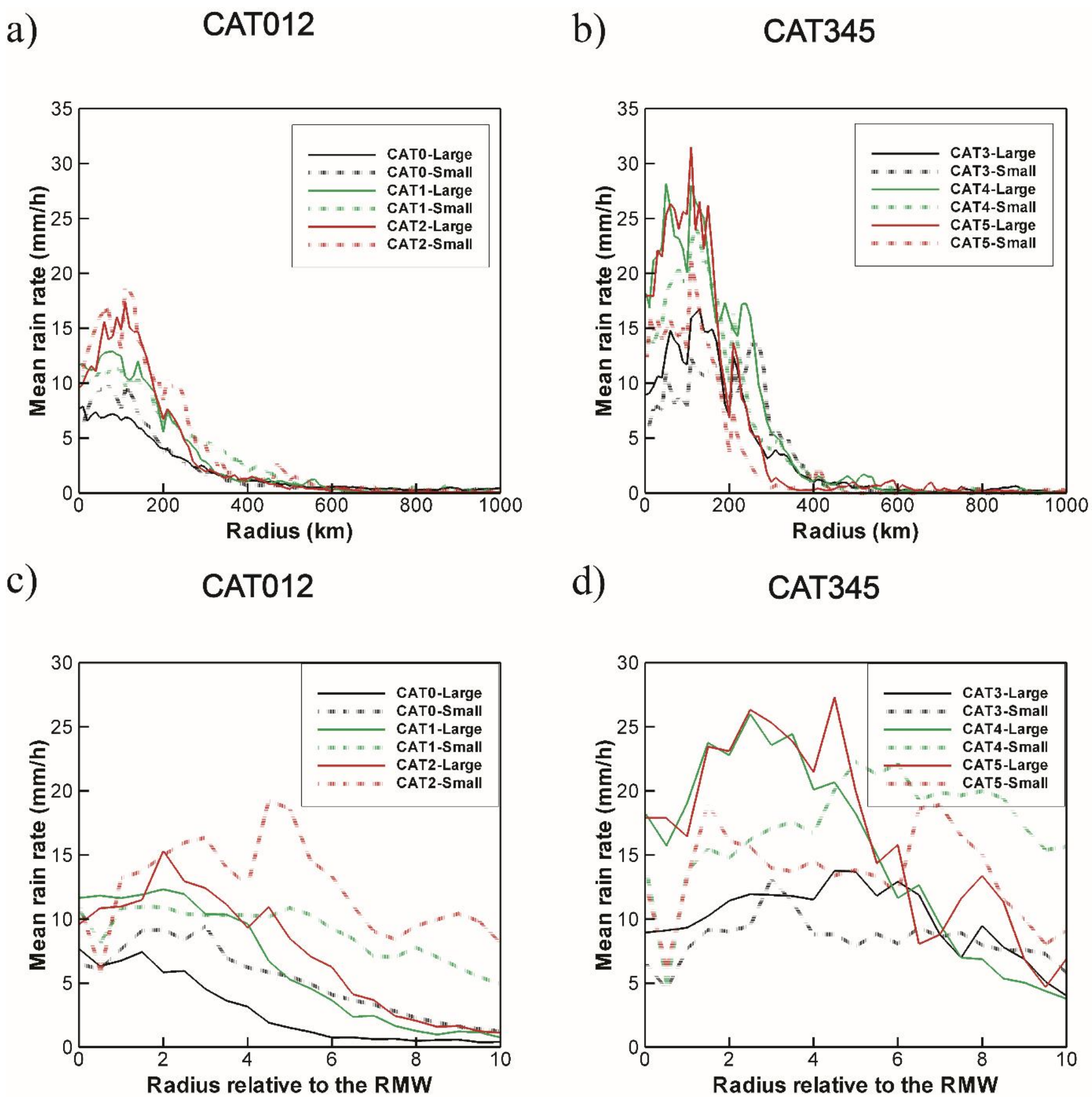

a)
Intensity (knots)
RMW (nm)
b)
RMW (km)
Intensity category
c)
RMW (nm)
Time
d)
MWS (Knots)
Time

Yu et al., 2022

Large TCs .vs. Small TCs



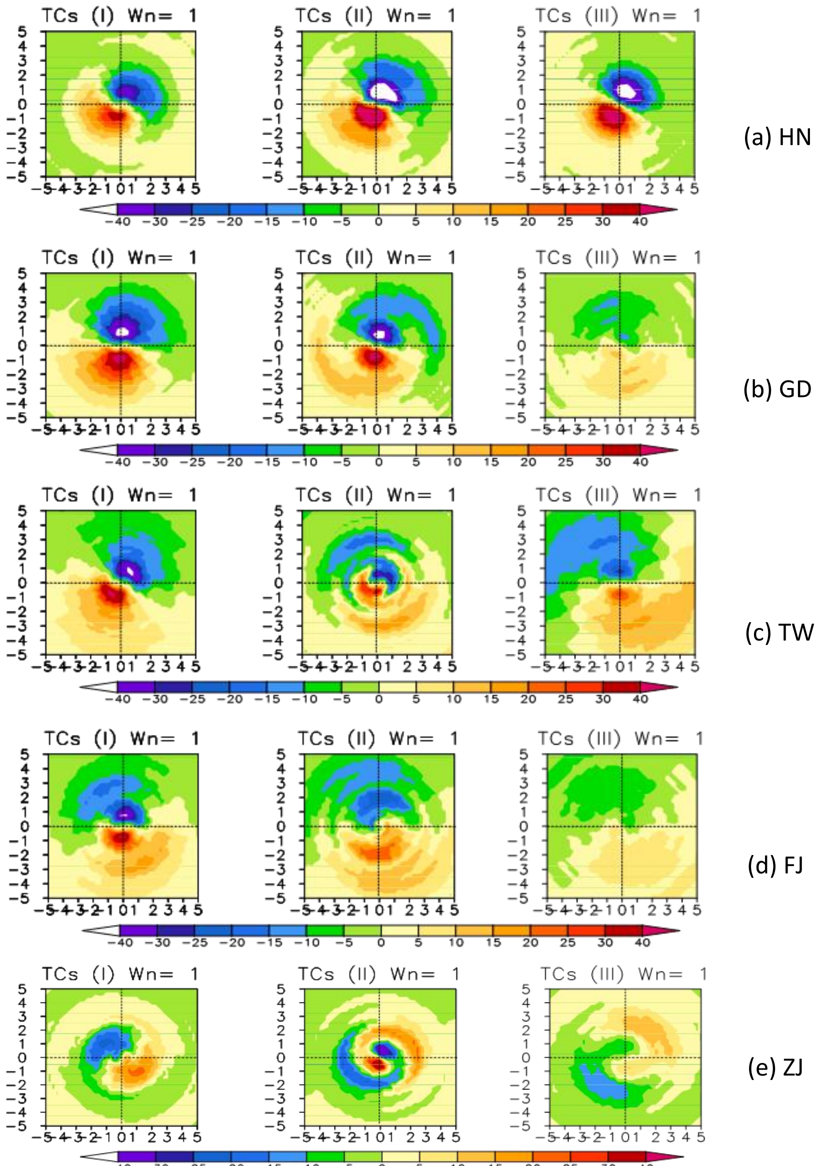
Yu et al., 2022


a)
CAT012
b)
CAT345
Mean rain rate (mm/h)
Radius (km)
CAT0-Large
CAT0-Small
CAT1-Large
CAT1-Small
CAT2-Large
CAT2-Small
CAT3-Large
CAT3-Small
CAT4-Large
CAT4-Small
CAT5-Large
CAT5-Small
c)
CAT012
d)
CAT345
Radius relative to the RMW

Yu et al., 2022

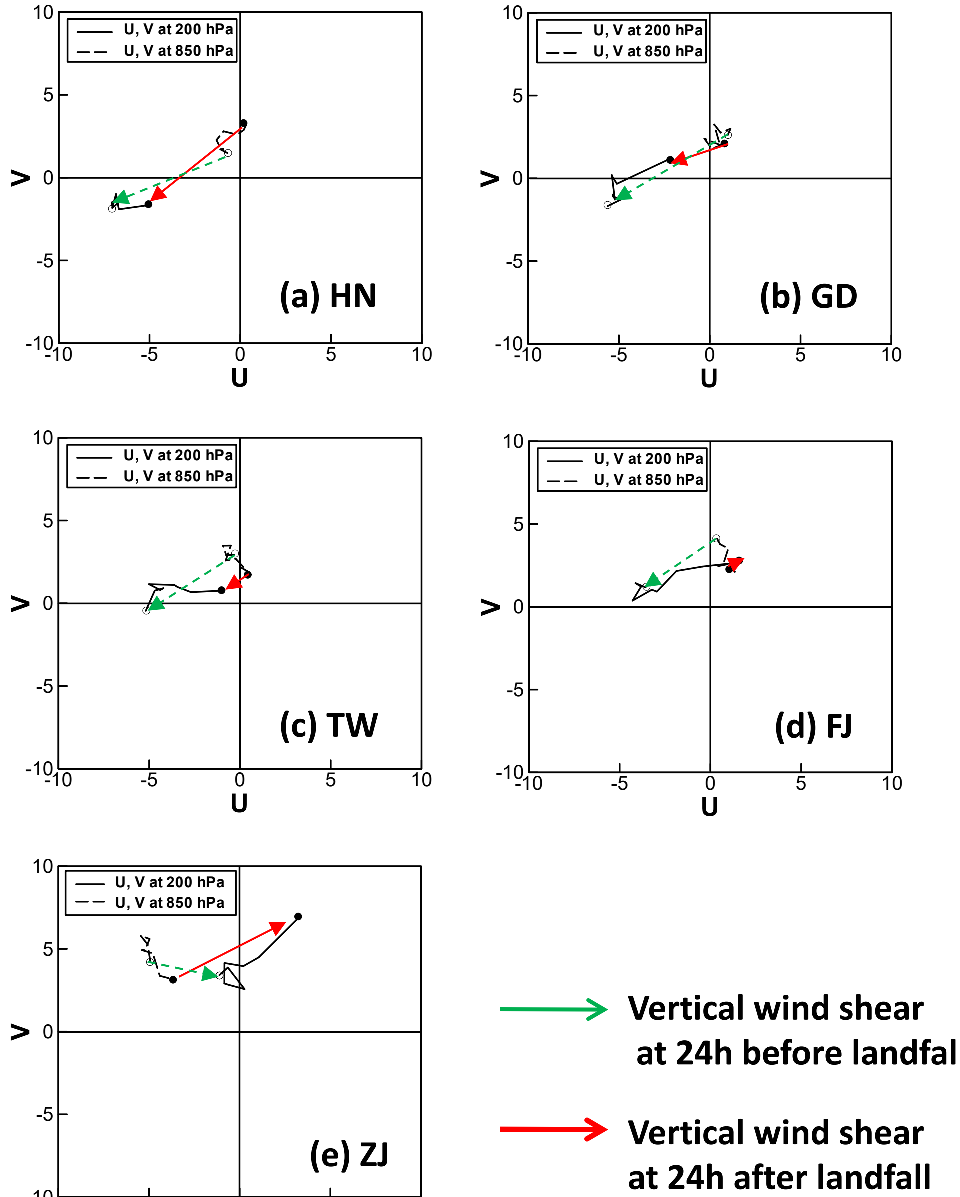
2) Asymmetric LTC rainfall prior to, after landfall

24h before landfall **at landfall** **24h after landfall**



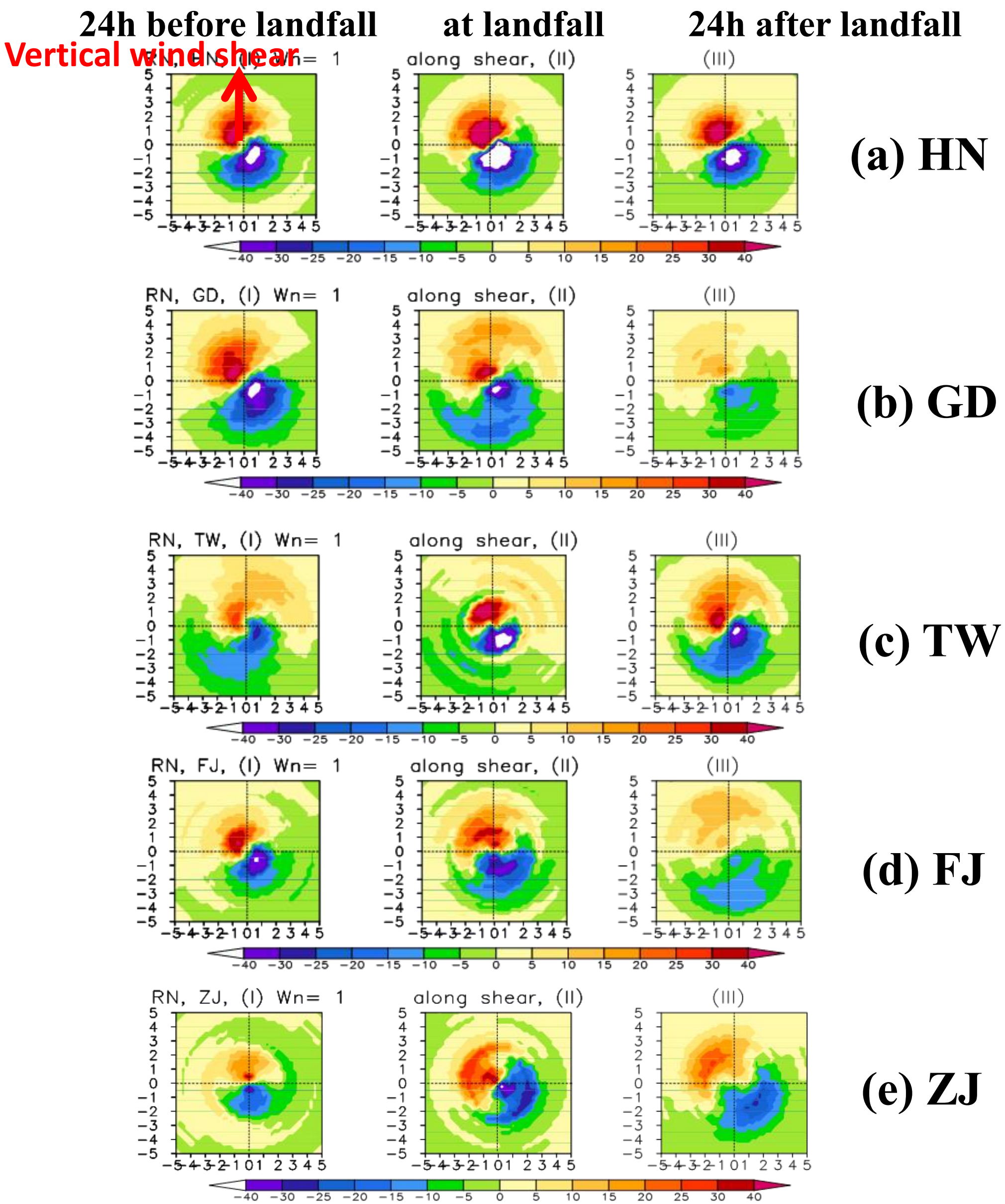
A cyclonic rotation from South China to East China in the location of the rainfall maximum of landfalling TCs is identified, which is related with the environmental VWS cyclonic rotation.

Easterly wind shear controls TCs at HN/GD/TW/FJ at most of times



(Yu et al. 2015)

The vertical wind shear is one main factor to the asymmetric rainfall distribution

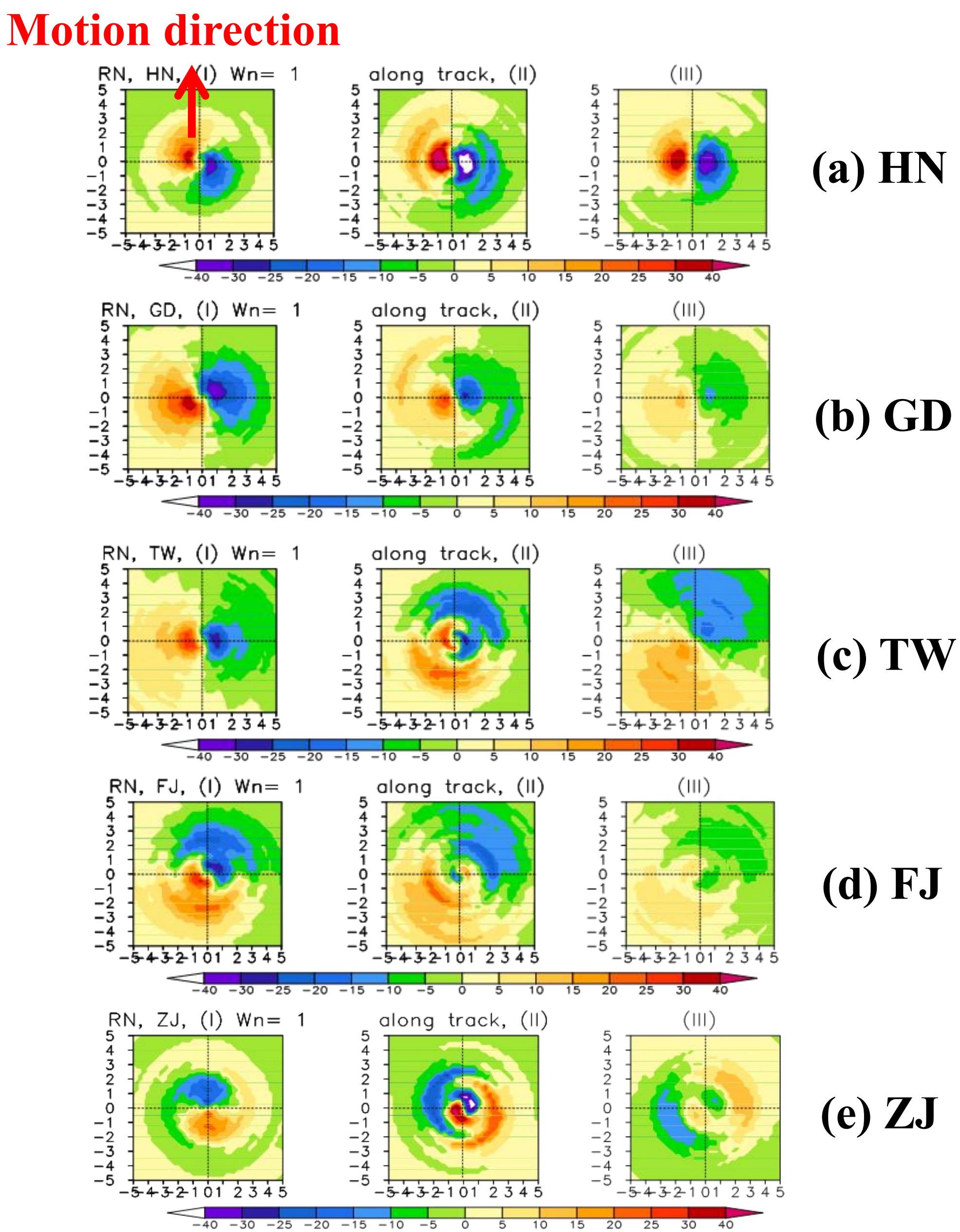


- **The wavenumber-one rainfall asymmetry (unit: mm) relative to the vertical wind shear.**

- X and Y axes are distance (degree) from the TC center (origins).

- Stage (I) is 24-h prior to landfall, stage (II) is at the time of landfall, and stage (III) is 24-h after landfall. The color scale indicates the amplitude of the asymmetry relative to the VWS.

TC asymmetries relative to TC motion

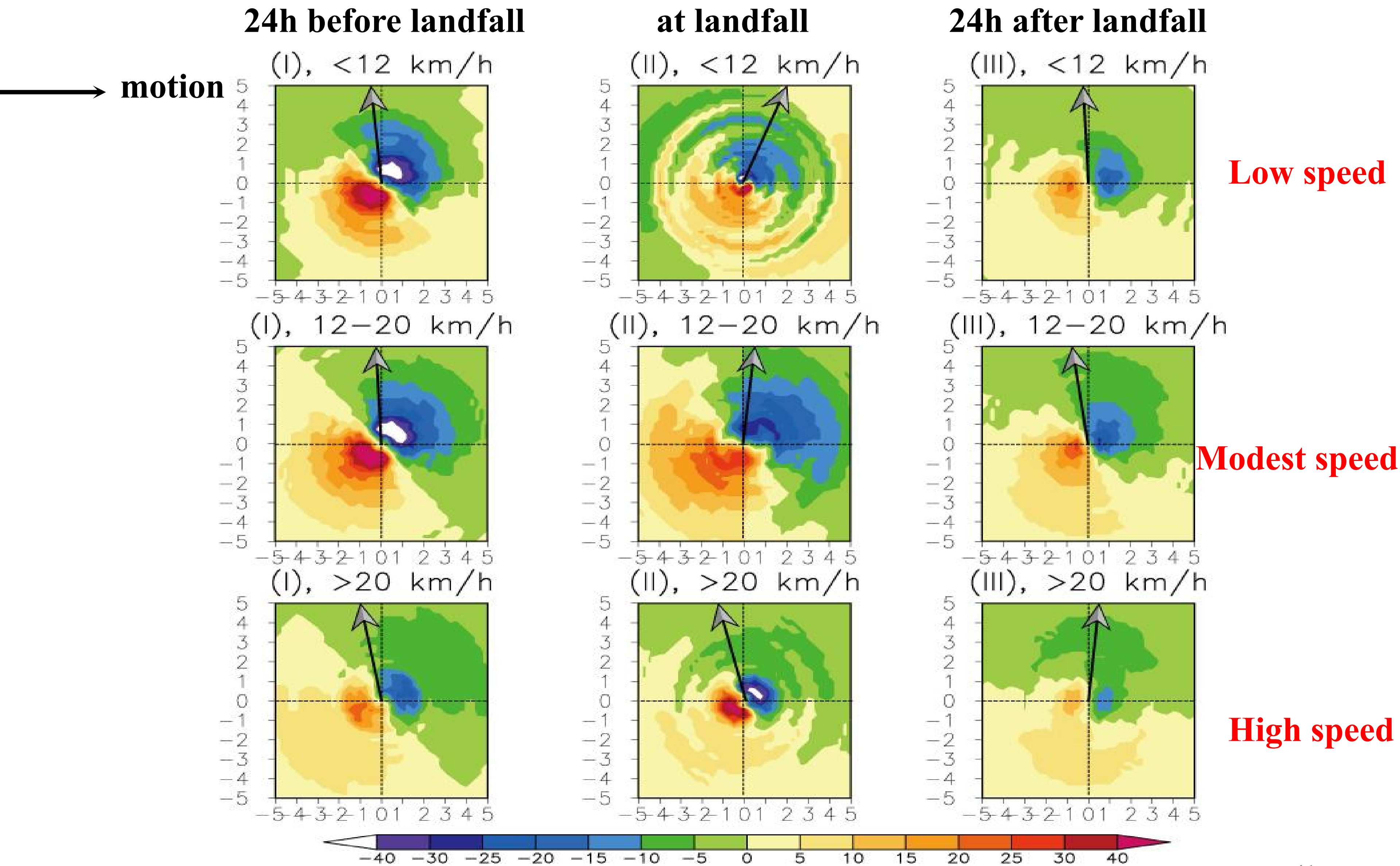


- **The wavenumber-1 rainfall asymmetry (unit: mm) relative to the storm motion.**

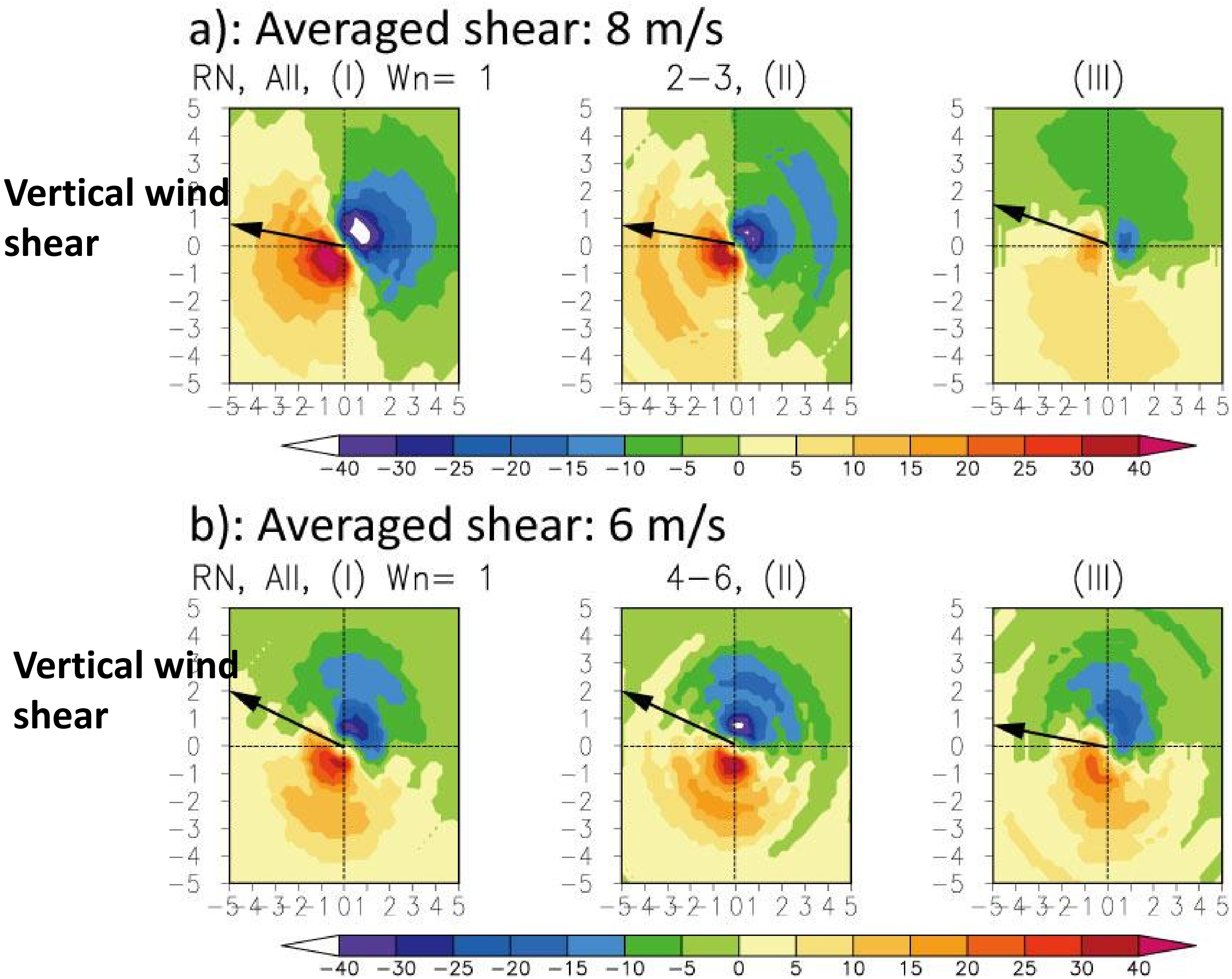
- The storm motion vector is aligned with the positive Y axis (upward).

- X and Y axes are distance (degree) from the TC center (origins). Stage (I) is 24-h prior to landfall, stage (II) is at the time of landfall, and stage (III) is 24-h after landfall. The color scale indicates the amplitude of the asymmetry relative to the storm motion.

Rainfall asymmetries .vs. TC motion speed



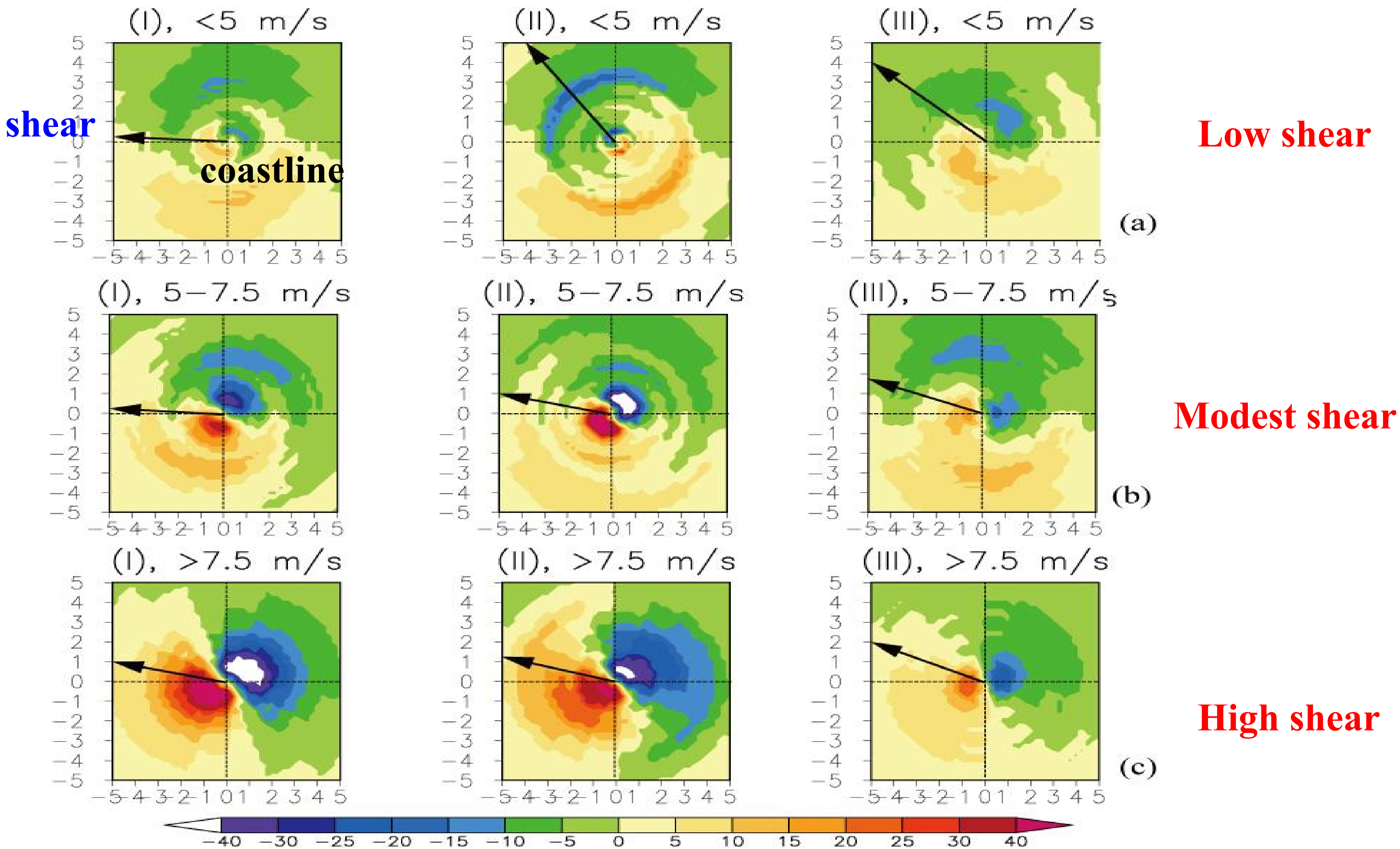
Asymmetric rainfall .vs. intensity



Weaker TCs (CAT23)

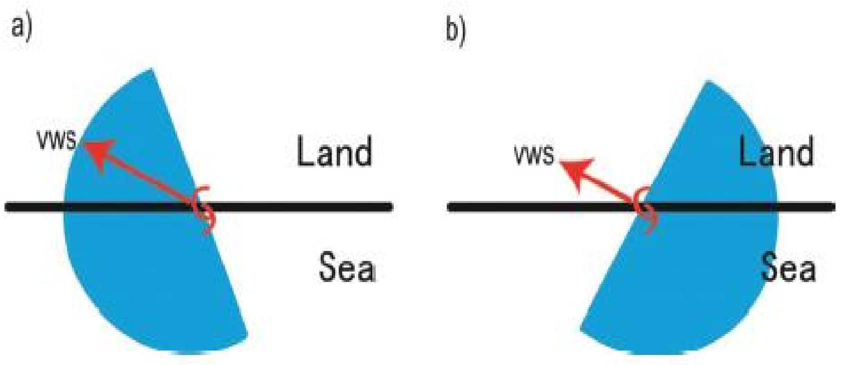
Stronger TCs (CAT456)

Rainfall asymmetries .vs. coastline & shear



Yu et al. 2017

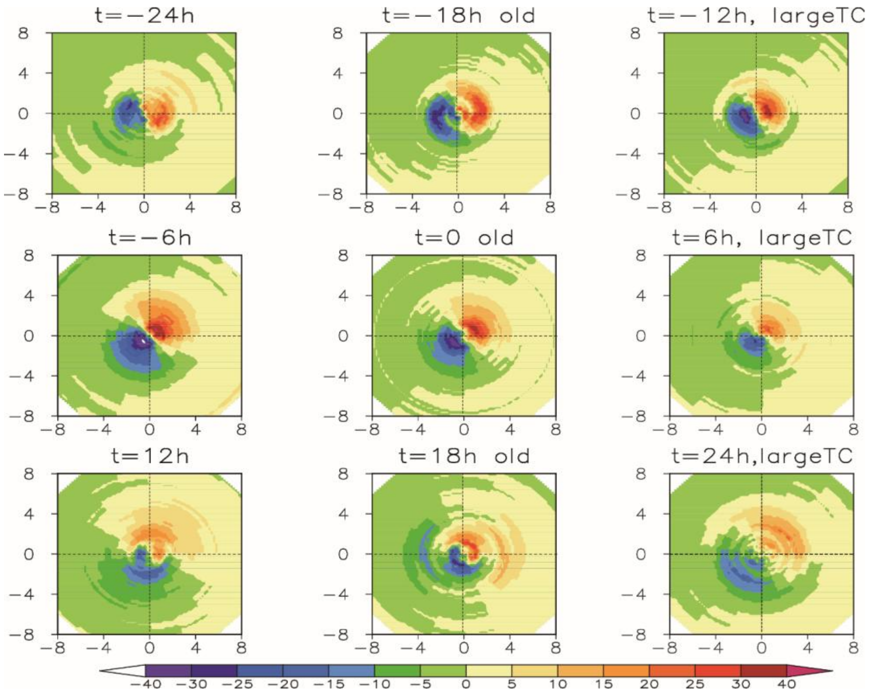
VWS and land-sea contrast combined effects

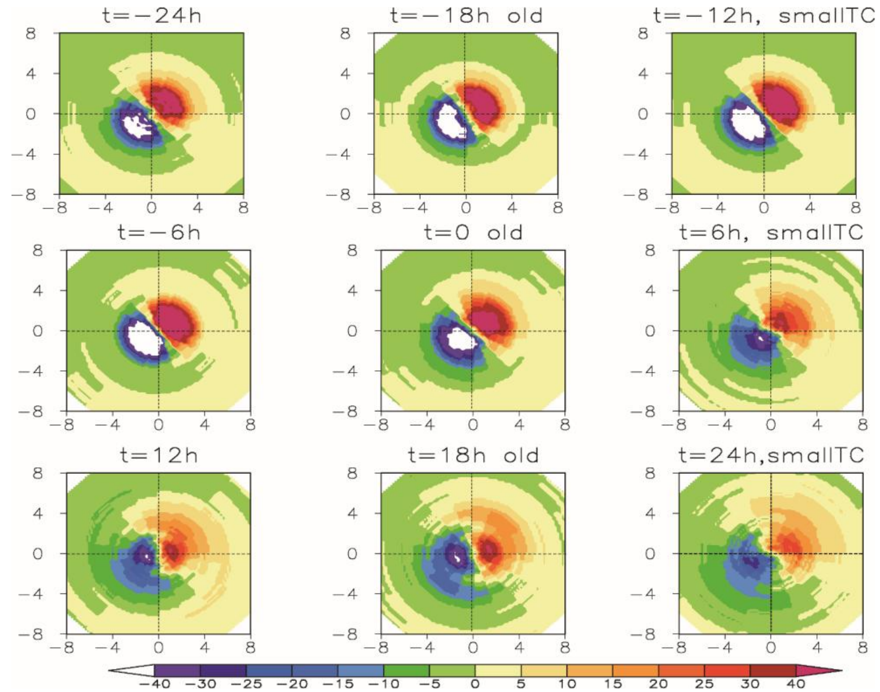


VWS: environmental Vertical Wind Shear (200- 850)
a) Strong VWS; b) Weak VWS

Yu, 2018, *Extreme Weather*

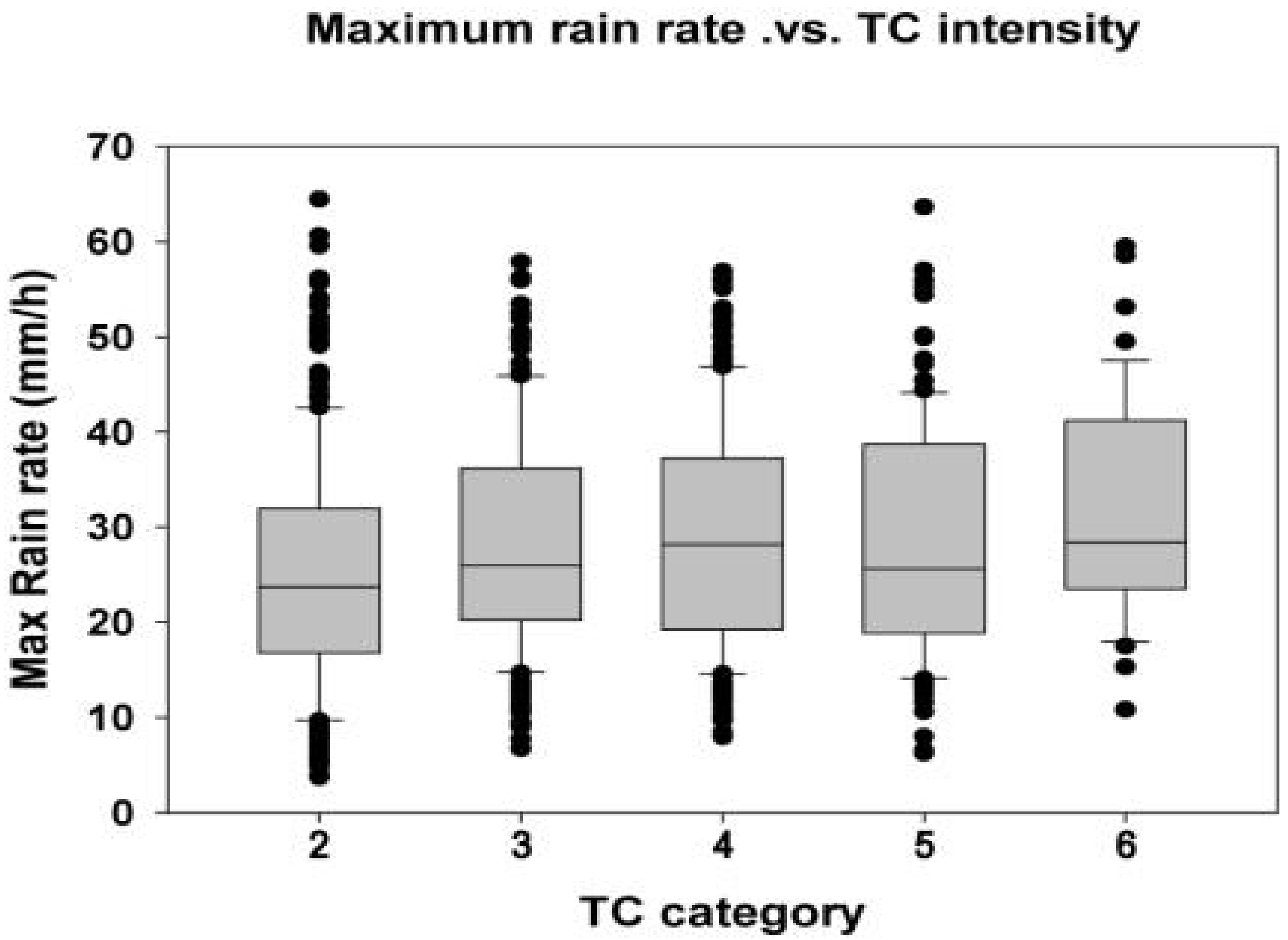
Large TCs .vs. Small TCs





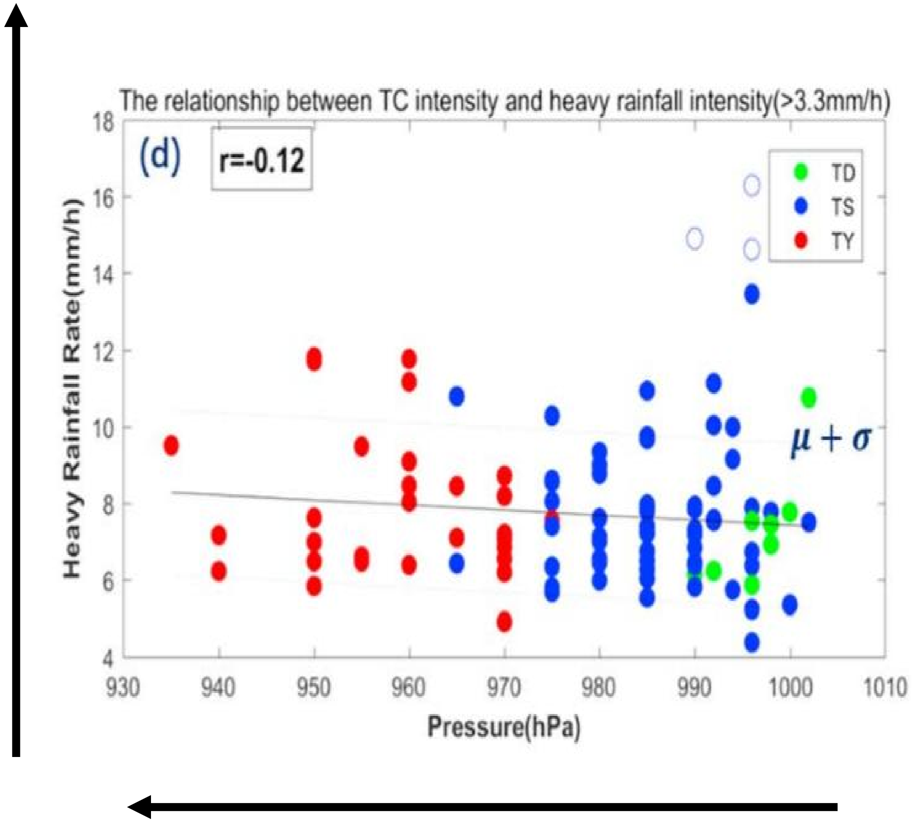
Yu et al., 2022

Maximum rain rate .vs. intensity



The relationship between TC intensity and heavy rainfall intensity

Heavy rain rate



intensity

TC intensity and Rainfall
From Feng and Shu (2018)

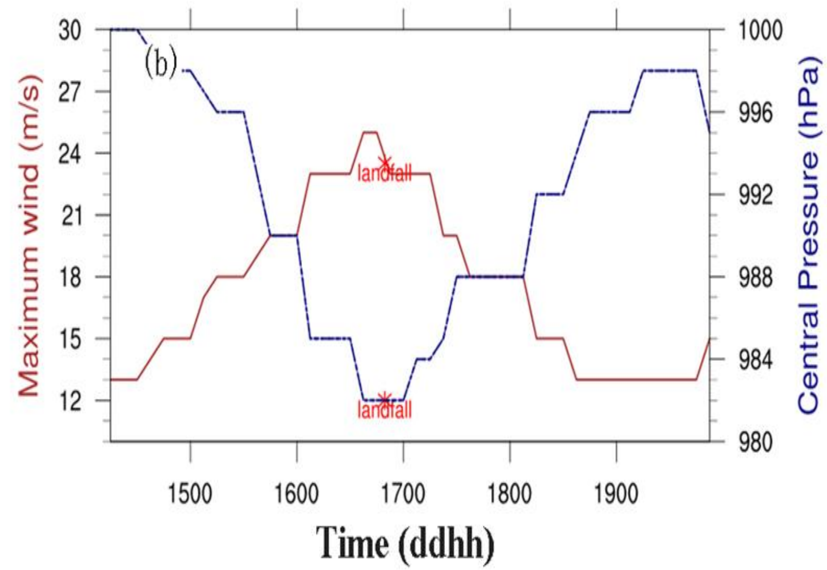
For landfalling TCs, no obvious relation with TC intensity

Heavy rainfall is not only from stronger TCs

A case study of weak landfalling TC rainfall evolution

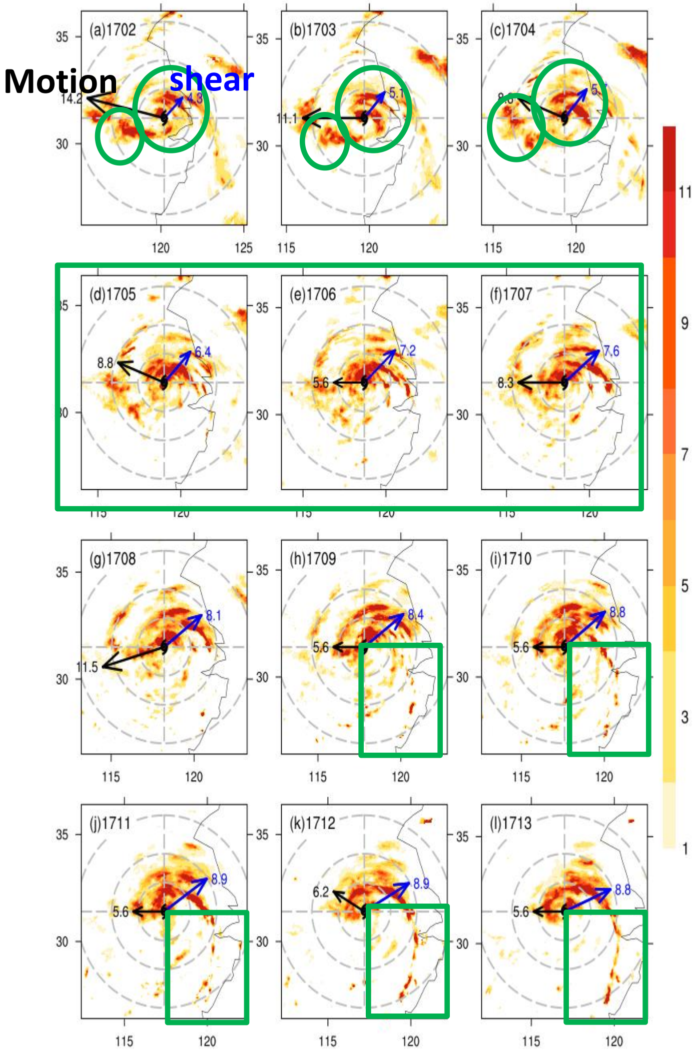
Weak TC Rumbia (2018) with heavy rainfall

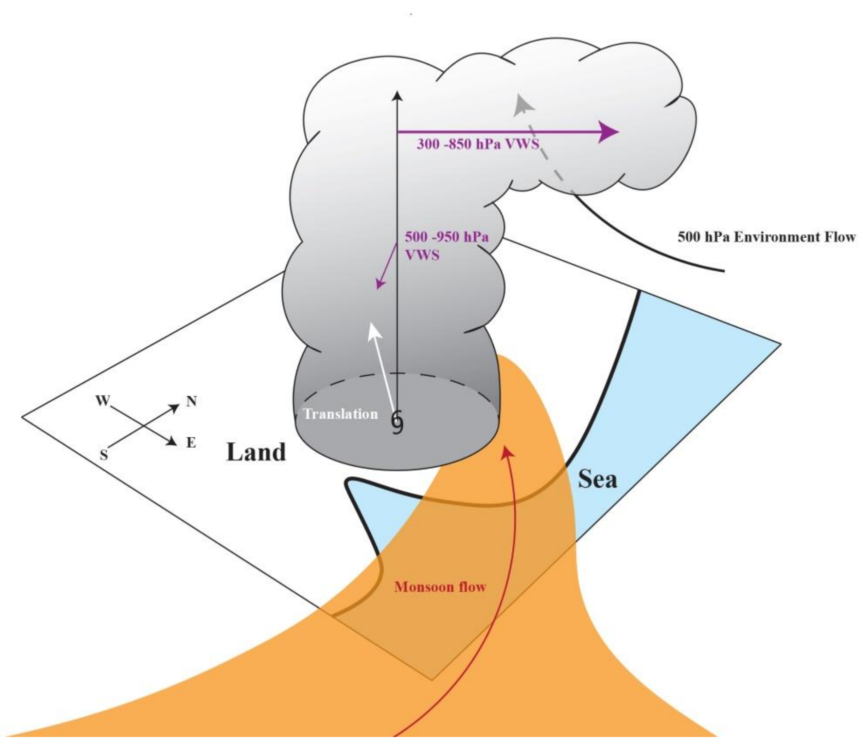
It made landfall in Shanghai as a STS (~ 24 m/s).



1. **Why the rainfall increased and maintained inland, even Rumbia kept weakening?**
2. **Why the rainfall deviated and located to the right side of the track?**

Case rainfall evolution conclusion





Tang, Wang, Yu*, 2021

Factors impacting rainfall distributions in landfalling TCs

- Storm track (location) (directly)
- TC motion speed and direction (depends on VWS)
- Storm intensity and inner-core size (directly) – the smaller/stronger the storm, the more it rains
- Landsea-contrast/Coastline/Topography – Positive in the upslope areas
- Wind shear (directcy) – leads to asymmetric rainfall maximum
- Nearby synoptic-scale features/Extratropical Transition

Considerations

Factors leading to higher rainfall

- Smaller inner-core size
- Higher intensity
- Down-VWS side
- Slow moving speed
- Convection should be concentrated near down-wind-mainland
- Significant topography
- Favorable trough and moisture transport

Factors leading to lower rainfall

- lower intensity (not for the extreme rainfall)
- larger inner-size than average
- Vertical wind shear could affect TC intensity
- Core of system expected to pass island

Flooding and landslides

- **Antecedent precipitation**: Saturated soil has greater flood potential than dry soil.
- **Speed of movement of the TC:** Slower movement leads to greater flooding.
- **Orographic enhancement**: Additional lifting of moist air by high terrain produces more precipitation. Intensification due to synoptic forcing: Interaction of the cyclone with midlatitude synoptic systems can sometimes enhance the low pressure and increase precipitation.
- **Hydrology**: Narrow river basins are easier to flood than flat, broad river basins. Confluence of multiple rivers can also aggravate flooding.

Flooding and landslides

- **Land use**: Urban landscapes are more prone to flash floods because of increased runoff and channeling which causes acceleration of surface water. Denuded hillsides are more prone to landslides; plant roots help to stabilize the soil.
- **Other geographical influences:** Flooding is also influenced by soil type. Soils with slow infiltration lead to greater runoff and flooding.

Conclusions

- The axisymmetric (wavenumber-0) rainfall in landfalling TCs is closely related to the TC intensity and intensity change.
- Small inner-core sized TCs have higher rain rate with higher axisymmetry than large TCs; both small and large TCs have rainfall within a radius of 5 lat. Higher intensity during landfall may partly contribute to the higher rain rate in small TCs than in the large TCs.
- The wavenumber-one rainfall asymmetry shows the downshear to downshear-left rainfall maximum in landfalling TCs. But when VWS is weak (less than 5 m s^{-1}), the coastline could influence the asymmetric rainfall maxima location.
- For the heavy rainfall, weak landfalling tropical cyclones would also produce very heavy rainfall. Heavy rainfall is not only from stronger TCs.
- Flood forecasts need pay attention on the precipitation itself, but also storm motion speed, and land-surface conditions.

References

•**Yu, Zifeng**, Wang, Y., Yu, H., & Duan, Y., 2022: The relationship between the inner-core size and the rainfall distribution in landfalling tropical cyclones over China. *Geophysical Research Letters*, 49, e2021GL097576.

•Tang Lichun, Yuqing Wang, **Zifeng Yu***, Lan Wang, 2021: The asymmetric precipitation evolution in weak landfalling Tropical Cyclone Rumbia over East China. *Frontiers in Earth Science*, 9: 747271.

•**Yu Zifeng,** Y. J. Chen, B. Ebert, N. E. Davidson, Y. Xiao, H. Yu. and Y. Duan, 2020: Benchmark Rainfall Verification of ACCESS-TC Operational Landfall Forecasts over China, *Meteorological Applications*. 27(1), 1–18. https://doi.org/10.1002/met.1842

•**Yu Zifeng,** and Y. Wang, 2018： Rainfall distribution in landfalling tropical cyclones. *Extreme Weather*. Publisher: InTech.

•**Yu, Zifeng,** Y. Wang, H. Xu, N. E. Davidson, Y. Chen, Y. Chen, and H. Yu, 2017: On the Relationship between Intensity and Rainfall Distribution in Tropical Cyclones Making Landfall over China. *Journal of Applied Meteorology and Climatology*, 56, 2883-2901.

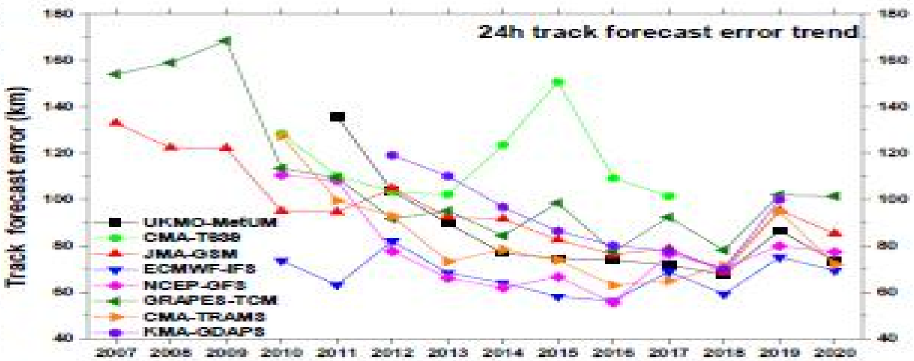
•**Yu Zifeng,** Y. Wang and H. Xu, 2015: Observed Rainfall Asymmetry in Tropical Cyclones Making Landfall over China. *Journal of Applied Meteorology and Climatology*, 54, 117–136.

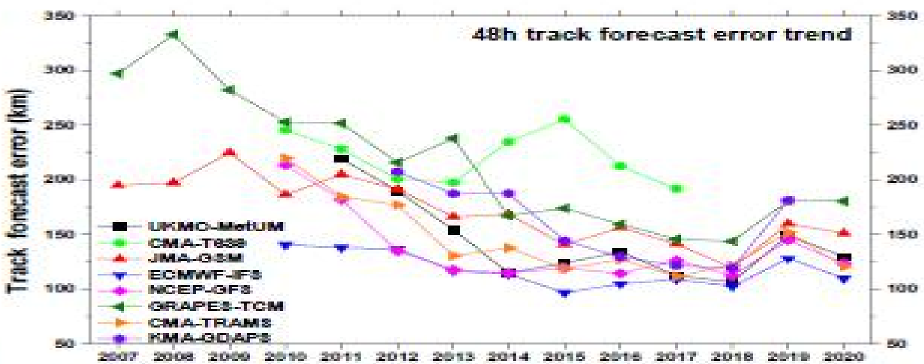
Current forecast of landfalling tropical cyclone rainfall

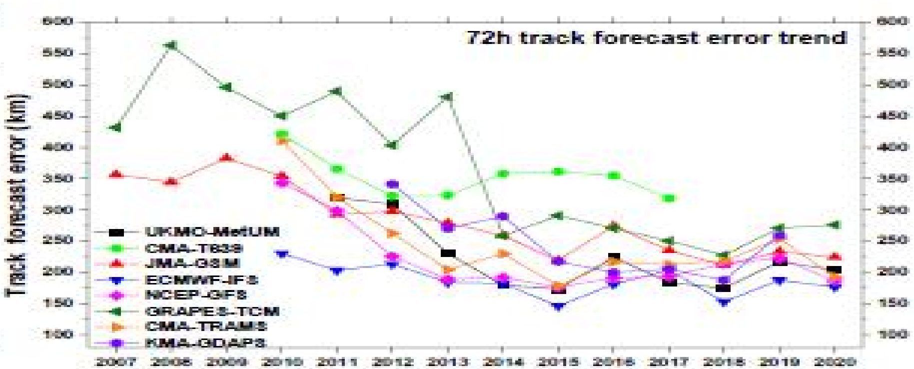
Outline

- TC QPFs verification
- Some methods to make QPF improvements
- Summary

TC Track forecast errors



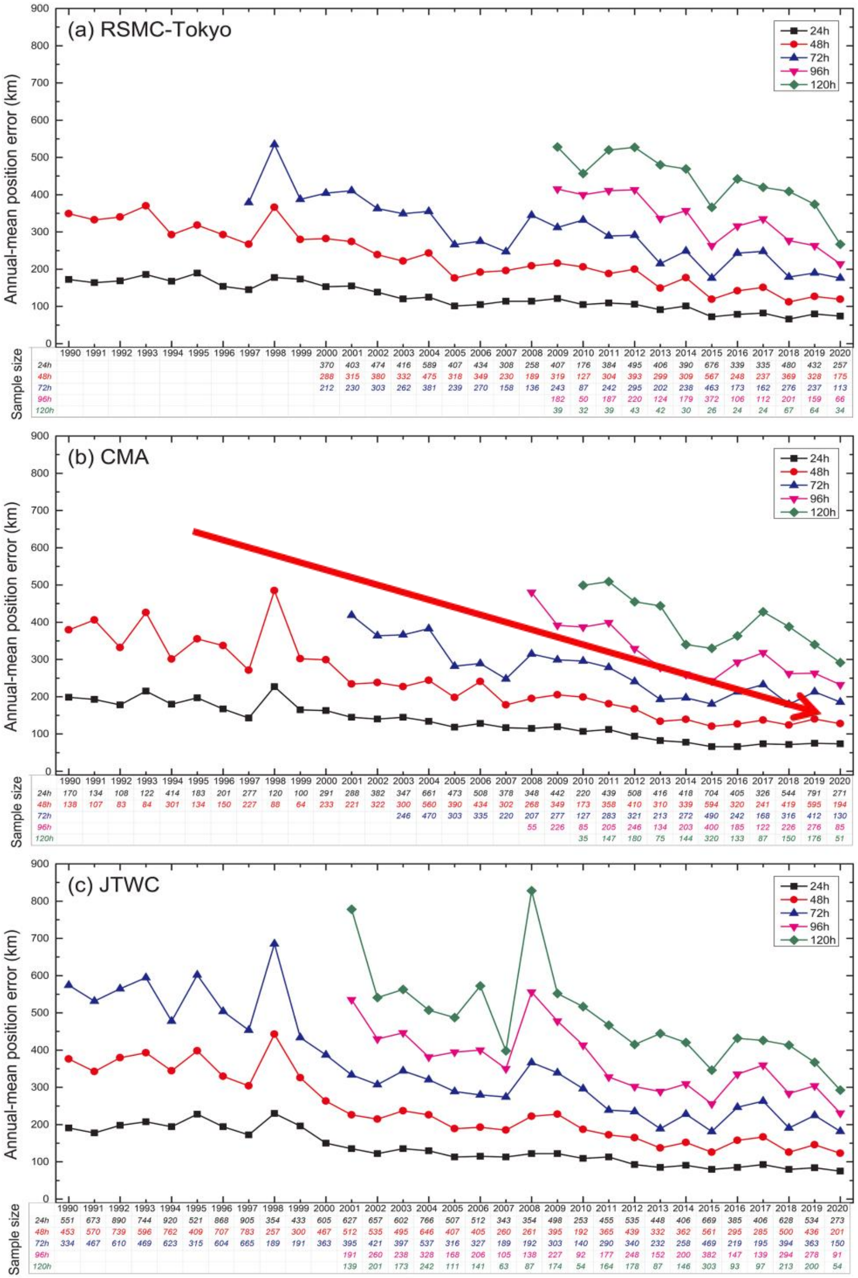




for global and regional NWP models from 2007 to 2020 at the lead times of 24, 48 and 72 h.

From WMO TLFDP progress report (2022)

Official Track forecast errors



24h forecast errors

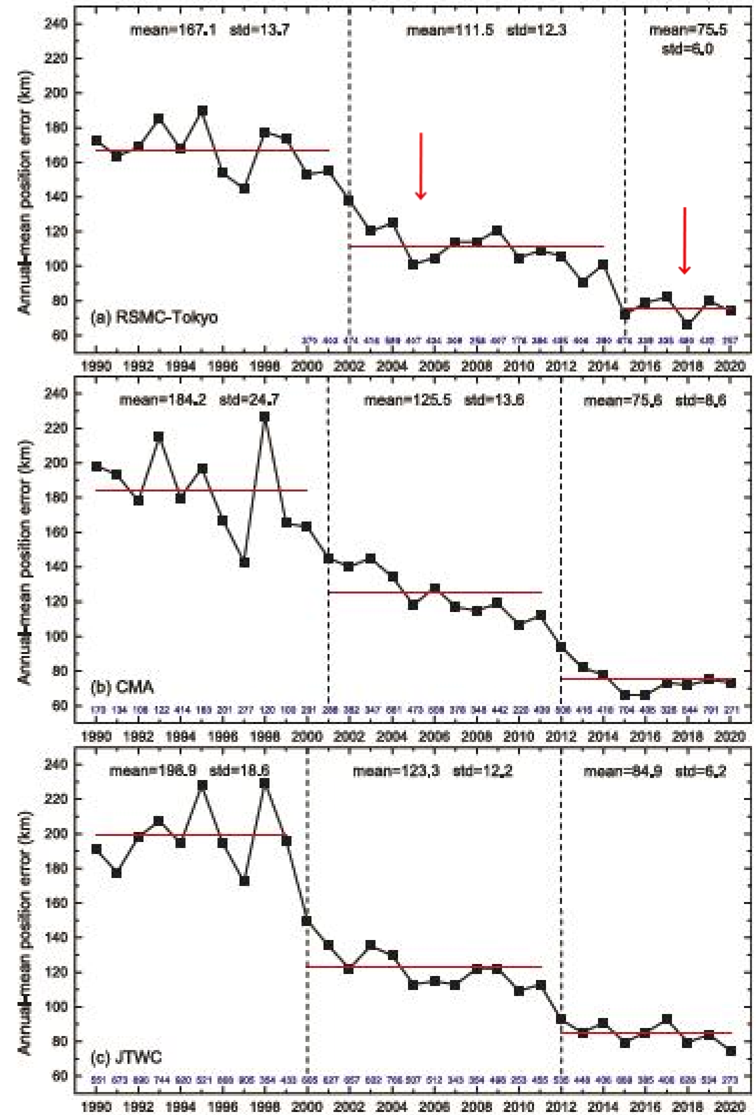
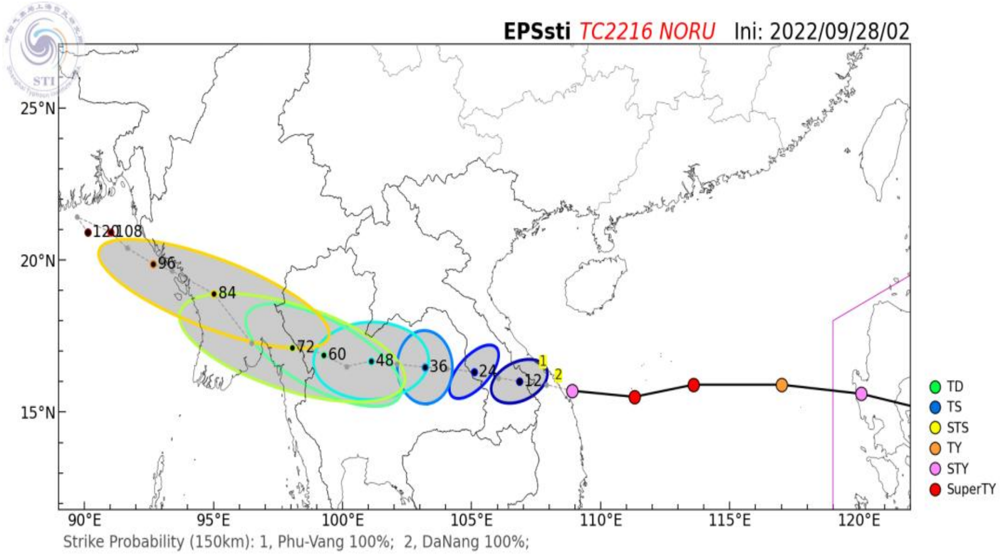
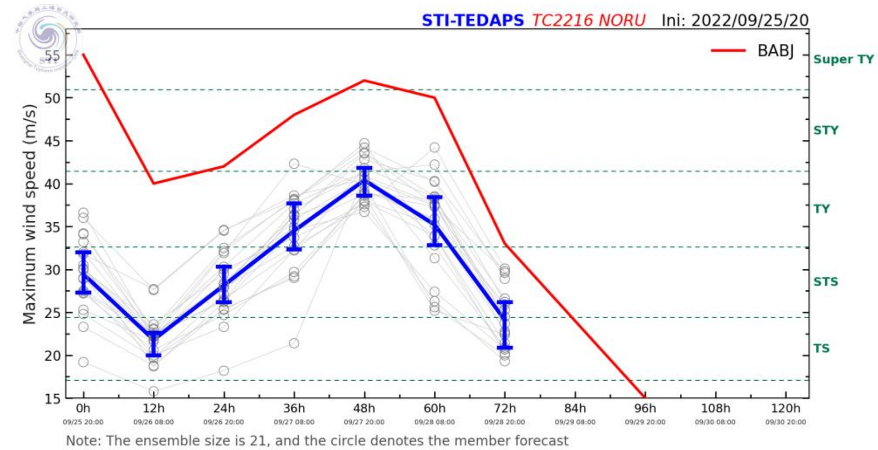
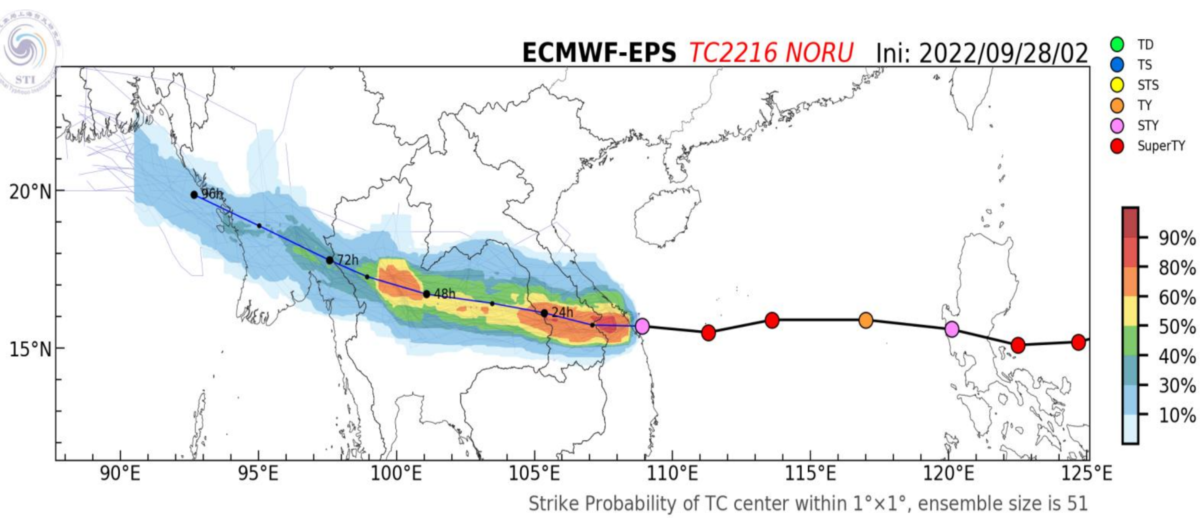
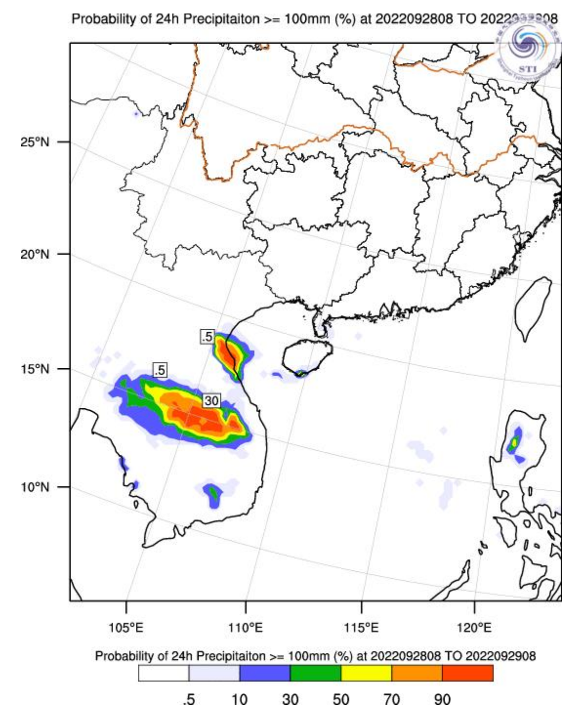


Fig. 2. Changepoint analyses of the 24-h PEs at (a) RSMC-Tokyo, (b) CMA, and (c) JTWC from 1990 to 2020. The sample sizes are listed at the bottom of each chart.


EPSsti TC2216 NORU Ini: 2022/09/28/02
TD
TS
STS
TY
STY
SuperTY
Strike Probability (150km): 1, Phu-Vang 100%; 2, DaNang 100%;


STI-TEDAPS TC2216 NORU Ini: 2022/09/25/20
BABJ
Maximum wind speed (m/s)
Super TY
STY
TY
STS
TS
Note: The ensemble size is 21, and the circle denotes the member forecast


ECMWF-EPS TC2216 NORU Ini: 2022/09/28/02
TD
TS
STS
TY
STY
SuperTY
Strike Probability of TC center within 1°×1°, ensemble size is 51


Probability of 24h Precipitaiton >= 100mm (%) at 2022092808 TO 2022092908

TC QPFs verification

Traditional rain verification measures

- ***Probability of detection:***

POD=H/（H+M）

- ***False alarm ratio:***

FAR=F/（H+F）

- ***Critical success index:***

CSI=H/（H+M+F）

- ***Equitable threat score:***

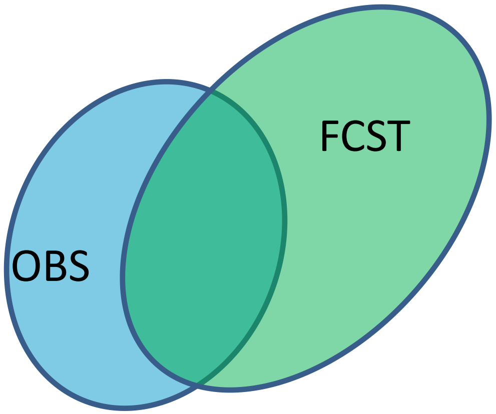
ETS= (H-CH)/（H+M+F-CH）

CH= = (H+M)(H+F)/（H+M+F+Z）

		Observed	
		yes	no
Forecast	yes	**H** *(hits)*	**F** *(false alarms)*
	no	**M** *(misses)*	**Z** *(correct negatives)*

What is the main rain forecast error resource?

- Errors in
  - Location
  - Size
  - Intensity
  - Orientation



- Results can
  - Characterize errors for individual forecasts
  - Show systematic errors
  - Give hints as to source(s) of errors

New verification method is important!

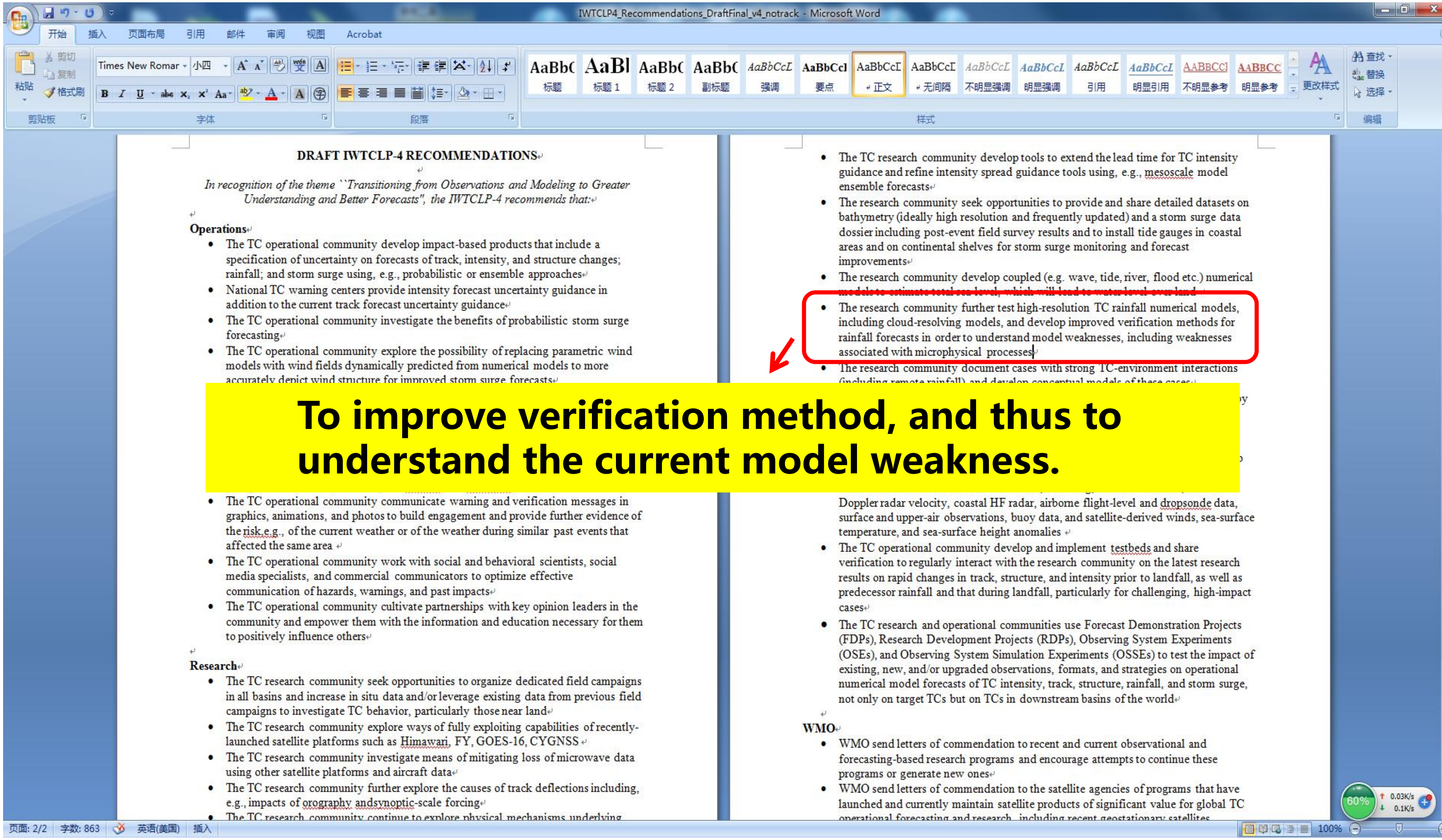
TC rain forecasts in 2009, from Wang (2012)

		TS					
		24/36h	48/60h	72/84h	96/108h	120/132h	144/156h
≧0.1mm	F	0.616	0.572	0.552	0.532	0.496	0.464
	JMA	0.555	0.542	0.521	0.495	0.472	0.456
	CMA	0.561	0.532	0.499	0.484	0.467	0.451
≧10mm	F	0.294	0.264	0.227	0.203	0.181	0.152
	JMA	0.303	0.257	0.213	0.163	0.148	0.138
	CMA	0.278	0.205	0.165	0.139	0.119	0.097
≧25mm	F	0.271	0.233	0.193	0.153	0.108	0.078
	JMA	0.218	0.19	0.153	0.078	0.057	0.058
	CMA	0.196	0.161	0.131	0.109	0.071	0.049
≧50mm	F	0.223	0.168	0.129	0.085	0.067	0.044
	JMA	0.164	0.101	0.072	0.017	0.021	0.03
	CMA	0.116	0.11	0.087	0.047	0.038	0.012
≧100mm	F	0.097	0.078	0.037	0.031	0.029	0.016
	JMA	0.051	0.02	0.021	0	0.011	0
	CMA	0.065	0.027	0.039	0.013	0.018	0.002

>50 mm
TS: <0.2

- **TC rainfall forecast is improved very slowly**
- **One reason: current conventional verification methods could not analyze the model error source information.**

Both operation and research need it



IWTCLP4_Recommendations_DraftFinal_v4_notrack - Microsoft Word

DRAFT IWTCLP-4 RECOMMENDATIONS

In recognition of the theme ``Transitioning from Observations and Modeling to Greater Understanding and Better Forecasts'', the IWTCLP-4 recommends that:

Operations

- The TC operational community develop impact-based products that include a specification of uncertainty on forecasts of track, intensity, and structure changes; rainfall; and storm surge using, e.g., probabilistic or ensemble approaches
- National TC warning centers provide intensity forecast uncertainty guidance in addition to the current track forecast uncertainty guidance
- The TC operational community investigate the benefits of probabilistic storm surge forecasting
- The TC operational community explore the possibility of replacing parametric wind models with wind fields dynamically predicted from numerical models to more accurately depict wind structure for improved storm surge forecasts
- The TC operational community communicate warning and verification messages in graphics, animations, and photos to build engagement and provide further evidence of the risk e.g., of the current weather or of the weather during similar past events that affected the same area
- The TC operational community work with social and behavioral scientists, social media specialists, and commercial communicators to optimize effective communication of hazards, warnings, and past impacts
- The TC operational community cultivate partnerships with key opinion leaders in the community and empower them with the information and education necessary for them to positively influence others

Research

- The TC research community seek opportunities to organize dedicated field campaigns in all basins and increase in situ data and/or leverage existing data from previous field campaigns to investigate TC behavior, particularly those near land
- The TC research community explore ways of fully exploiting capabilities of recently-launched satellite platforms such as Himawari, FY, GOES-16, CYGNSS
- The TC research community investigate means of mitigating loss of microwave data using other satellite platforms and aircraft data
- The TC research community further explore the causes of track deflections including, e.g., impacts of orography andsynoptic-scale forcing
- The TC research community continue to explore physical mechanisms underlying
- The TC research community develop tools to extend the lead time for TC intensity guidance and refine intensity spread guidance tools using, e.g., mesoscale model ensemble forecasts
- The research community seek opportunities to provide and share detailed datasets on bathymetry (ideally high resolution and frequently updated) and a storm surge data dossier including post-event field survey results and to install tide gauges in coastal areas and on continental shelves for storm surge monitoring and forecast improvements
- The research community develop coupled (e.g. wave, tide, river, flood etc.) numerical models to estimate total sea level, which will lead to water level over land
- The research community further test high-resolution TC rainfall numerical models, including cloud-resolving models, and develop improved verification methods for rainfall forecasts in order to understand model weaknesses, including weaknesses associated with microphysical processes
- The research community document cases with strong TC-environment interactions (including remote rainfall) and develop conceptual models of these cases

Doppler radar velocity, coastal HF radar, airborne flight-level and dropsonde data, surface and upper-air observations, buoy data, and satellite-derived winds, sea-surface temperature, and sea-surface height anomalies

- The TC operational community develop and implement testbeds and share verification to regularly interact with the research community on the latest research results on rapid changes in track, structure, and intensity prior to landfall, as well as predecessor rainfall and that during landfall, particularly for challenging, high-impact cases
- The TC research and operational communities use Forecast Demonstration Projects (FDPs), Research Development Projects (RDPs), Observing System Experiments (OSEs), and Observing System Simulation Experiments (OSSEs) to test the impact of existing, new, and/or upgraded observations, formats, and strategies on operational numerical model forecasts of TC intensity, track, structure, rainfall, and storm surge, not only on target TCs but on TCs in downstream basins of the world

WMO

- WMO send letters of commendation to recent and current observational and forecasting-based research programs and encourage attempts to continue these programs or generate new ones
- WMO send letters of commendation to the satellite agencies of programs that have launched and currently maintain satellite products of significant value for global TC operational forecasting and research, including recent geostationary satellites

To improve verification method, and thus to understand the current model weakness.

WMO suggestion notebook，2018

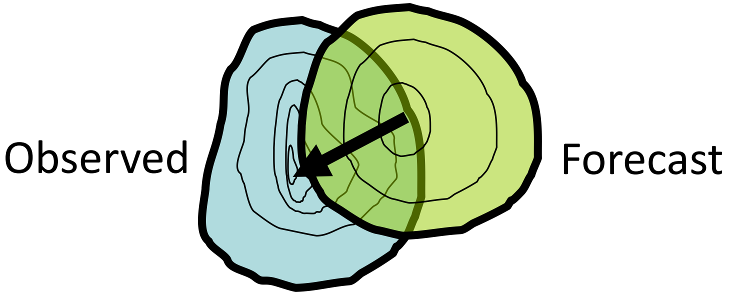
CRA vs. MODE

	CRA	MODE
Verification area definition	CRA threshold	Rain threshold
Error decomposition	Y	N
Location error	Y (explicitly, show direction)	Y (implicitly, through centroid distance and locations)
Pattern match?	Y, simply use correlation coefficient	Y, Total interest (combination of size, distance, intensity, volume, etc)
Rain Volume	Y	Y
Rain Area	Y, simply compare CRA grid points	Y, also with Intersection and Union, Symmetric difference area

Contiguous Rain Area (CRA) Approach

Ebert and McBride, *J. Hydrol.*, 2000

- Define entities using threshold (Contiguous Rain Areas)
- Horizontally translate the forecast until a *pattern matching* criterion is met:
  - minimum total squared error between forecast and observations
  - maximum correlation
  - maximum overlap



- The displacement is the vector difference between the original and final locations of the forecast.

CRA error decomposition

Total mean squared error (MSE)

$$MSE_{total} = MSE_{displacement} + MSE_{rotation} + MSE_{volume} + MSE_{pattern}$$

The *displacement error* is the difference between the mean square error before and after translation

$$MSE_{displacement} = MSE_{total} - MSE_{shifted}$$

$$MSE_{rotation} = MSE_{shifted} - MSE_{shifted+ratated}$$

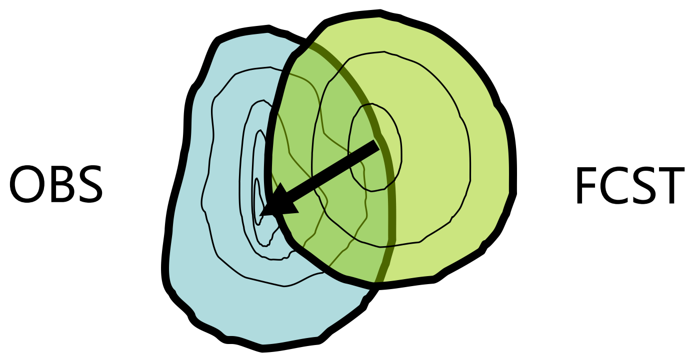
$$MSE_{volume} = (\overline{F} - \overline{X})^2$$

$$MSE_{pattern} = MSE_{shifted+ratated} - MSE_{volume}$$

The *volume error* is the bias in mean intensity, where $\overline{F}$ and $\overline{X}$ are the mean forecast and observed values after shifting.

Chen, Ebert, et al, 2015

To find out the error source



CRA (Contiguous Rain Area)

Ebert and McBride, *J. Hydrol.*, 2000

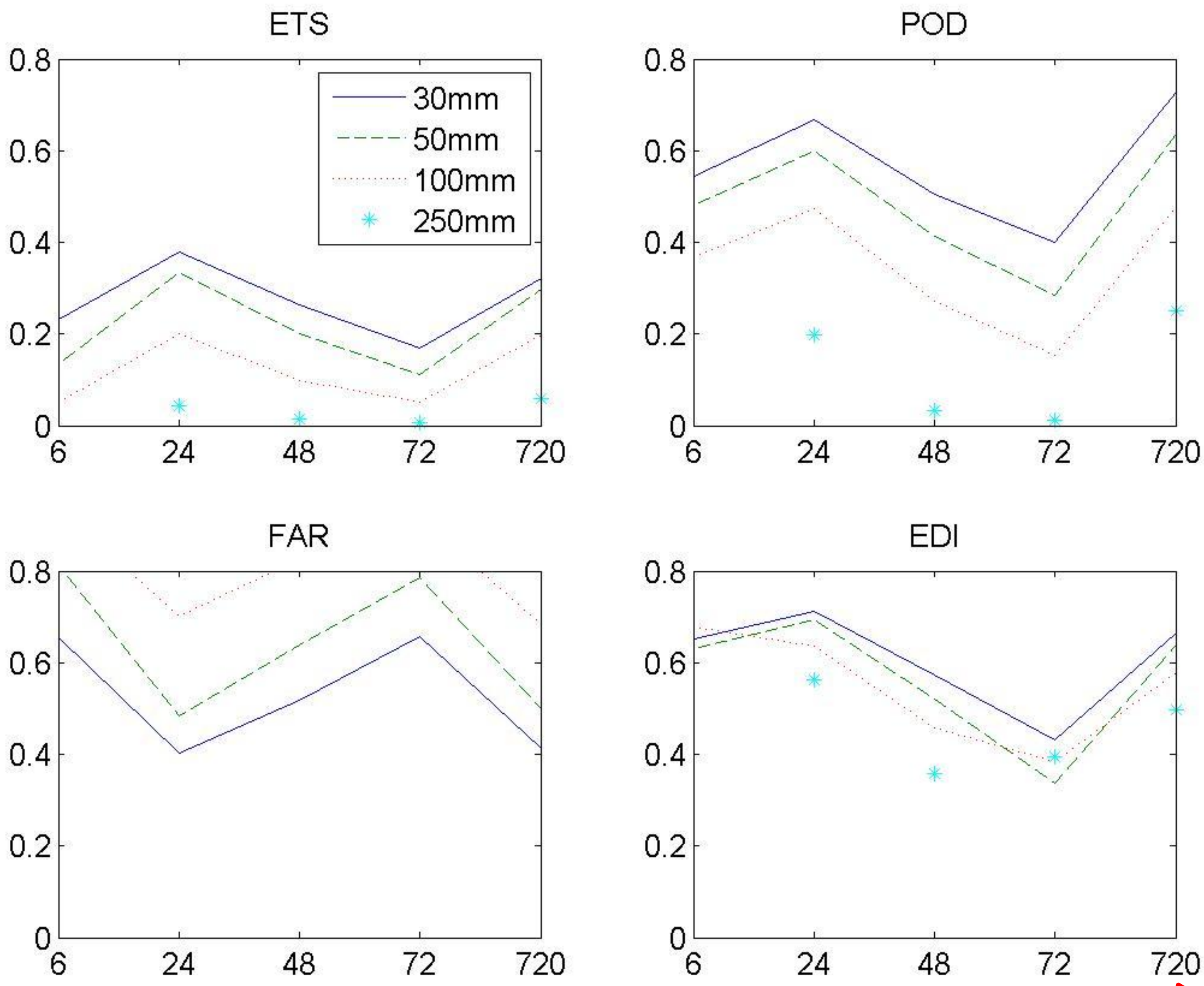
- **Rain error sources from**
  - **location**
  - **area (pattern)**
  - **intensity**
  - **orientation**
- **Could provide**
  - **Errors for each case**
  - **Systematic errors**
  - **Error sources**

Yu et al，2020

Data and methodology

- STI/CMA Best Track data (**2012-2015, 25 TCs**)
- Satellite-Gauge merged rainfall data (1h, 0.1degree)
- ACCESS_TC rain, track data (1h, 0.11degree)
- CRA verification method
- Time period: **24h before landfall – the end of a TC's life**

Conventional verification results

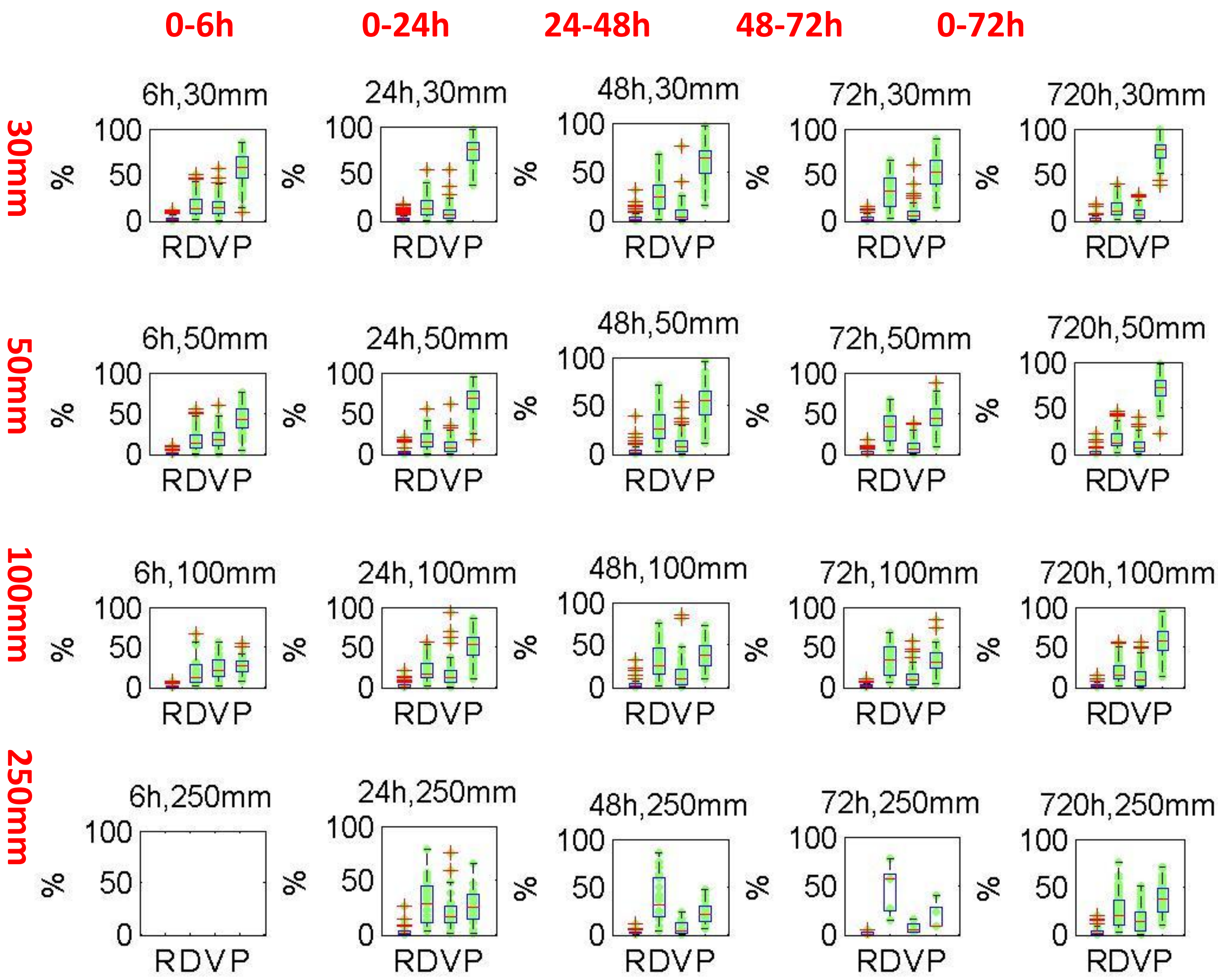


0-6h 0-24h 24-48h 48-72h 0-72h

Forecast time (hr)

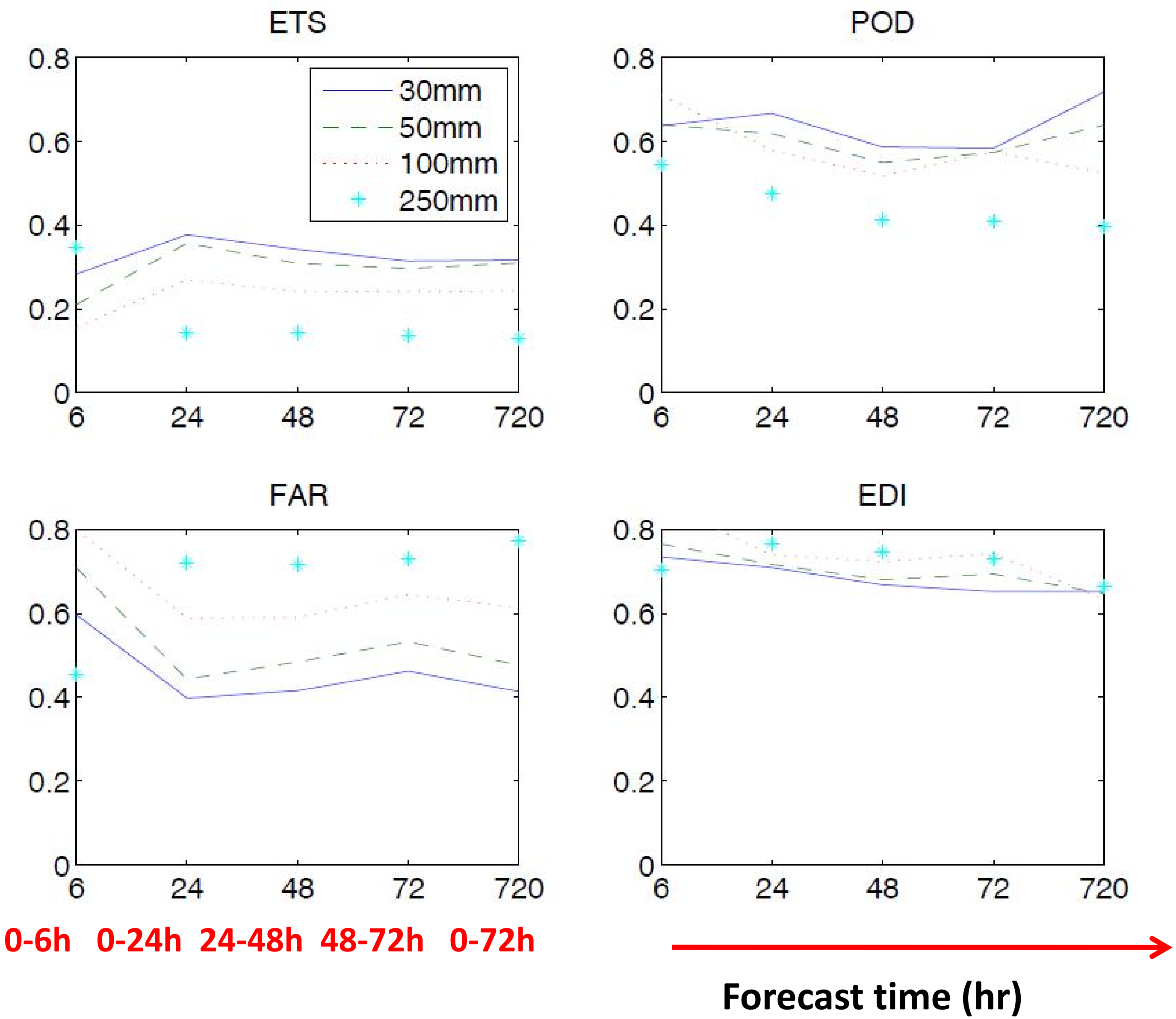
Yu et al. 2020

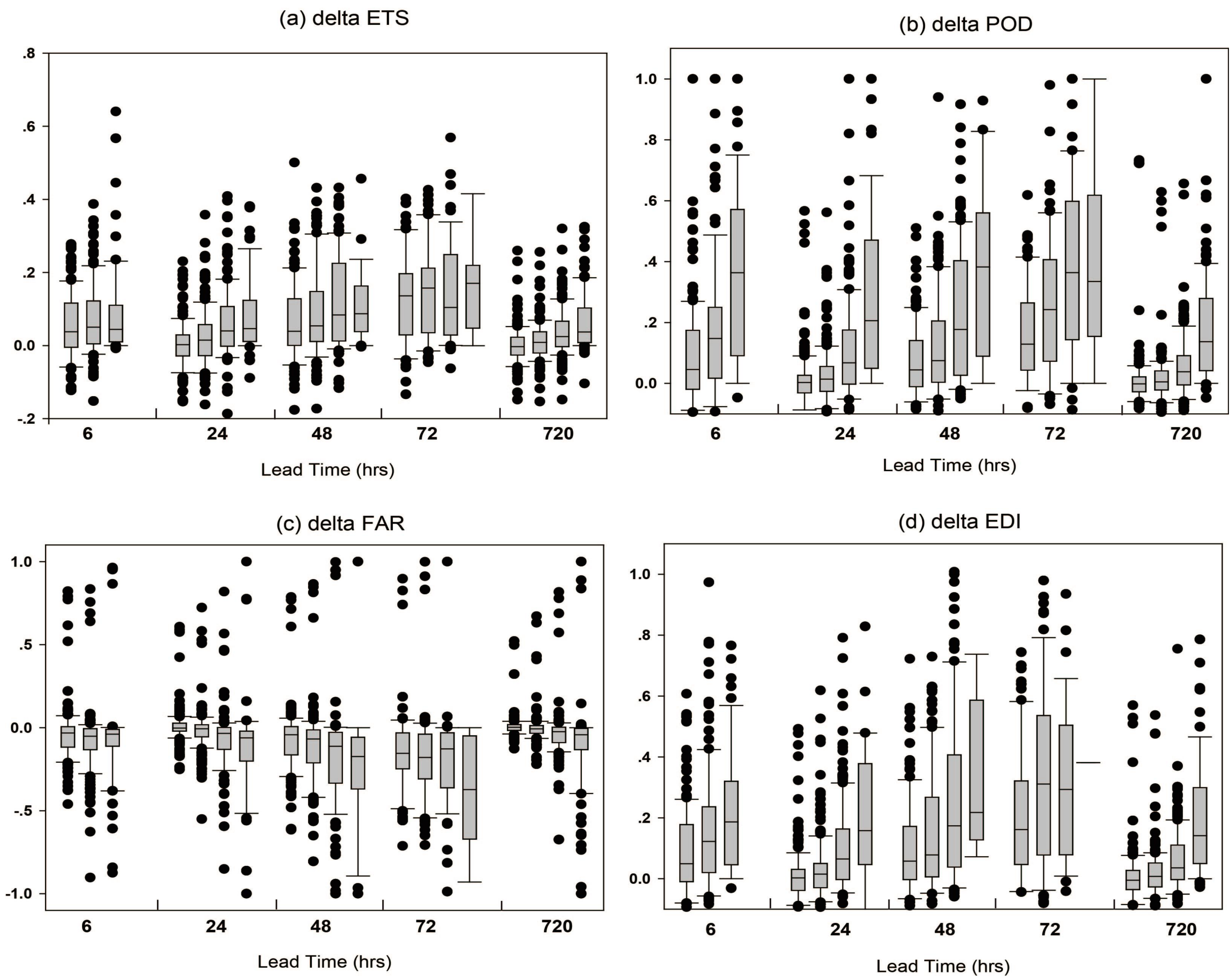
Error decomposition



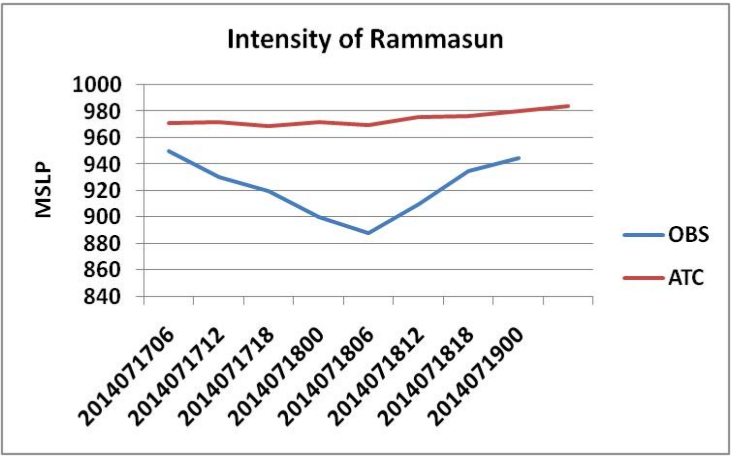
R, D, V, P: errors of Rotation, Displacement, Volume, Pattern (>50%)

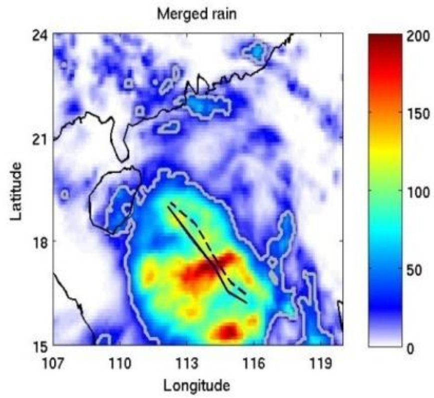
New verification results after shift

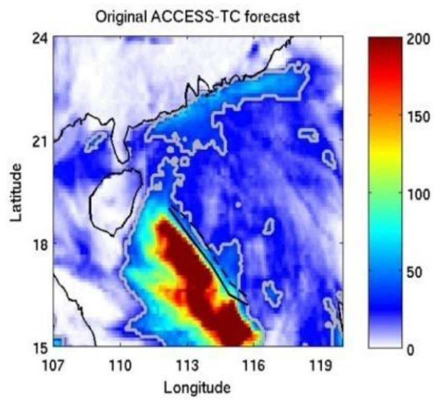


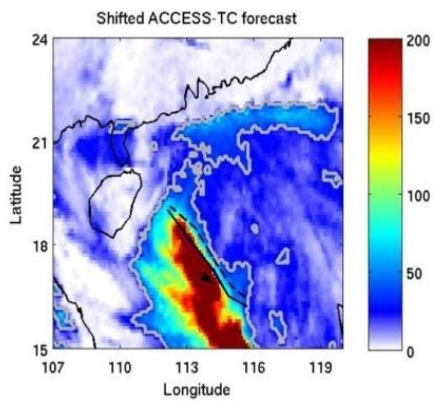

(a) delta ETS
.8
.6
.4
.2
0.0
-.2
6
24
48
72
720
Lead Time (hrs)
(b) delta POD
1.0
.8
.6
.4
.2
0.0
6
24
48
72
720
Lead Time (hrs)
(c) delta FAR
1.0
.5
0.0
-.5
-1.0
6
24
48
72
720
Lead Time (hrs)
(d) delta EDI
1.0
.8
.6
.4
.2
0.0
6
24
48
72
720
Lead Time (hrs)

Case 1: Rammasun (2014)









CRA Rammasun2014.2014.07.17.00-2014.07.18.00,24lead

Verif. grid= 0.10° CRA threshold= 30 mm d^{-1}

	Obs	Fcst
Gridpoints >= 30 mm d^{-1}	3174	2543
Average rainrate (mm d^{-1})	59	62
Maximum rainrate (mm d^{-1})	203	695
90% rainrate (mm d^{-1})	123	165
Rain volume (km^3)	32	34

Displacement (E,N,Rot)=[0.47, -0.27, -10]

	Fcst	Move	M+R
Correlation coefficient	0.54	0.59	0.62
RMSE (mm d^{-1})	82.8	75.6	67.5

Skill scores (30mm threshold):

Probability of detection (POD)	0.62	0.55
False alarm ratio (FAR)	0.28	0.32
Equitable threat score (ETS)	0.39	0.32
Extremal dependence index (EDI)	0.67	0.60

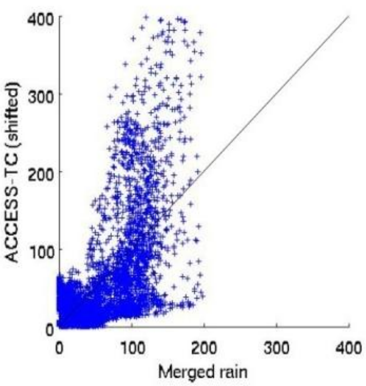
Error decomposition:

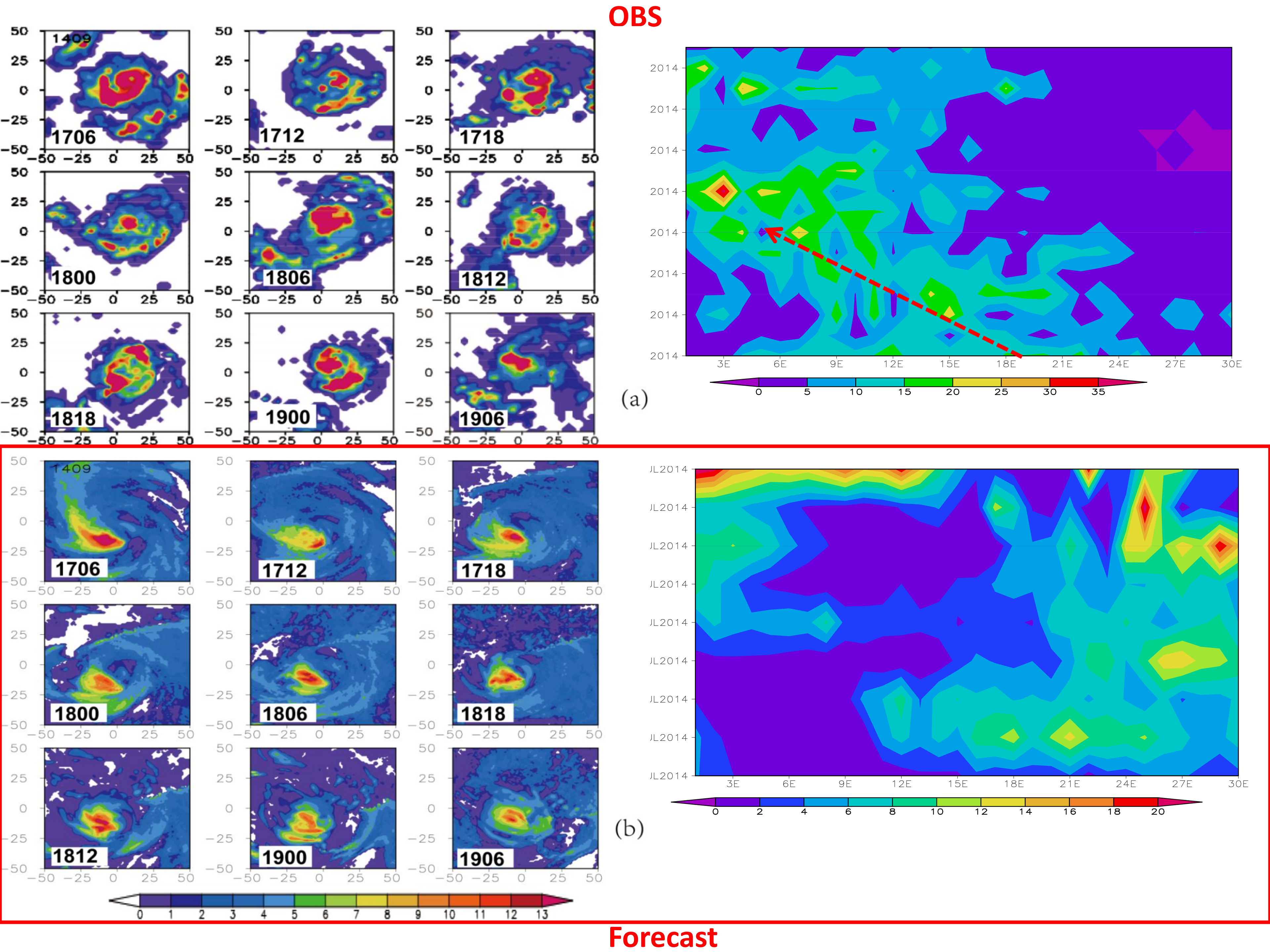
Rotation error = 4%

Displacement error = 6%

Volume error = 0%

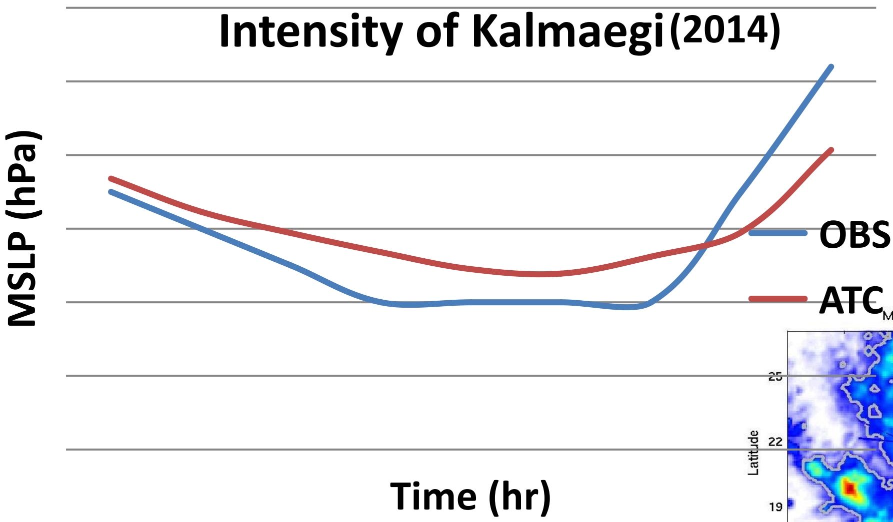
Pattern error = 90%

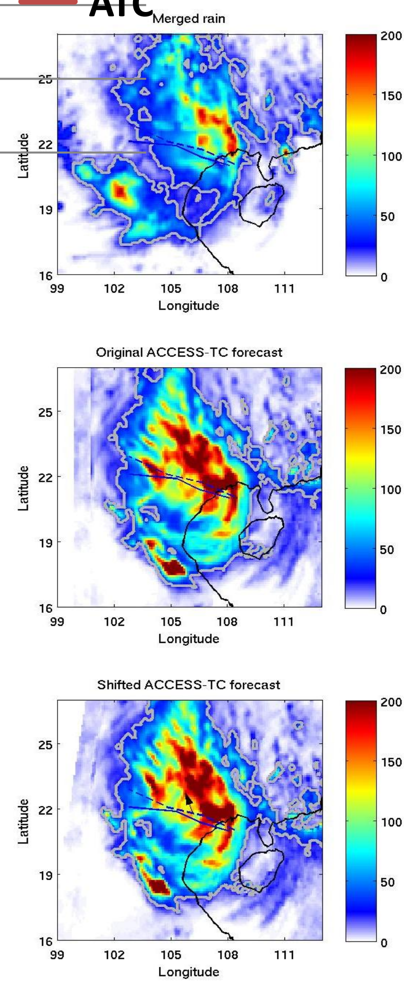




OBS
1409
1706
1712
1718
1800
1806
1812
1818
1900
1906
2014
3E 6E 9E 12E 15E 18E 21E 24E 27E 30E
0 5 10 15 20 25 30 35
(a)
1409
1706
1712
1718
1800
1806
1818
1812
1900
1906
JL2014
3E 6E 9E 12E 15E 18E 21E 24E 27E 30E
0 2 4 6 8 10 12 14 16 18 20
(b)
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Forecast

Case 2: Kalmaege (2014)





CRA Kalmaegi2014.2014.09.16.12-2014.09.17.12,24lead

Verif. grid= 0.10 ° CRA threshold= 25 mm d⁻¹

	Obs	Fcst
Gridpoints >= 25 mm d^{-1}	5281	5797
Average rainrate (mm d^{-1})	45	71
Maximum rainrate (mm d^{-1})	222	532
90% rainrate (mm d^{-1})	90	159
Rain volume (km^3)	39	62

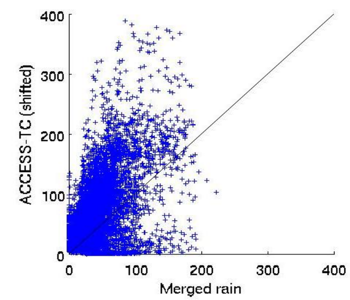
Displacement (E,N,Rot)=[-0.05, 0.41, -10]

	Fcst	Move	M+R
Correlation coefficient	0.41	0.50	0.52
RMSE (mm d^{-1})	64.1	60.3	60.0

Skill scores (25mm threshold):

Probability of detection (POD)	0.78	0.77
False alarm ratio (FAR)	0.30	0.30
Equitable threat score (ETS)	0.40	0.41
Extremal dependence index (EDI)	0.74	0.74

Error decomposition:
Rotation error = 2%
Displacement error = 9%
Volume error = 17%
Pattern error = 72%

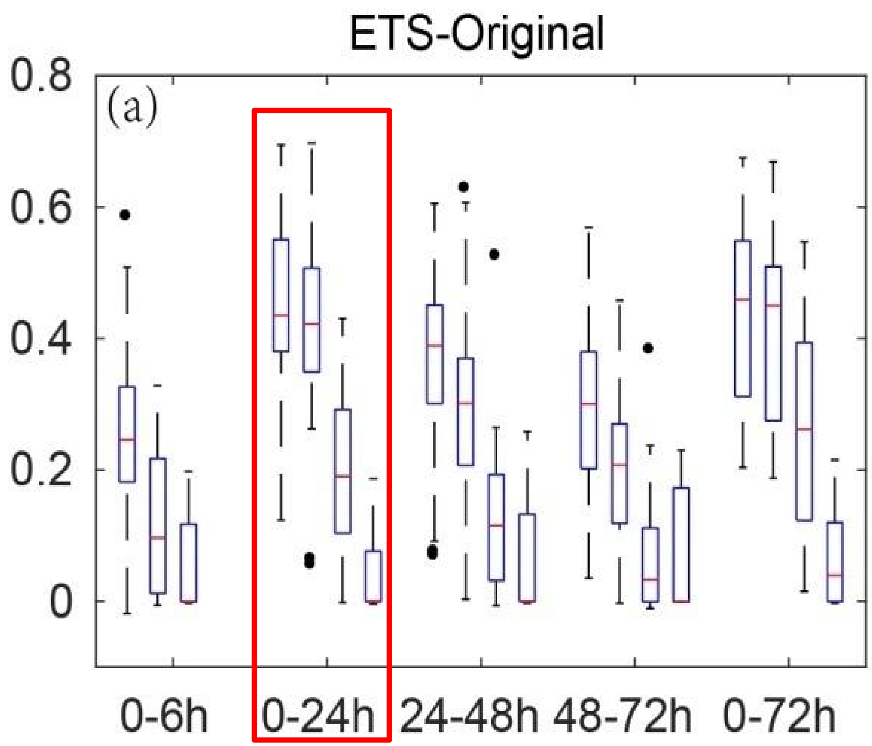


- More work is needed to improve the initialization and prediction of TC structure.

ECMWF Rainfall verification results

Table 1 Forecast cases for typhoons landing in or approaching near China in 2019.

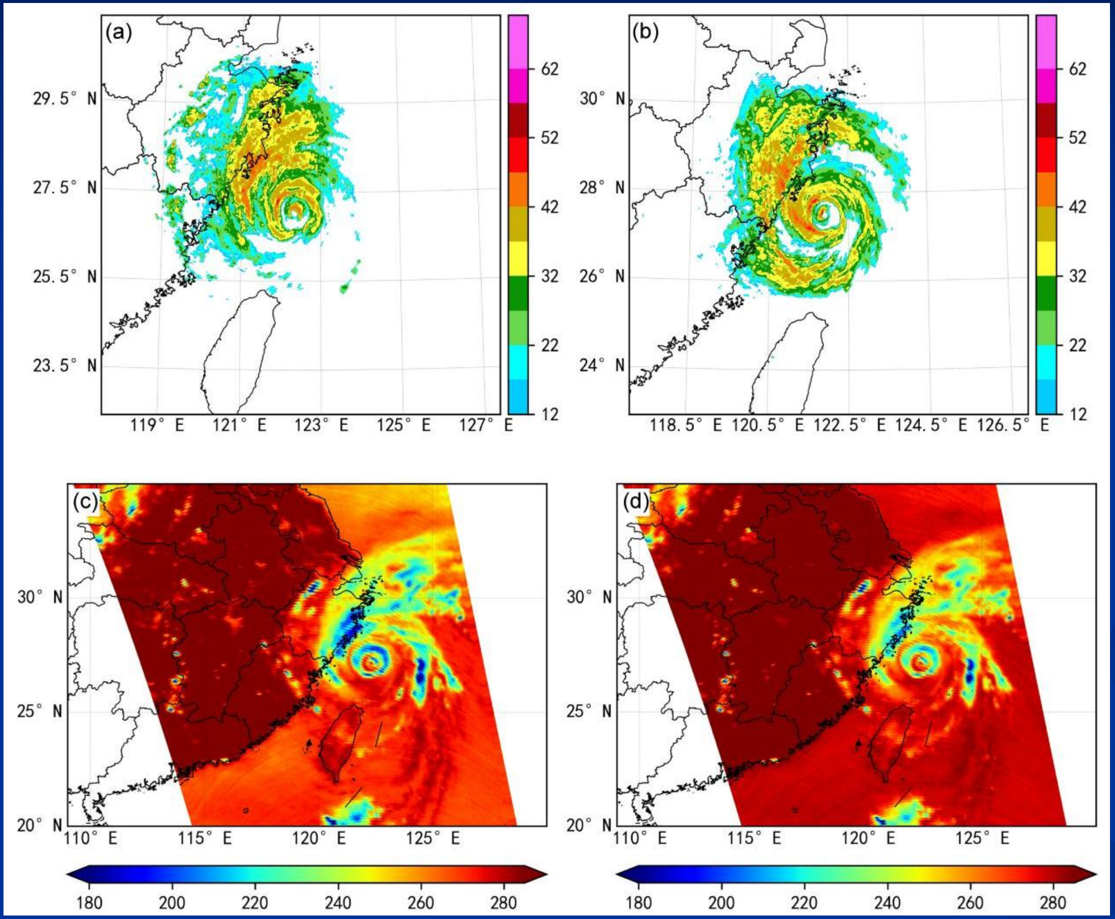
台风名称	模式初始时次范围	模式预报次数
Mun	2019.07.02-2019.07.04	4
Wipha	2019.07.30-2019.08.03	7
Lekima	2019.08.08-2019.08.13	8
Bailu	2019.08.24-2019.08.25	4
Podul	2019.08.28-2019.08.29	3
Lingling	2019.09.06-2019.09.07	3
Tapah	2019.09.20-2019.09.22	5
Mitag	2019.09.30-2019.10.02	5



He and Yu, 2023

For 25, 50, 100, 250 mm

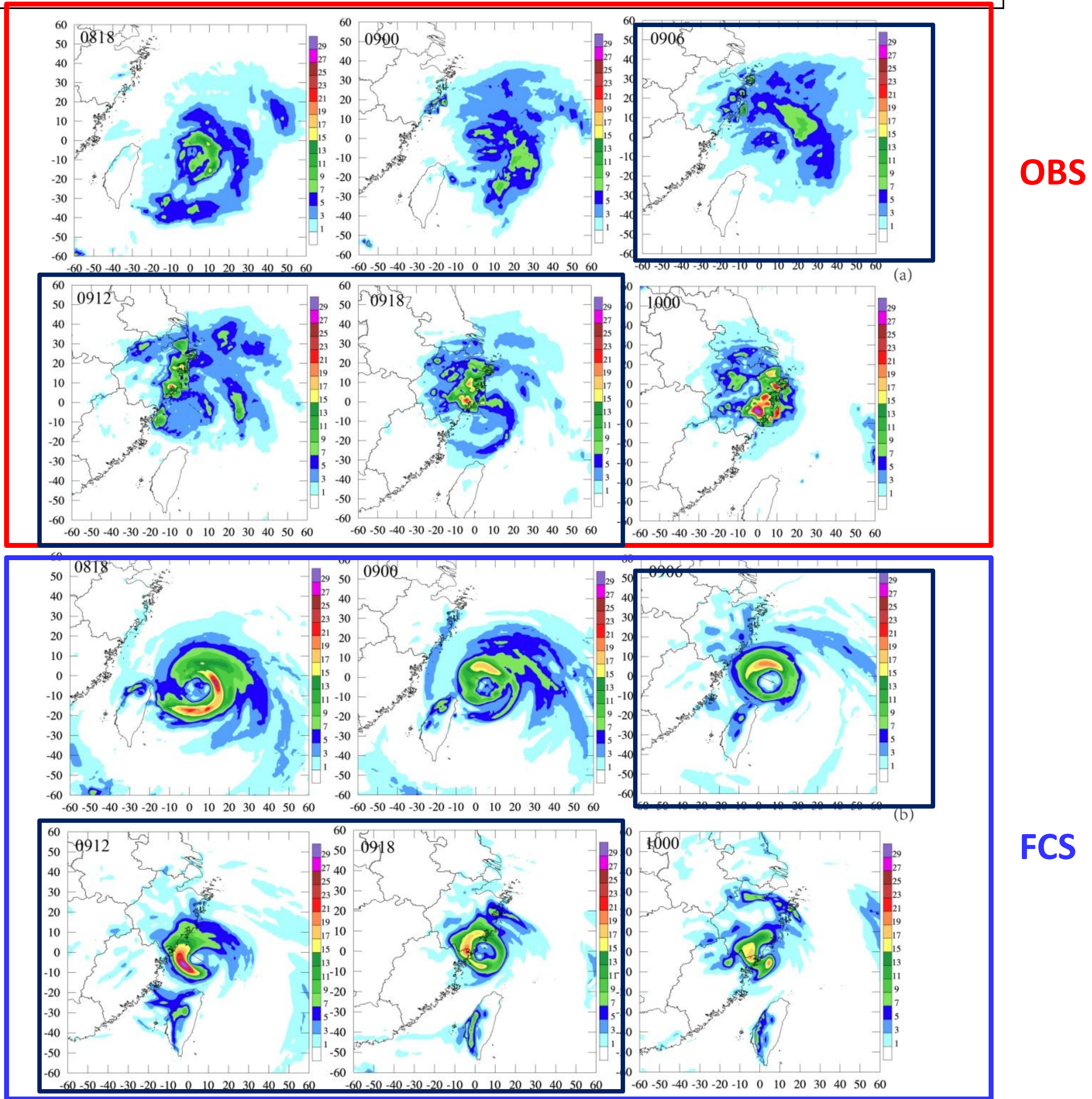
QPF Example: Lekima (1909)



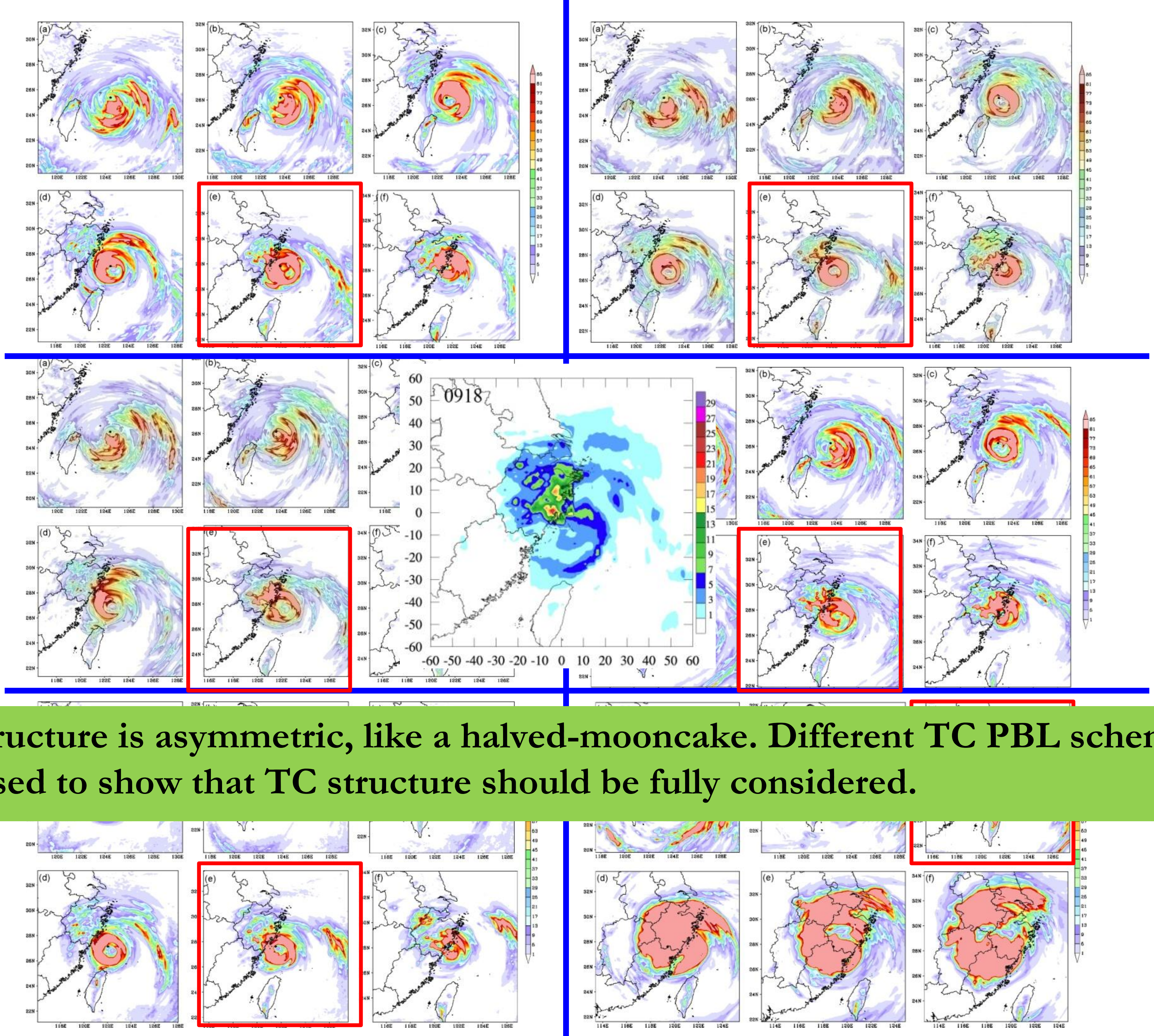
A Super typhoon **Lekima (1909)** reached its maximum wind speed (MWS) of 62 m s^{-1} and made landfall to Wenling city of Zhejiang province of China, with MWS of 52 m s^{-1} and MSLP of 930 hPa.

6-h Rainfall evolution near landfall

Lekima (2019)

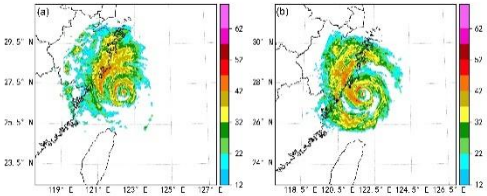


WRF

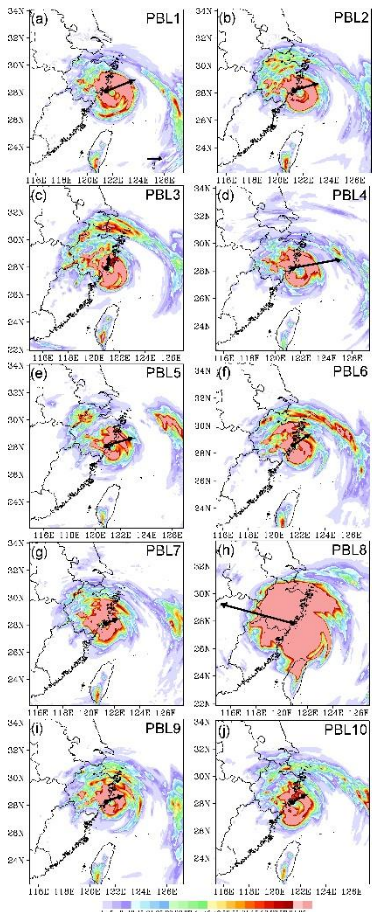


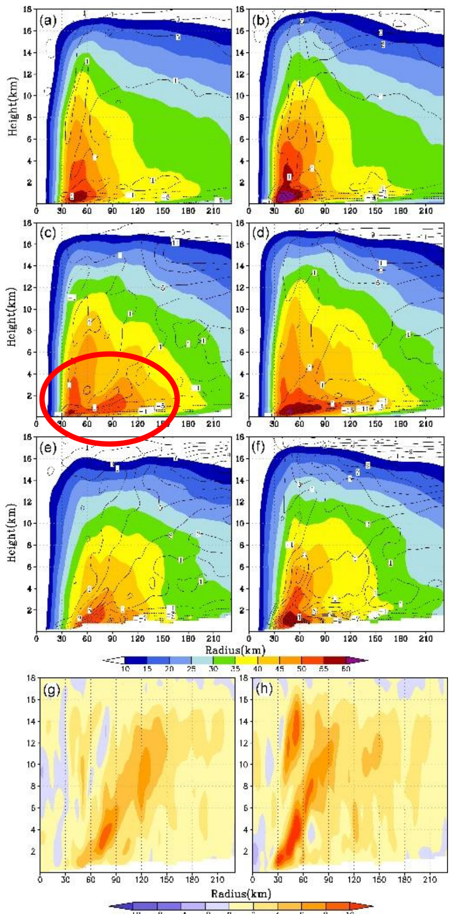
Its structure is asymmetric, like a halved-mooncake. Different TC PBL schemes are used to show that TC structure should be fully considered.

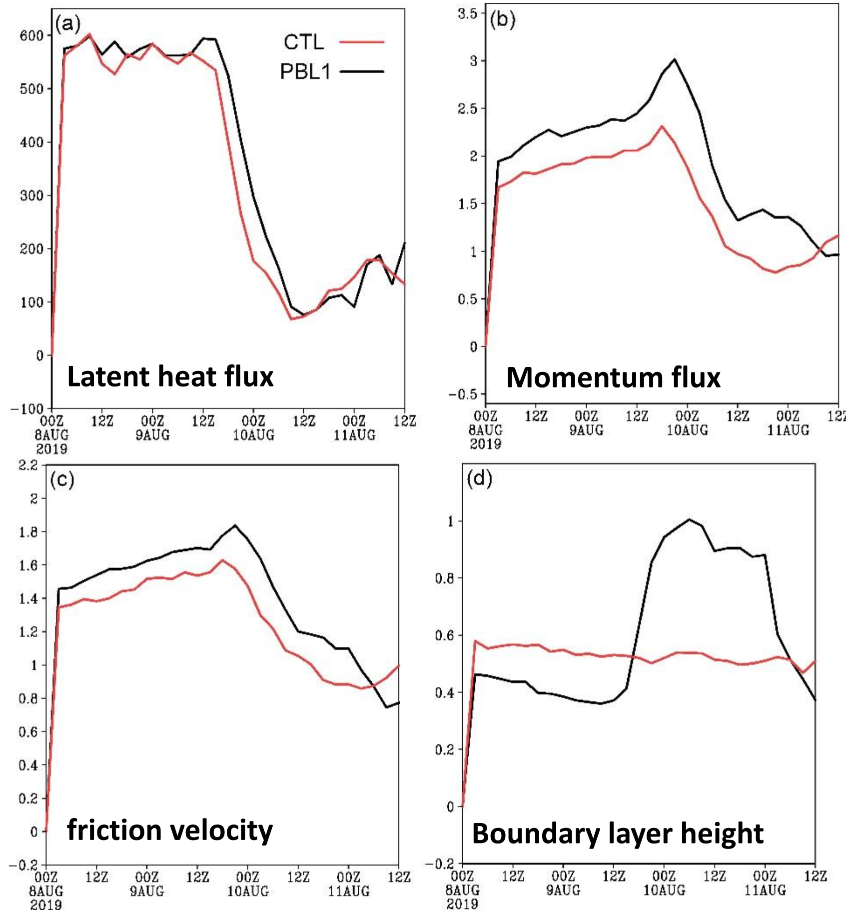
Sensitivity test



Near landfall





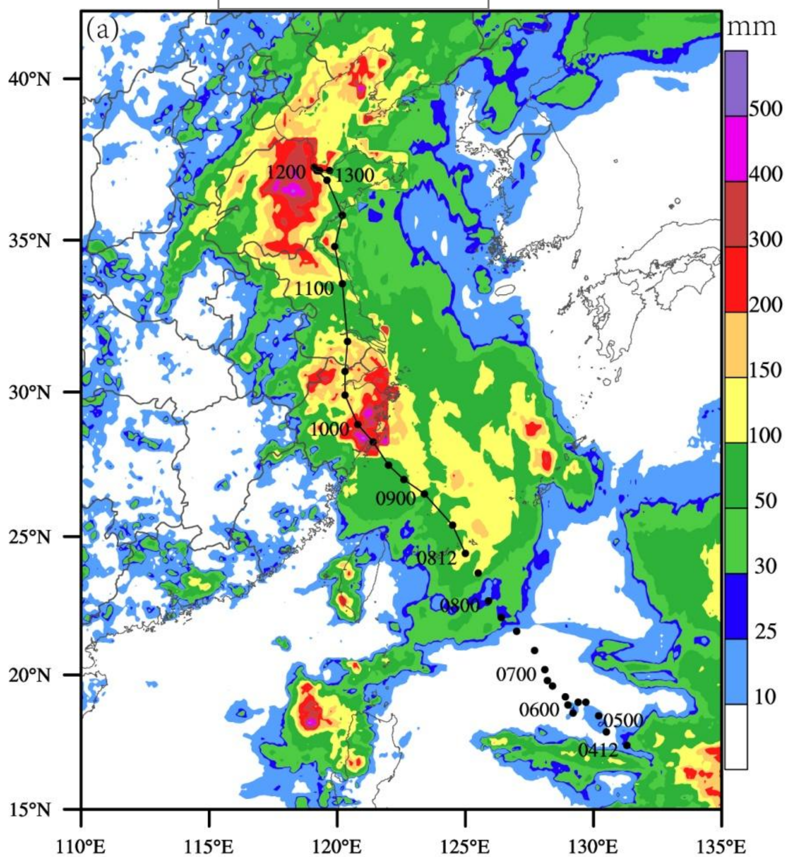


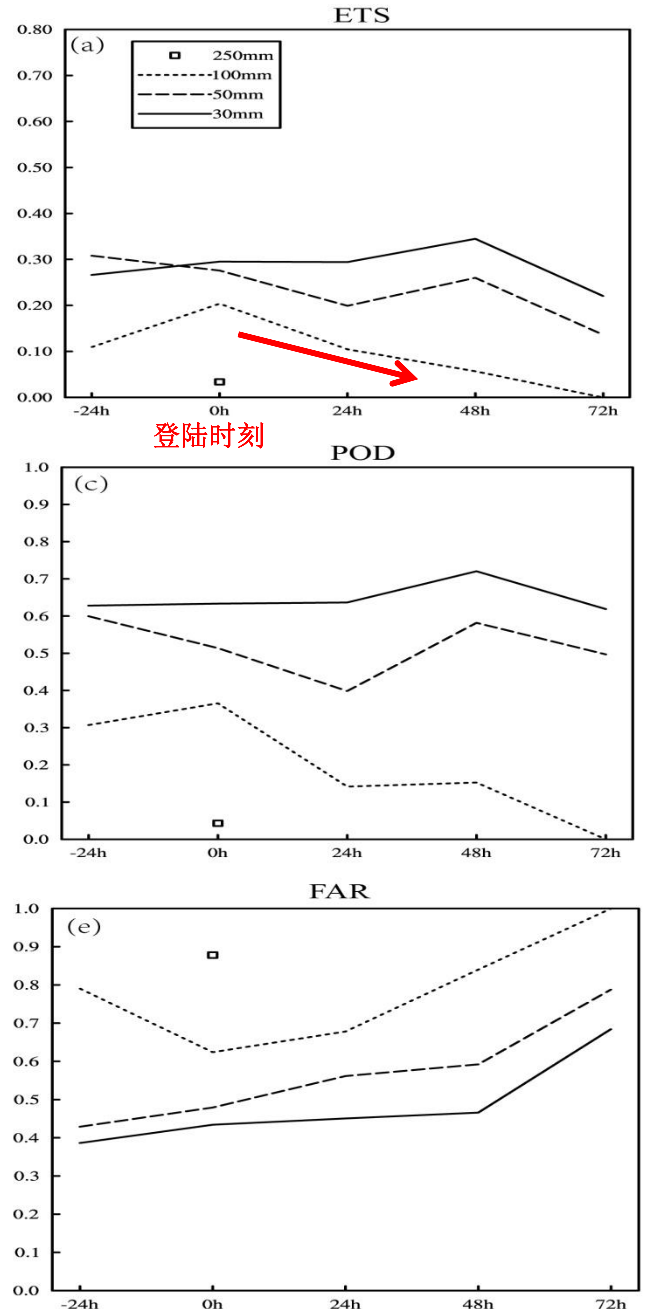
● **Model PBL schemes largely influence the simulated tropical cyclone (TC) intensity and structure including asymmetric rainfall distribution during landfall.**

Duan and Yu*, 2022

Forecast ability in different landfall stages

Lekima (2019)





He et al. (2022)

Outline

- TC rainfall verification
- **Some methods to make QPF improvements**
- Summary

1. Data assimilation for TC QPFs

Initial conditions significantly affect the prediction by numerical models. In particular, a poor representation of a TC in the initial condition can lead to poor or even unsuccessful forecasts of the TC structure, and thus false QPFs for the TC. **Doppler radar observations from onshore radar sites provide useful information about the storm structures of a tropical cyclone near landfall.**

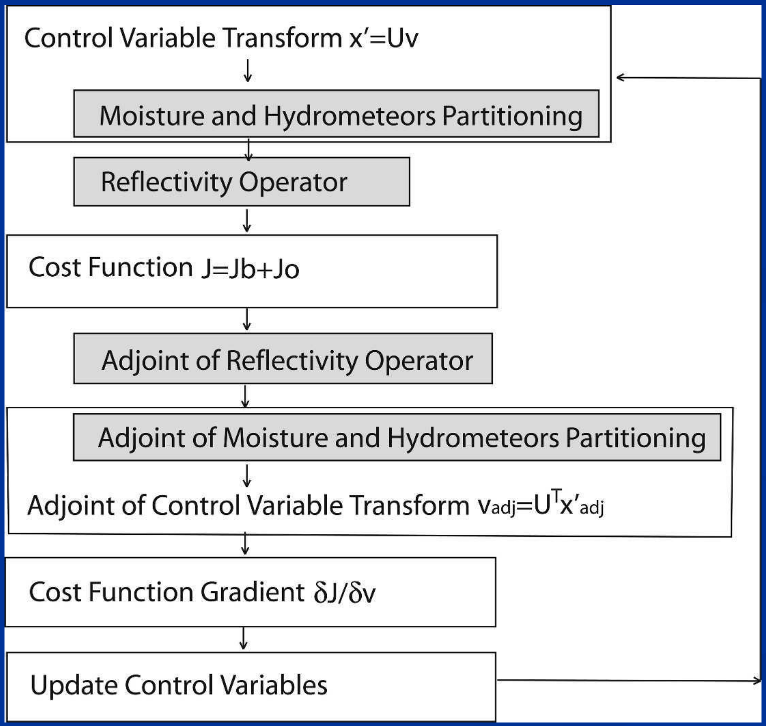
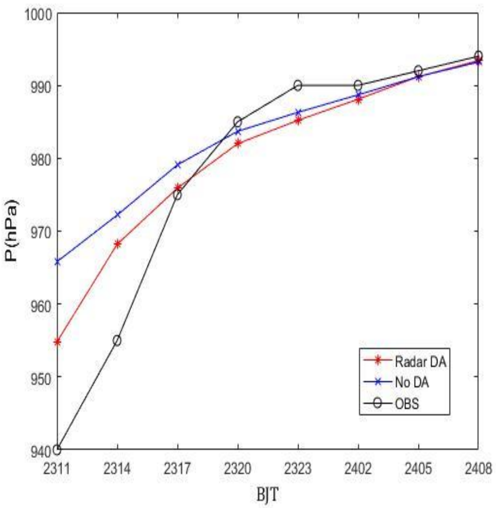


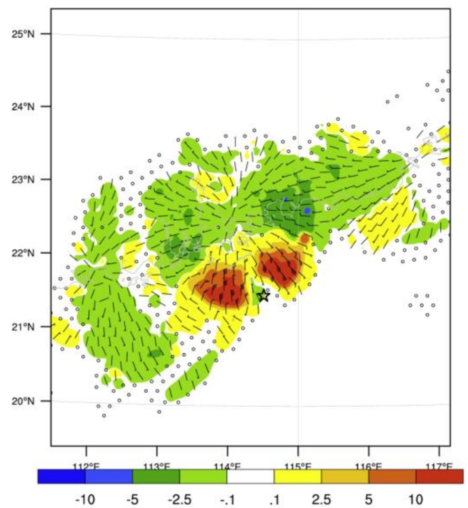
FIG. Flowchart of the radar reflectivity data assimilation in minimization procedure of the MM5 3DVAR system. The new additions of the reflectivity assimilation components to the 3DVAR are shaded. From Xiao et al. (2007).

Data assimilation of radar radial wind

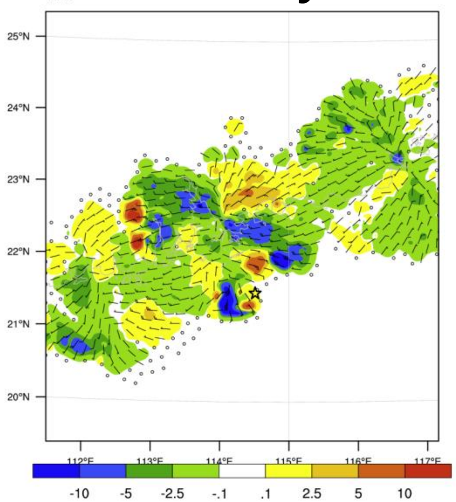
Hato（2017）



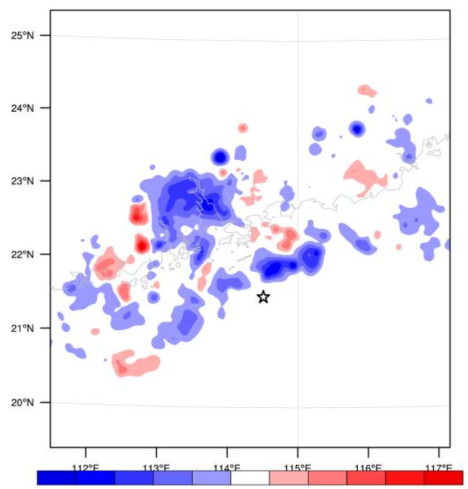
24h Intensity forecasts



500hPa wind



700hPa wind



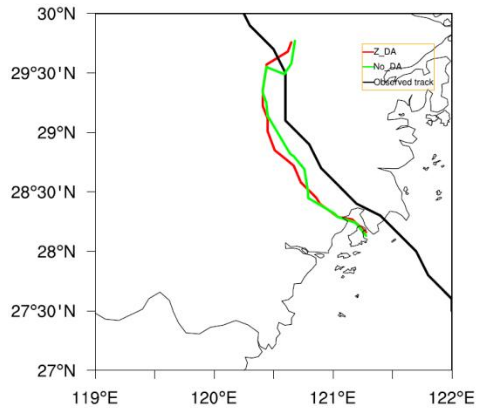
Moisture

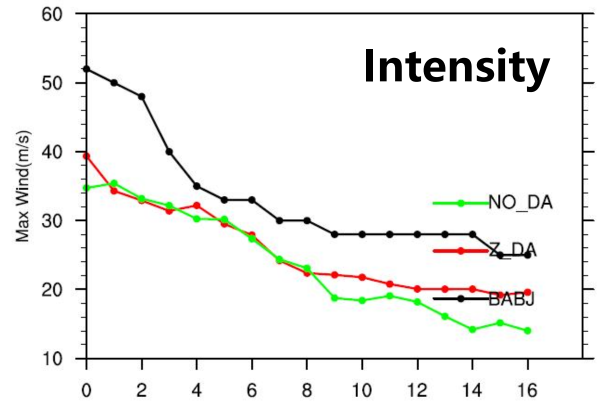
(Luo J., 2019)

GSI-EnKF data assimilation of radar Reflectivity

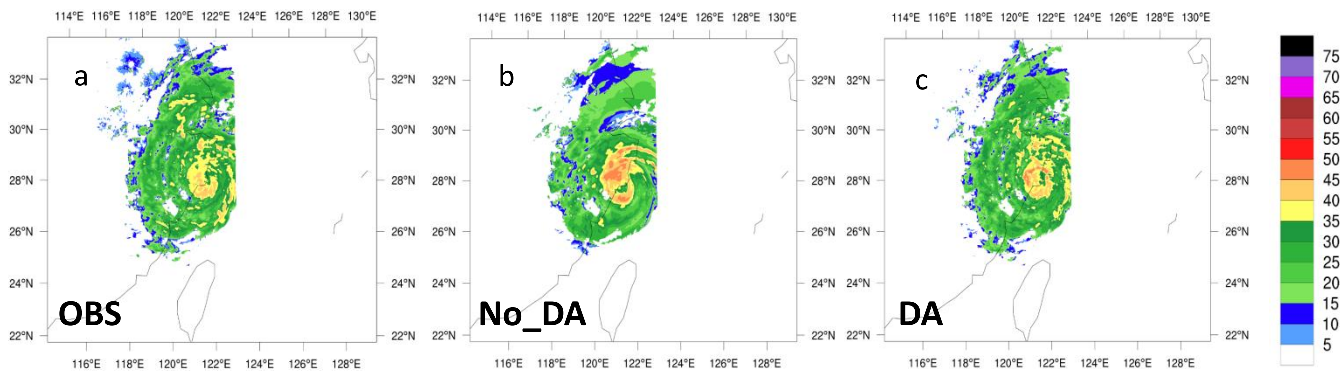
Lekima（2019）

Track

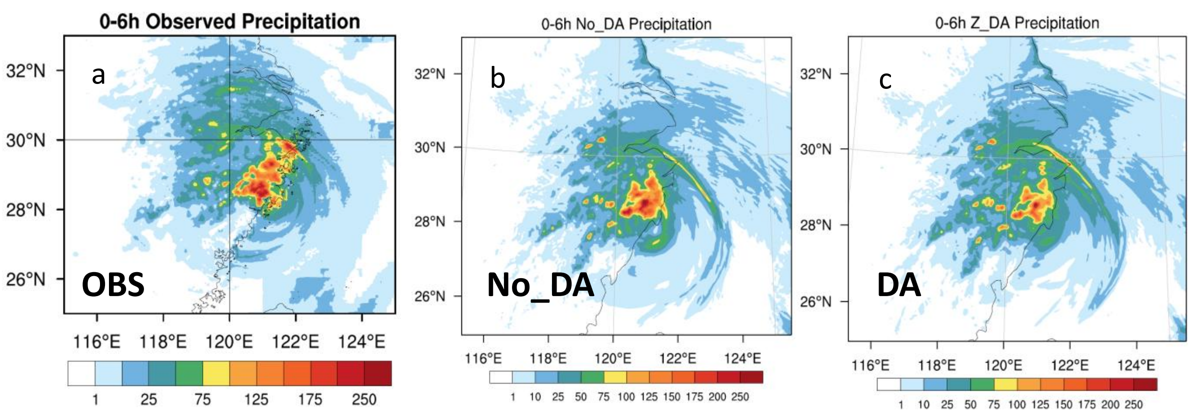




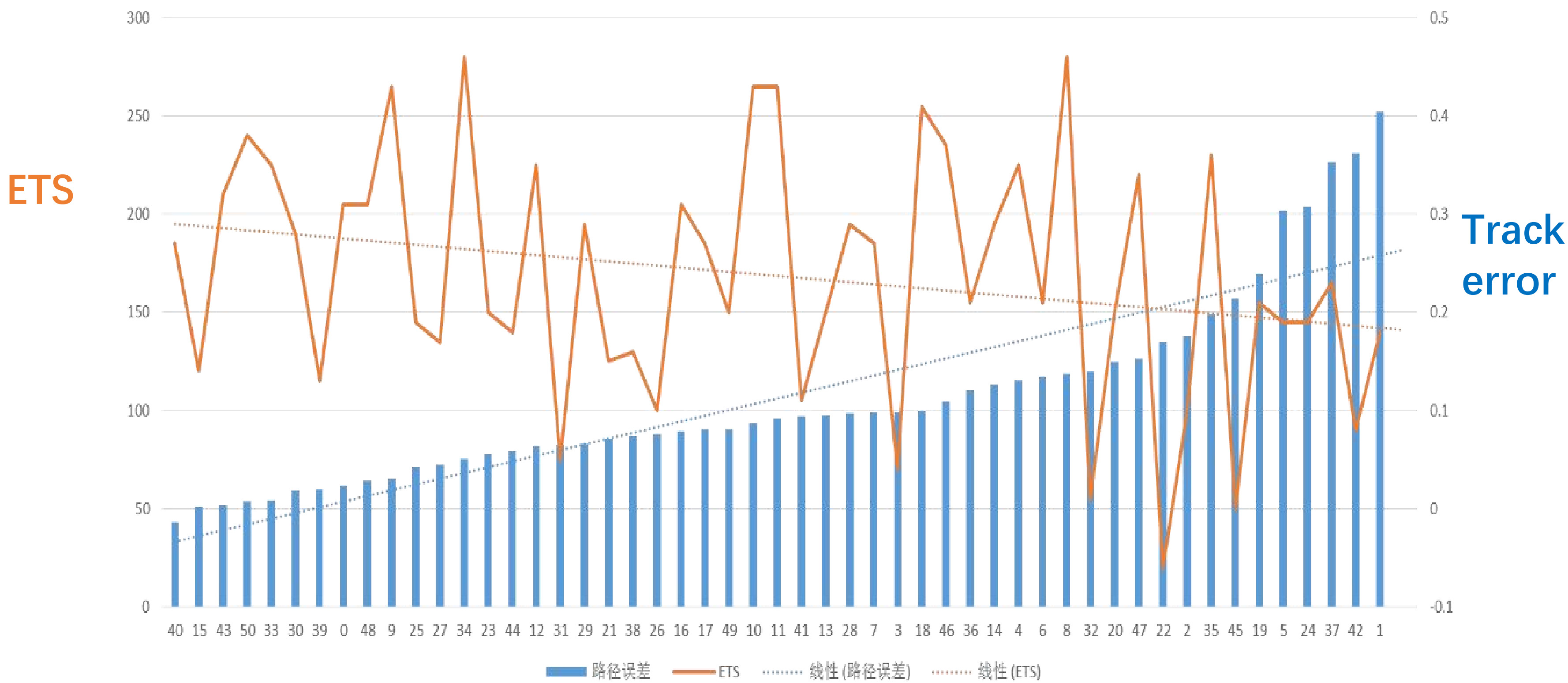
dBZ



Rainfall



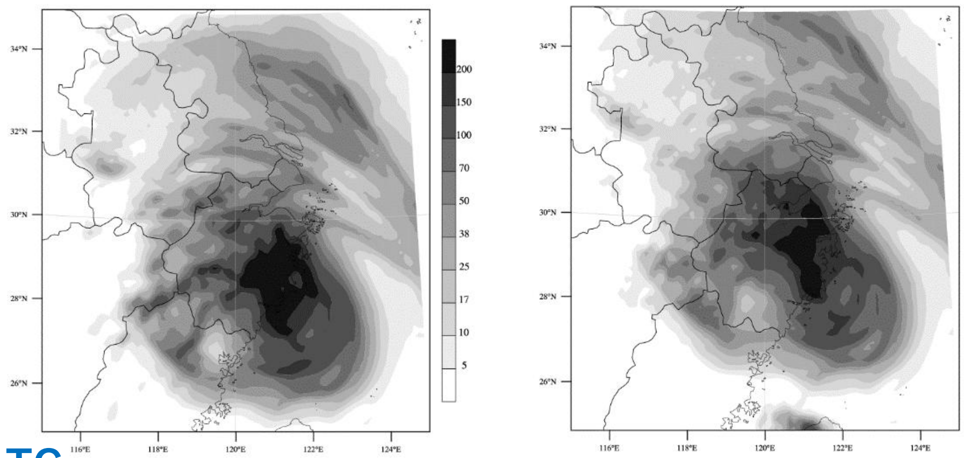
2. TC track modification and QPF improvements



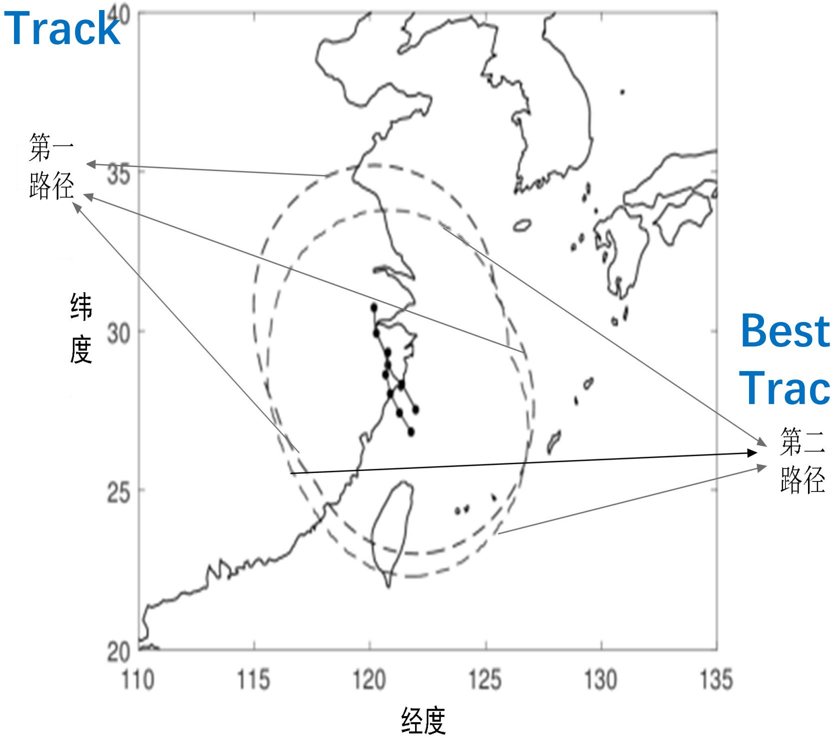
Mean errors of TC track and ETS of QPF

(Ji X., 2019)

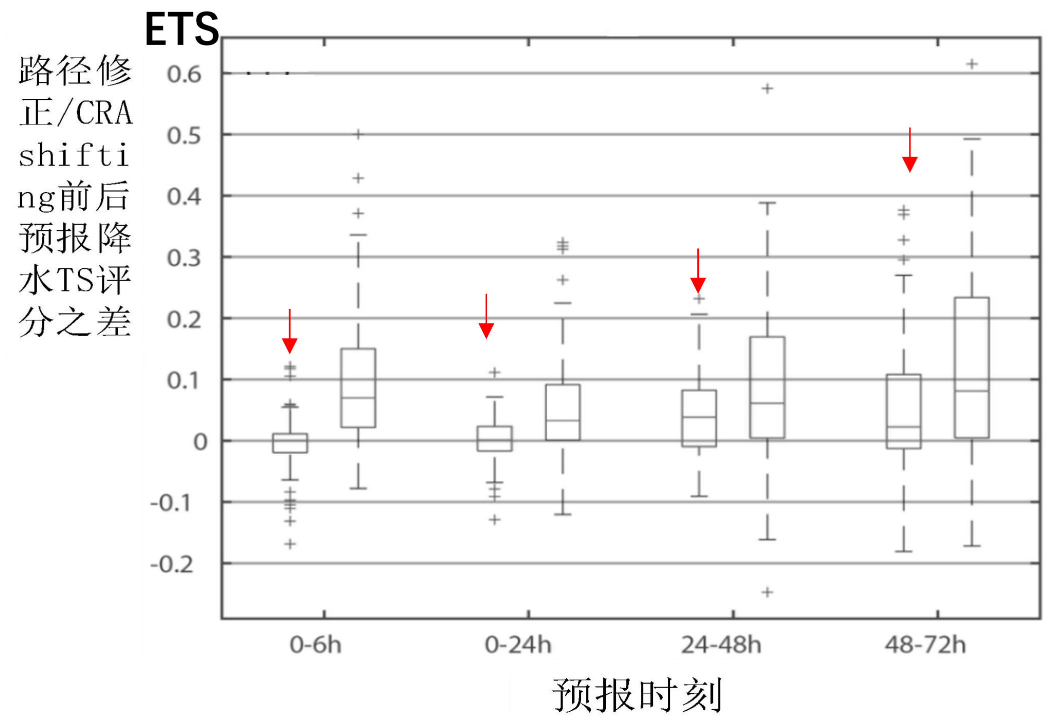
Corrected Rainfall forecasts based on TC track shift



TC forecast Track



Best TC Track



3. TER – method
for QPF correction considering terrain effects

Consider the additional rainfall caused by terrain (P_{eff}), and add it to the model forecast rainfall (P_{ec}) to get the corrected rainfall forecasts (P_{dz}):

$$P_{dz} = P_{ec} + P_{eff}$$

where,

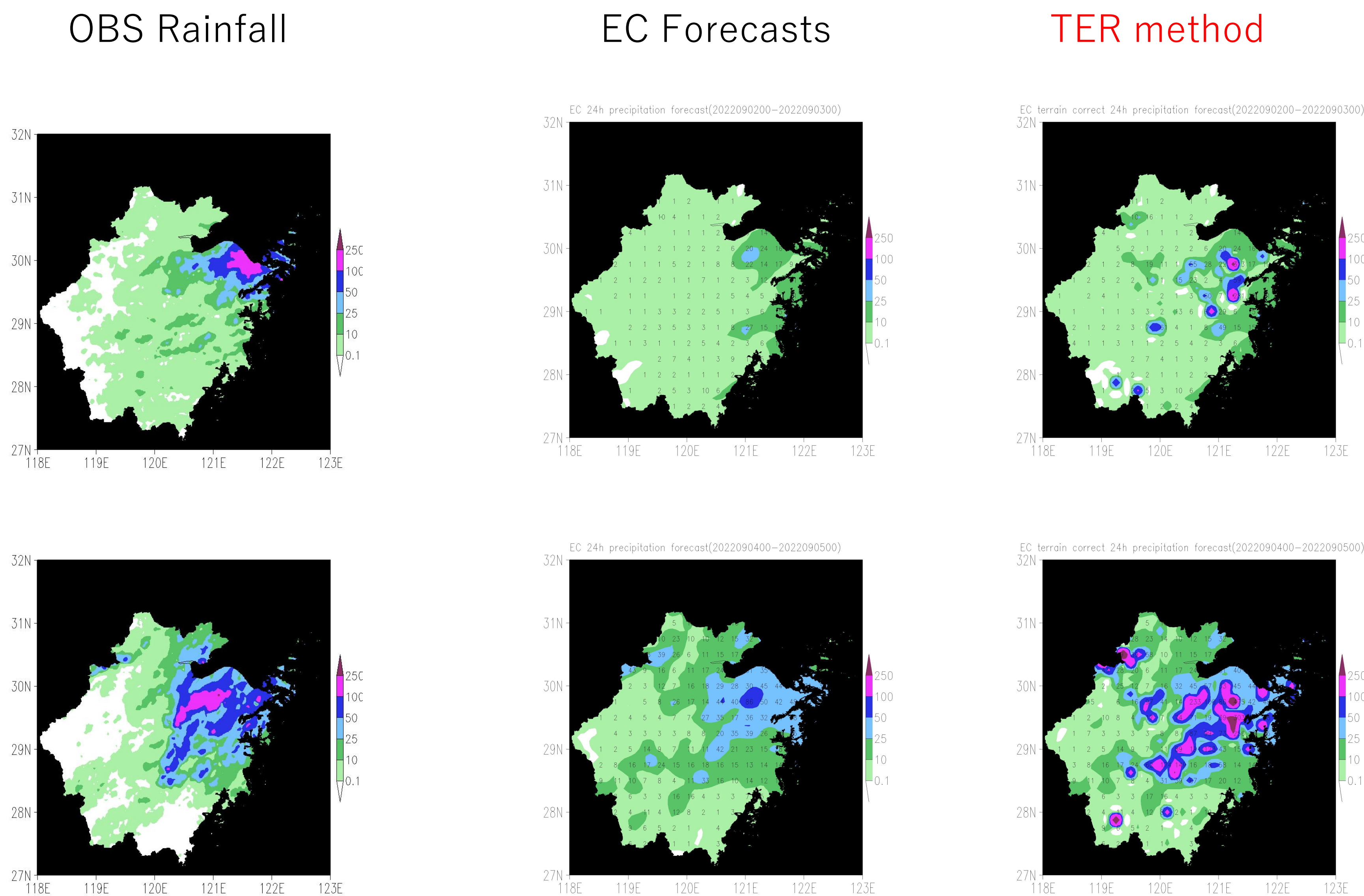
$$P_{eff} = R * T * E$$

T is time, E is rain effiency (0.25), R is rain rate caused by upslope of terrain.

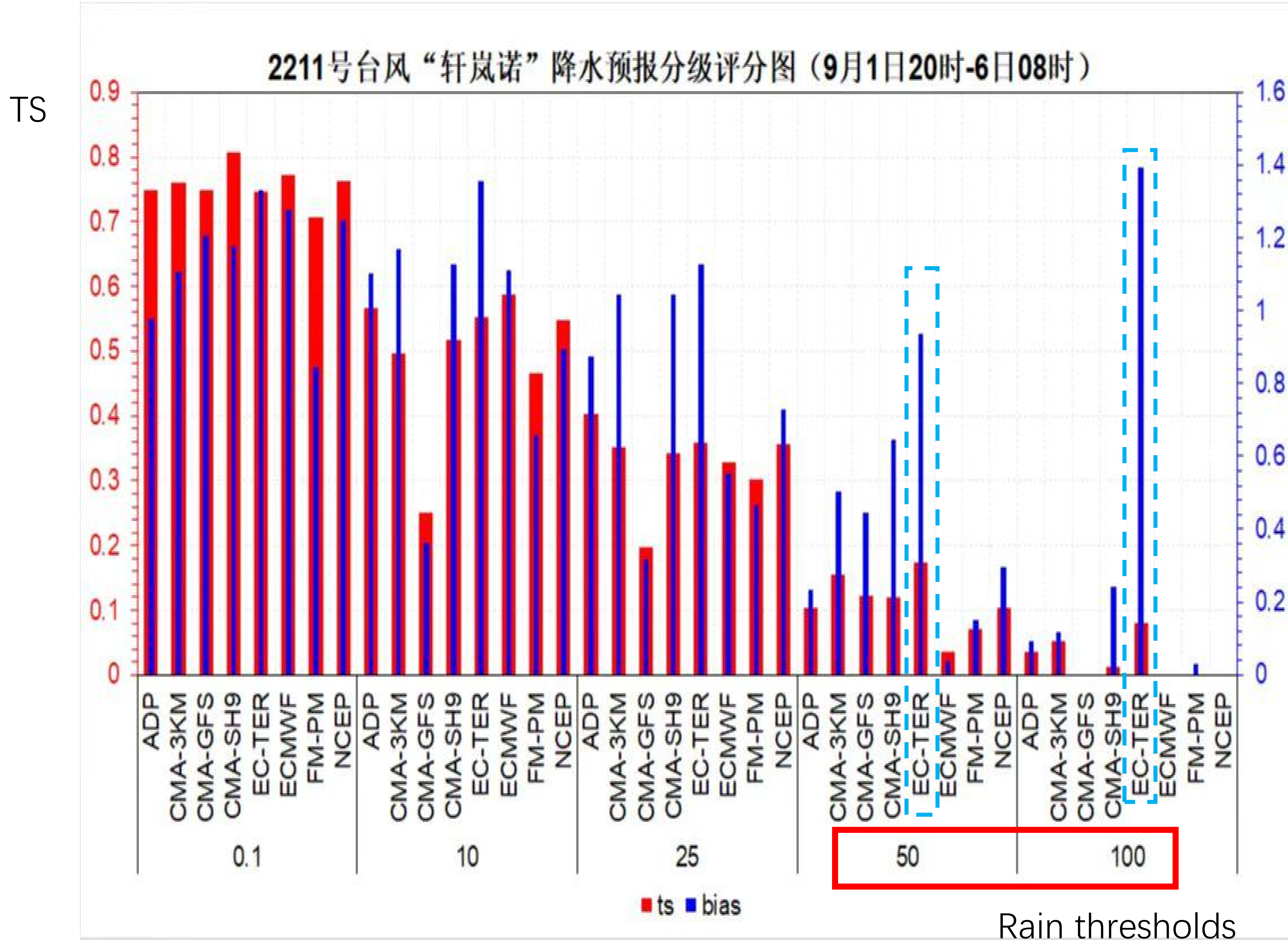
$$R = \int_0^{\infty} w \frac{d\rho_{w_s}}{dz} \quad \textbf{(Smith, 1979)}$$

$$w(z) = \vec{V}(z) \cdot \nabla H = u(z)\frac{\partial H}{\partial x} + v(z)\frac{\partial H}{\partial y}$$

(Xu Y., 2019)



2211 Typhoon Hinnamnor in 2022



EC-TER is the TER method

Conclusions

- **For the extremely heavy rain event (>250mm) of LTCs, current model forecast ability is very low.**
- **The maximum rain forecast error rescource is from the Pattern error in general, while for the very heavy rainfall(>100mm) it is from the Displacement error (which is likely related to the TC track error).**
- **Rainfall prediction will continue to be improved with improved track prediction.**
- **But more work is needed on initialization and prediction of TC structure.**

Remaining issues and challenges in the rainfall distribution of landfalling TCs (LTCs)

- ✓ **Most of the findings discussed are basic understanding and based on the composite analyses of satellite retrieved products, so that individual LTC may be considerably deviated from the composite because of other possible involved complex scale multiple interactions and the complicated effect of topography.**

- ✓ **Limited observational capability of rainfall in LTCs, such that the satellite quantitative precipitation estimates for LTCs still need large improvements because of their existing limitations, e.g., they would underestimate the heavy rain rates and the maximum rain rates.**

- ✓ **Still rainfall forecast ability of numerical forecast models is very limited, especially for the extremely heavy rainfall (>250 mm).**

✓The rainfall diurnal cycle in LTCs has recently been revealed, but more work is needed to understand the involved physical mechanisms.

✓The extreme rainfall in spiral rainbands is another topic not discussed/included here but needs to be investigated because many extreme rainfall events in LTCs could be induced in spiral rainbands not in the inner core region.

✓Particularly, with the development of both new observing systems and advanced numerical weather prediction models, some important physical processes, such as the boundary layer process and cloud microphysics could be investigated and understood more comprehensively in the near future.

Thank you for your attention！
Any qustions?

Main references：

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•He Bin, **Zifeng Yu*,** Yan Tan, Yan Shen, 2022: Rainfall forecast ability in different lifetime of Lekima (2019) during landfall, *Frontiers of Earth Science*, https://doi.org/10.1007/s11707-021-0894-9.

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•Yu Hui, Y. Wang and H. Xu, et al., 2022: Are We Reaching the Limit of Tropical Cyclone Track Predictability in the Western North Pacific? *BAMS. https://doi.org/10.1175/BAMS-D-20-0308.1*.

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