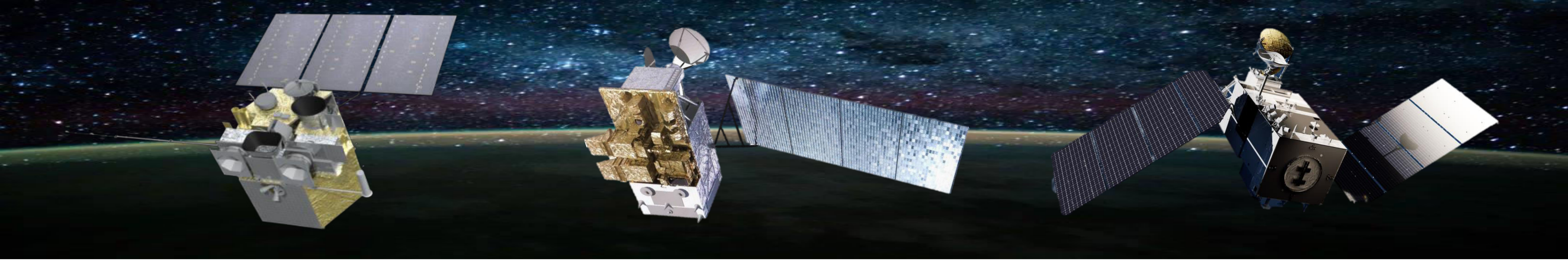

Retrieval of Tropical Cyclone Inner-core Size from Geostationary Satellite Infrared Imagery

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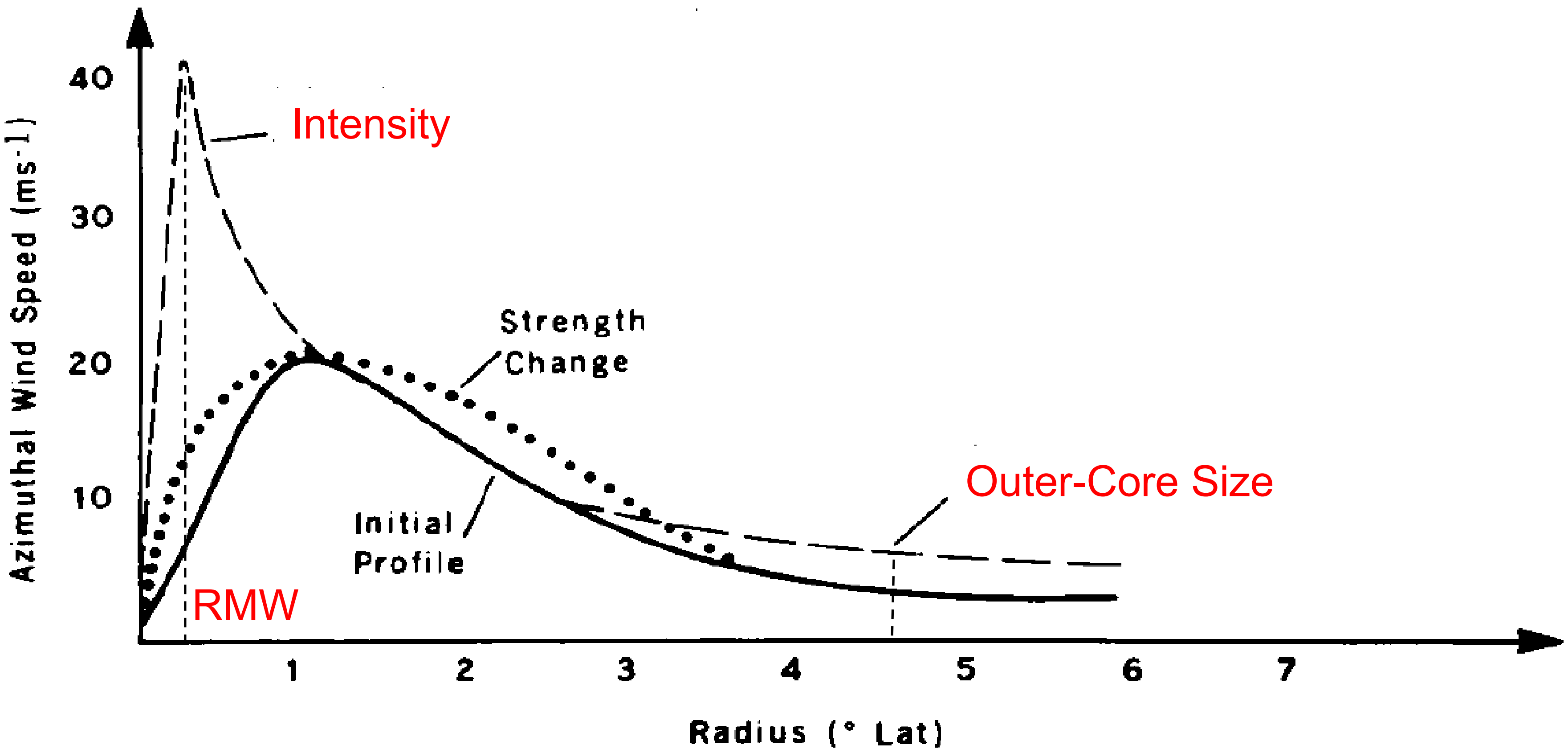
December 3, 2025

Outline

- Backgrounds
- Error Analysis of JTWC Best Track Dataset
- RMW Retrieval for Eyed Typhoons
- RMW Retrieval for Non-Eye Typhoons
- Potential Error Sources of Current Algorithms
- Summary

Significance

- ❑ Estimating the typhoon sizes, including the radius of maximum wind (RMW) and the wind radii, is a challenging aspect of typhoon monitoring and forecasting.



Cited from Holland and Merrill (1984)

Size information in the best track dataset

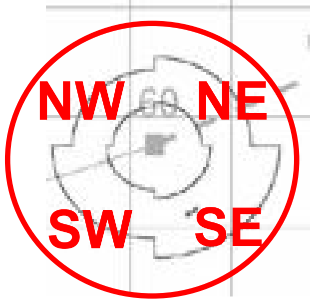
JTWC best tracks

RMW
ROCI
***R*34 in four quadrants**
***R*50 in four quadrants**
***R*64 in four quadrants**

Started since 2001

Commonly used since 2004

Quality controlled except RMW since 2016

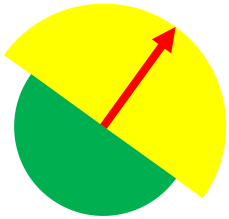


RSMC best tracks

Direction of the longest *R*30
The longest *R*30
The shortest *R*30
Direction of the longest *R*50
The longest *R*50
The shortest *R*50

Started since 1977

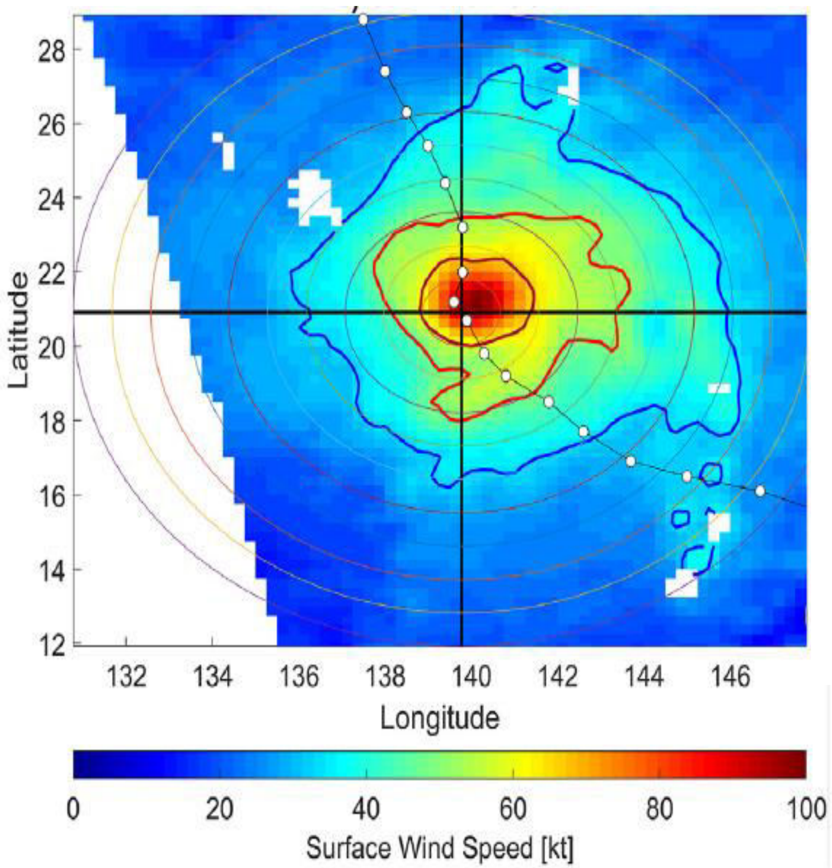
Commonly used since 2004



1 : Northeast (NE)
2 : East (E)
3 : Southeast (SE)
4 : South (S)
5 : Southwest (SW)
6 : West (W)
7 : Northwest (NW)
8 : North (N)
9 : (symmetric circle)

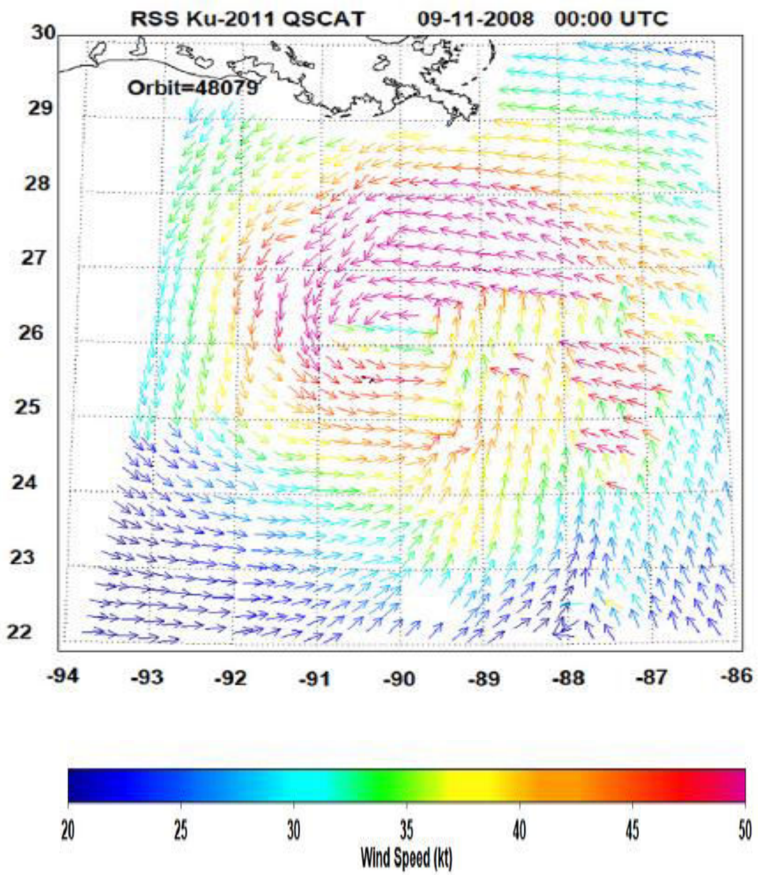
Several satellite-borne wind measurement instruments

Microwave Imager



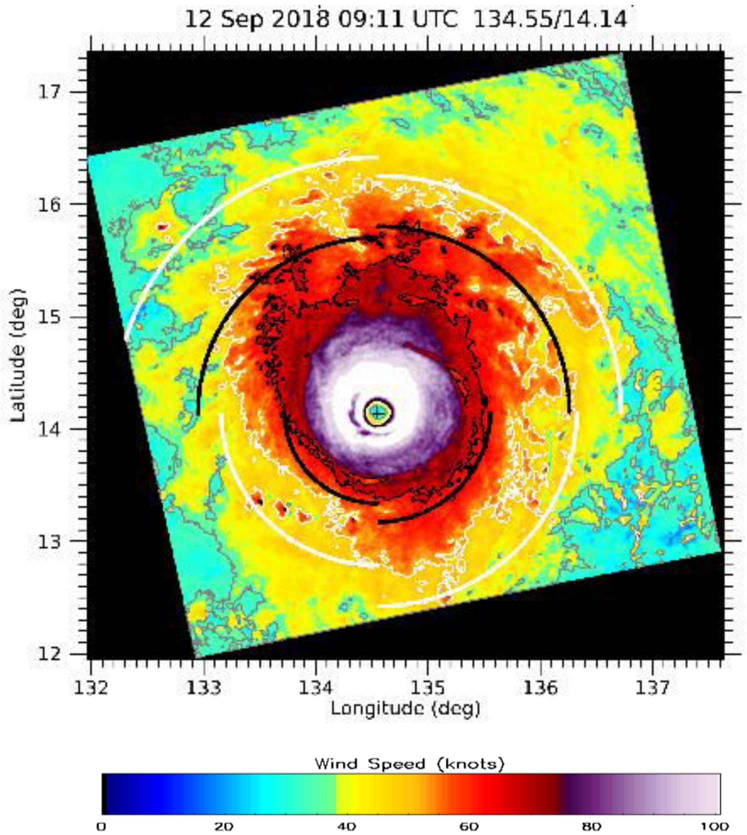
Spatial resolution 40~60 km

Microwave Scatterometer



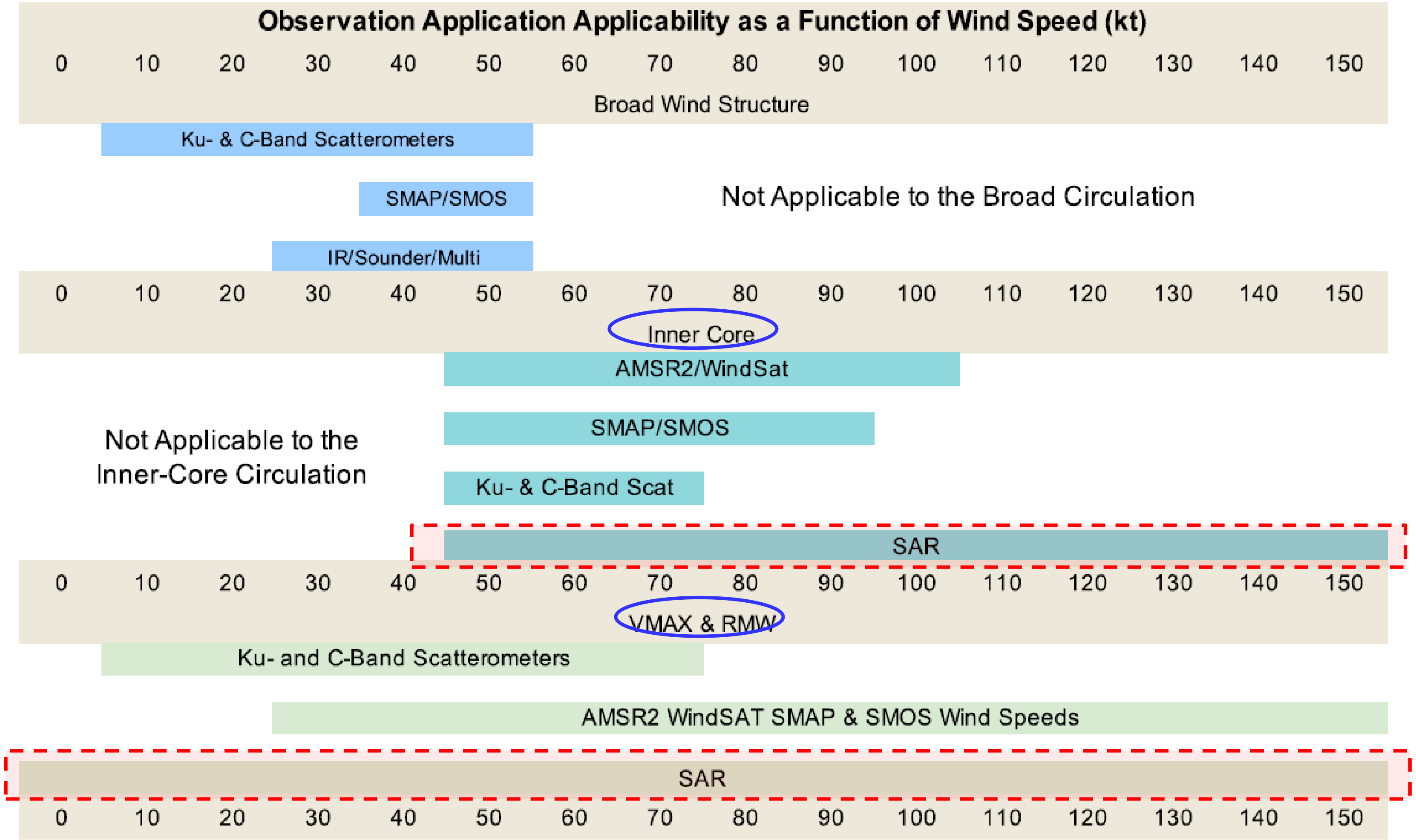
Spatial resolution >25km
Maximum Detectable Wind Speed-60kt

Synthetic Aperture Radar



Spatial resolution 0.1~3km

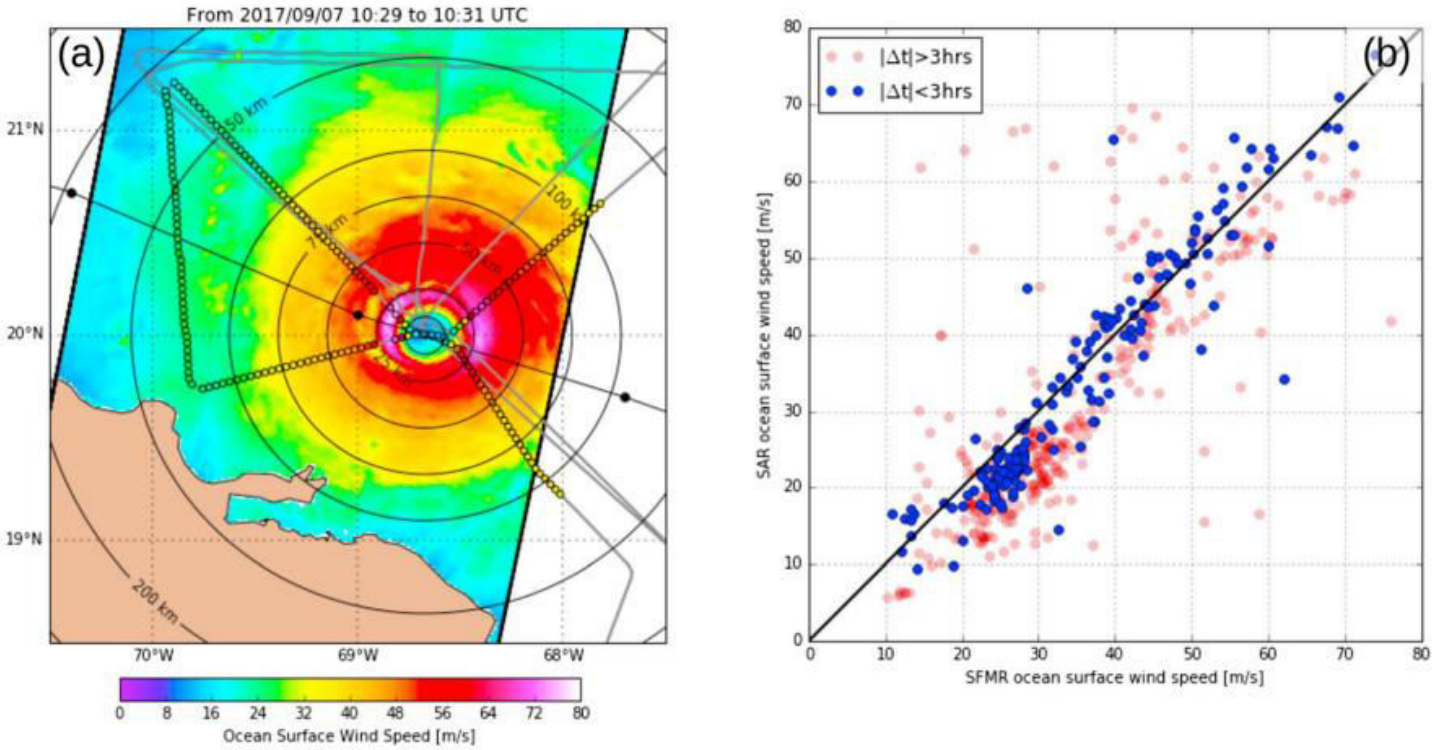
Suggested uses for satellite-based sensors for determining operational estimates of TC structure



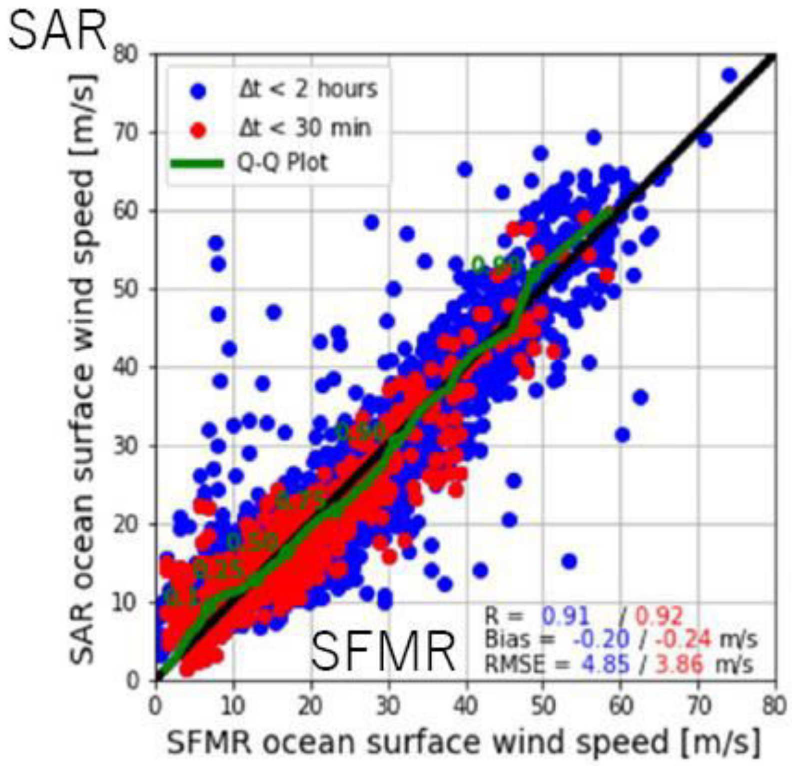
Knaff et al. (2021)

Detection accuracy of SAR

- Verification results show that SAR winds are consistent with SFMR winds, with a RMSE (Root Mean Square Error) less than 5 m/s.
- Rain attenuation can cause a 5–10 m/s underestimation in the retrieved wind speed.



Mouche et al. (2019)



Combot et al. (2020)

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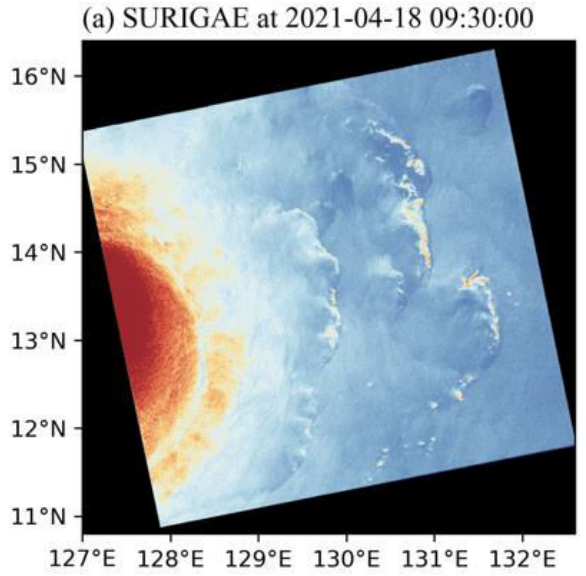
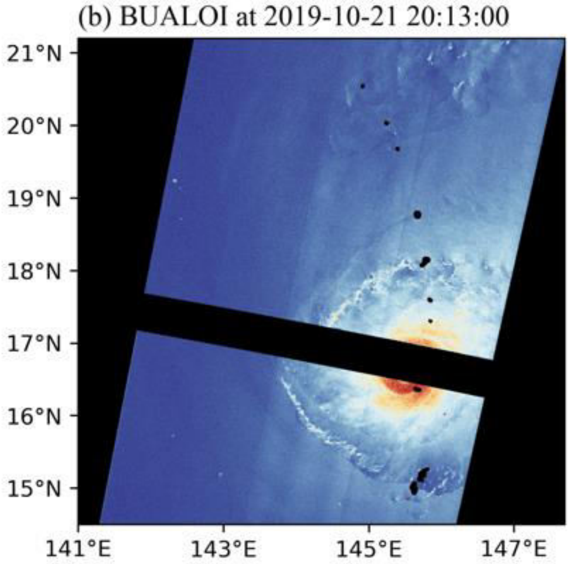
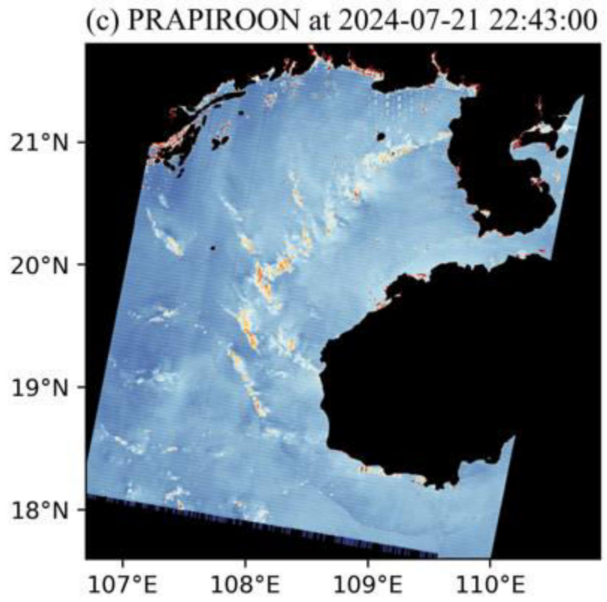
Quality control of SAR observations

Incomplete inner-core region affects the estimation of the wind radii.

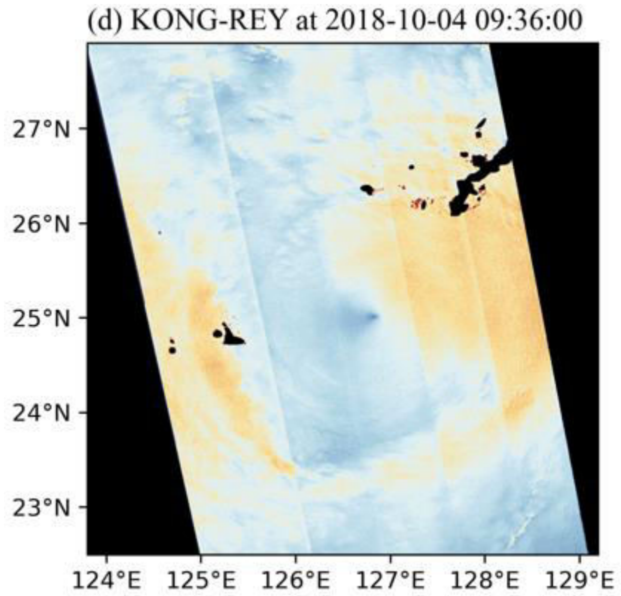




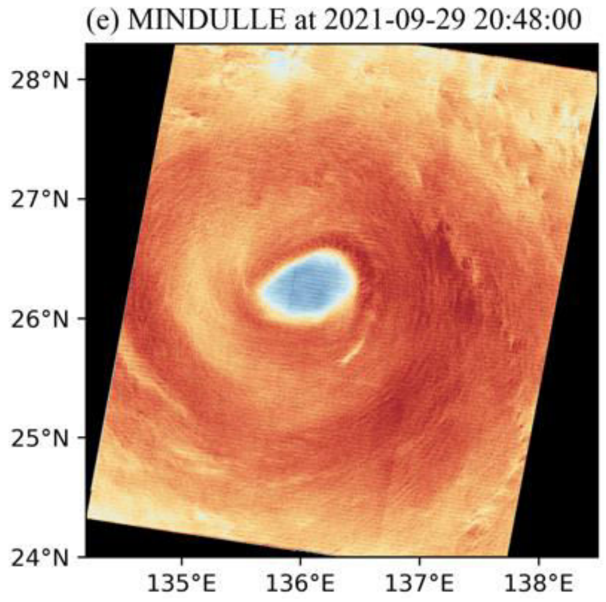
Inner-core region is affected by land.

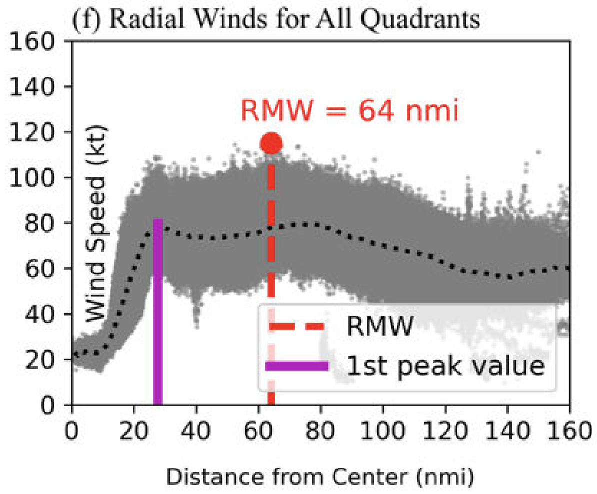


Stripes severely affect wind field estimation.



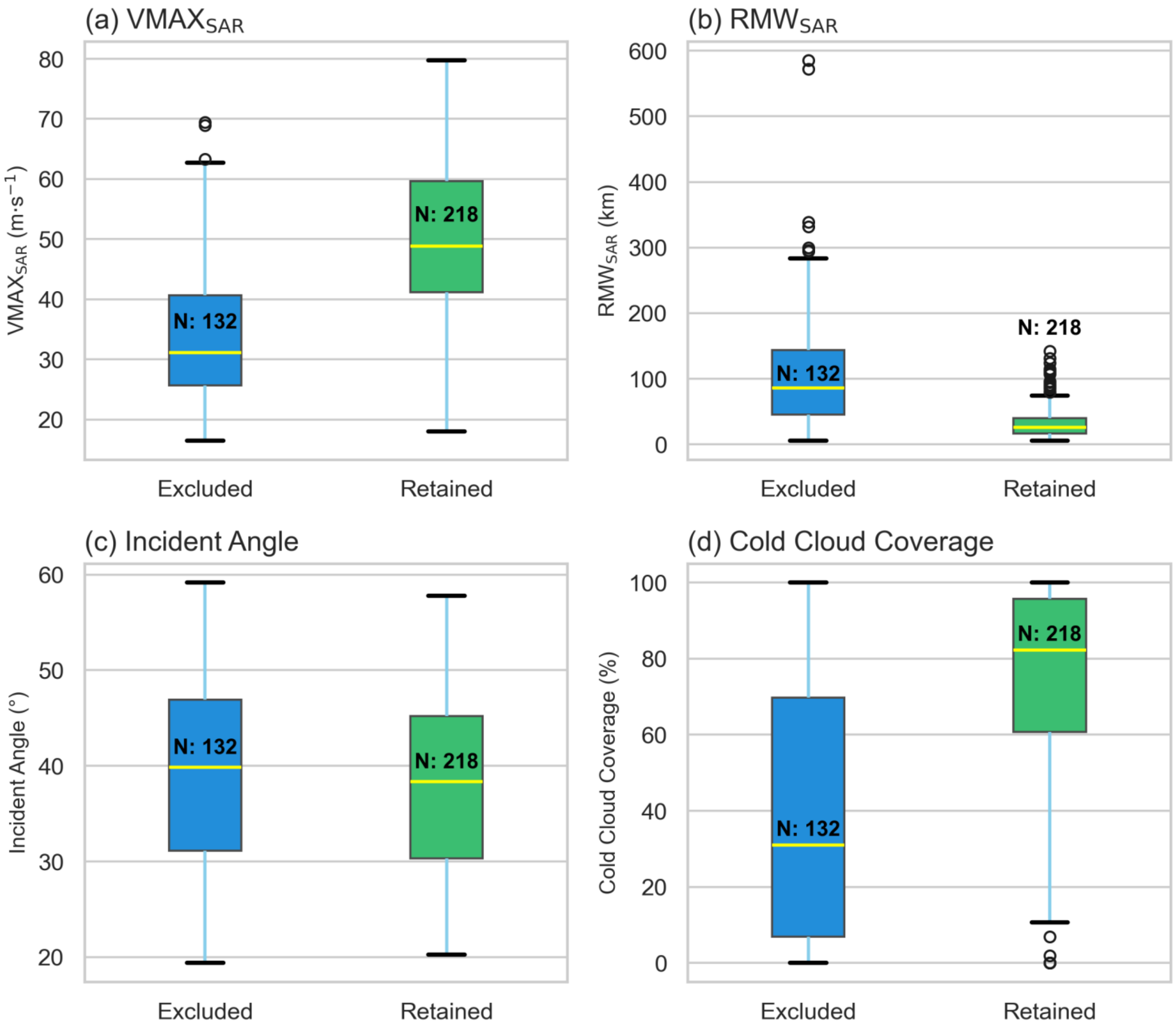
RMW significantly deviates from the first wind speed peak (Possibly due to strong precipitation attenuation or a double eyewall).





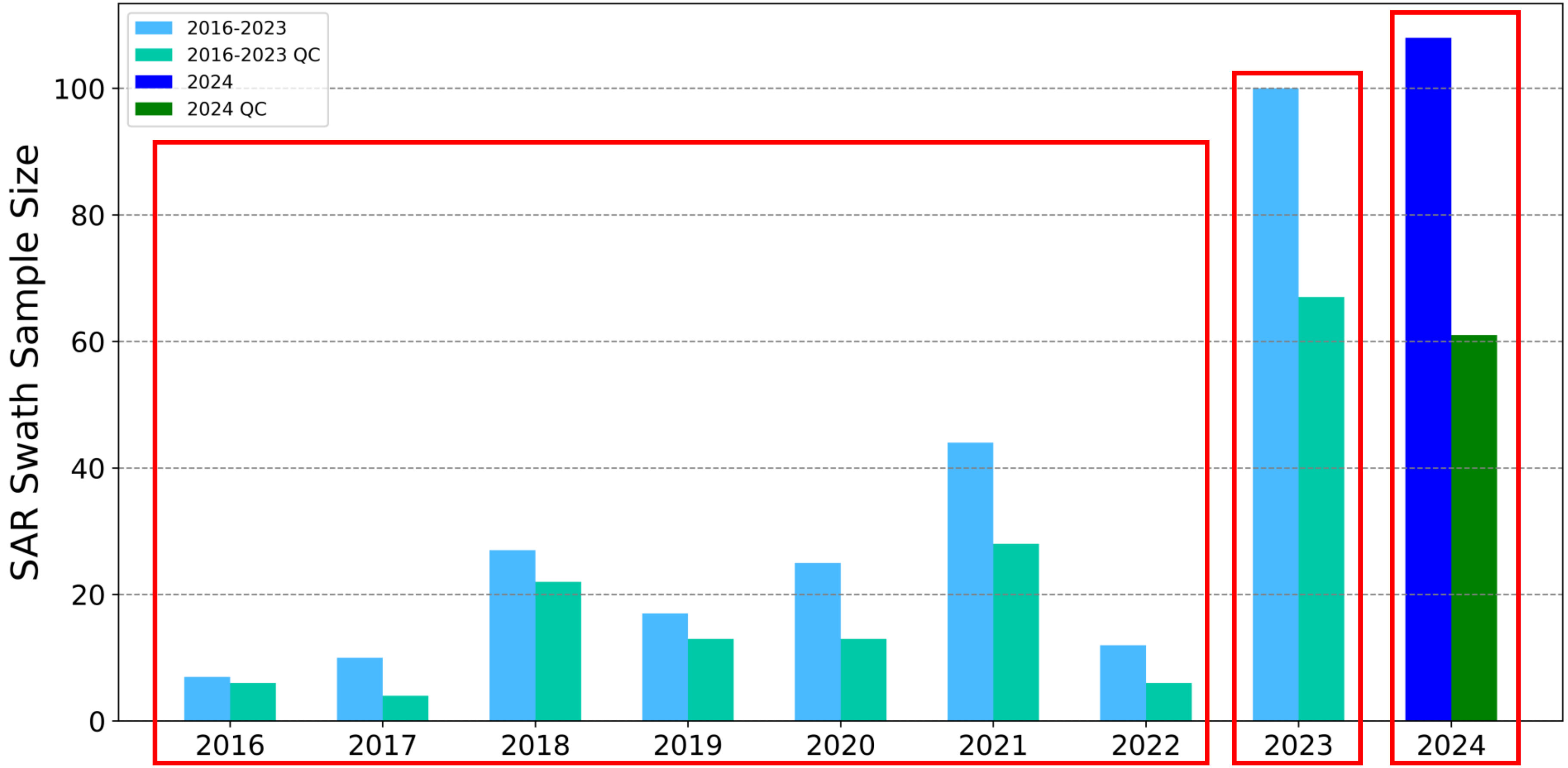
Distribution characteristics after QC

- **Sample Size (N):** 139 samples excluded and 221 samples retained
- **TC Intensity ($VMAX_{SAR}$):** Excluded samples were weaker than that of retained samples
- **RMW_{SAR}:** Outliers were removed. Excluded samples were larger than those of retained samples
- **SAR Incident Angle:** The distribution was relatively consistent
- **Cold Cloud Coverage:** Excluded samples was not as symmetric as retained samples

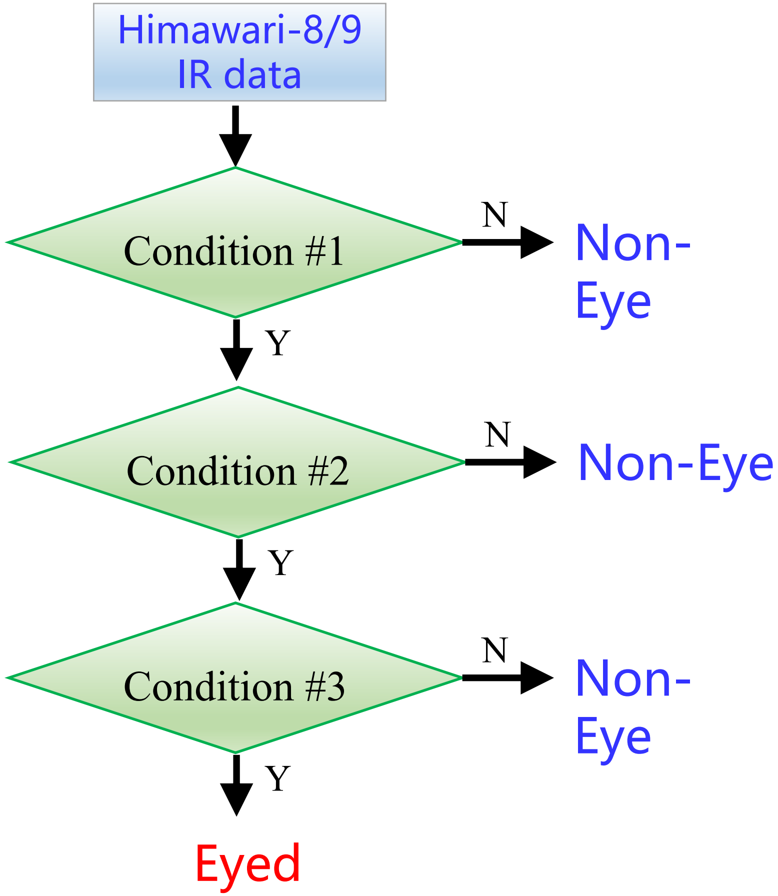


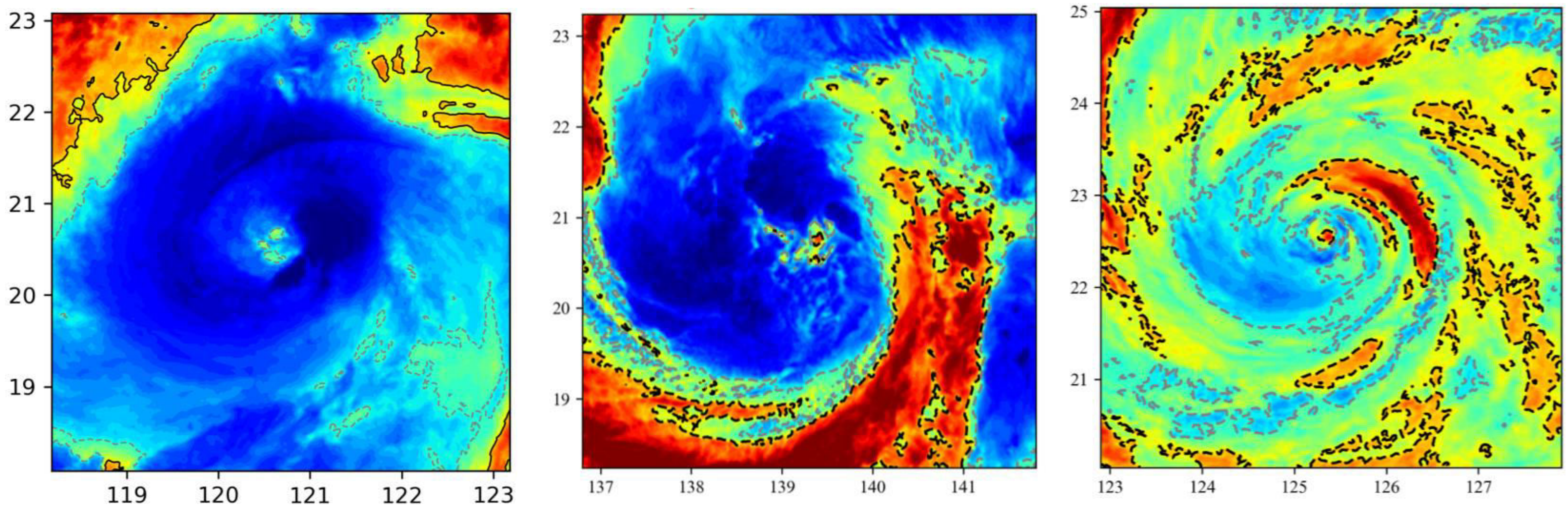
SAR sample distribution over years

- 152 typhoon SAR observations for year 2016–2022; 95 retained after QC.
- 100 typhoon SAR observations for year 2023; 66 retained after QC.
- 108 typhoon SAR observations for year 2024; 61 retained after QC.



Distinguish Eyed vs. Non-Eye TC





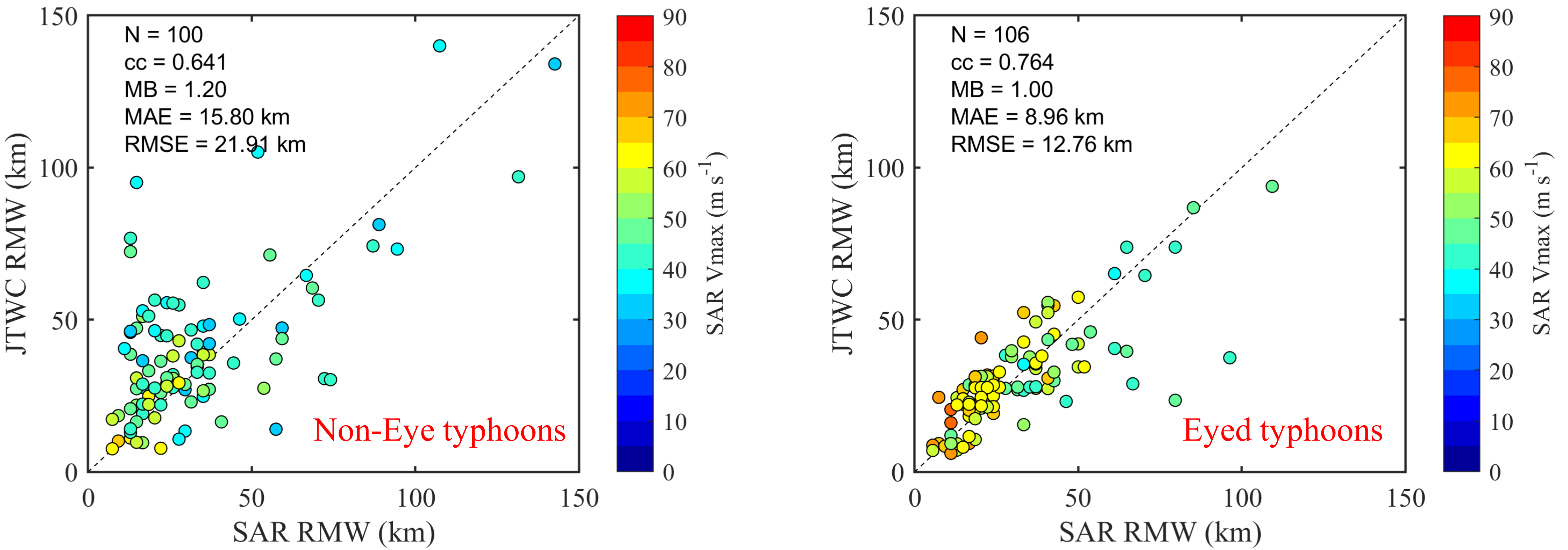
Condition #1:
TC center features a -20°C isotherm

Condition #2:
Less than 3 patches with BT ≥-20°C & area < 100 km²

Condition #3:
ΔBT > 30°C between r<24km (excluding pixels <-20°C) and 24≤r≤136km

In year 2016–2024: 106 eyed and 100 non-eye typhoon SAR samples are found.

Assessment results



- Non-Eye Typhoons exhibit significant RMW errors (cc=0.64, MAE=15.8km, RMSE=21.9km).
- For eyed typhoons, RMW errors are also large: cc=0.76, MAE=8.96 km, RMSE=12.8 km.

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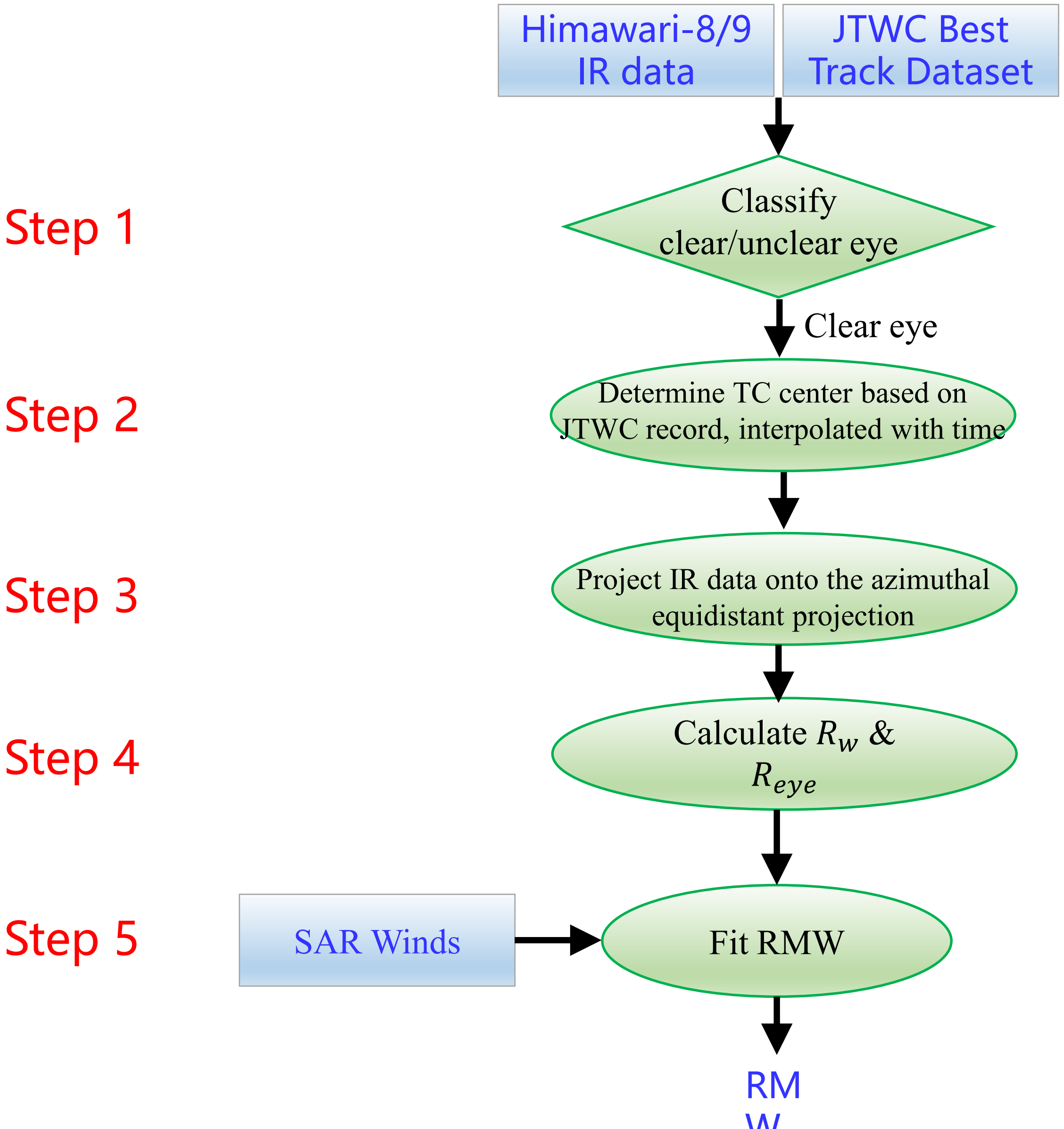
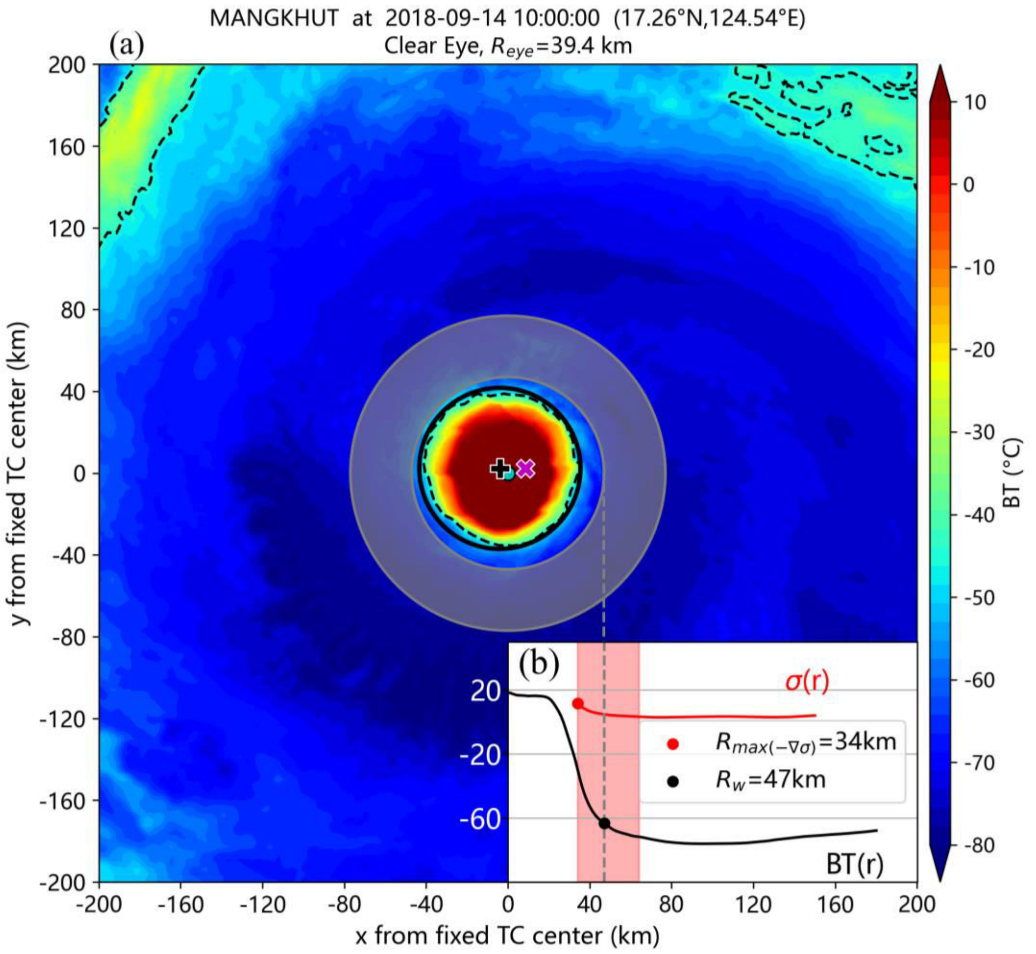
Flowchart of RMW algorithm for Clear-Eyed Typhoons



Based on Tsukada & Horinouchi (2023)

Step 3: Calculate R_w

- Compute standard deviation ($\sigma(r)$) of brightness temperatures in the annulus from r to r+30km ($0<r\leq150$ km, excluding regions >-10°C), with $R_{\max(-\nabla\sigma)}$ marking the radius at which the radial gradient of $\sigma(r)$ is negatively maximized.
- Calculate the averaged brightness temperature ($\overline{BT}$) of the annulus from $R_{\max(-\nabla\sigma)}$ to $R_{\max(-\nabla\sigma)} + 30km$.
- Within the range $R_{\max(-\nabla\sigma)} \leq r \leq R_{\max(-\nabla\sigma)} + 30\,\text{km}$, identify the radius R_w at which the azimuthally averaged brightness temperature, $BT(r)$, is closest to $\overline{BT}$.



$R_{\max(-\nabla\sigma)} \leq r \leq R_{\max(-\nabla\sigma)} + 30km$ R_w ~ R_w+30km

Tsukada & Horinouchi (2023)

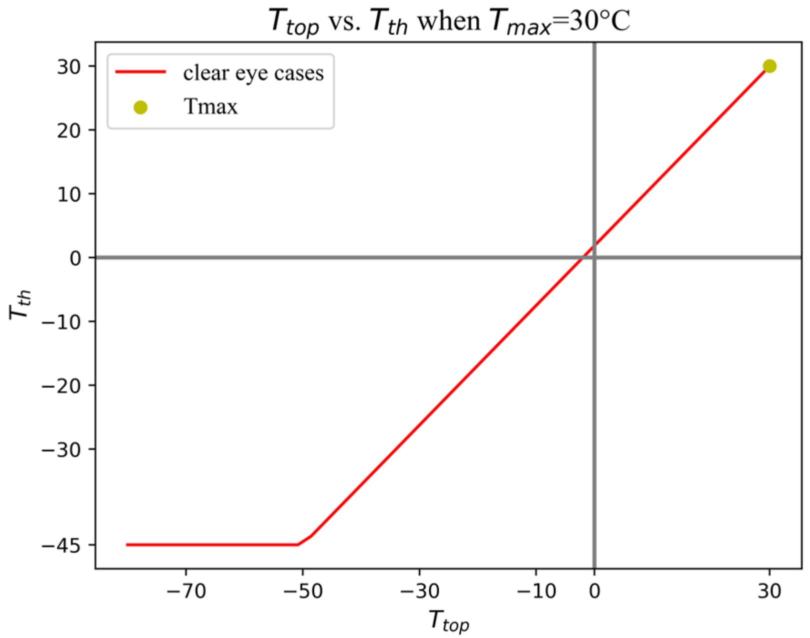
Step 4: Calculate R_{eye}

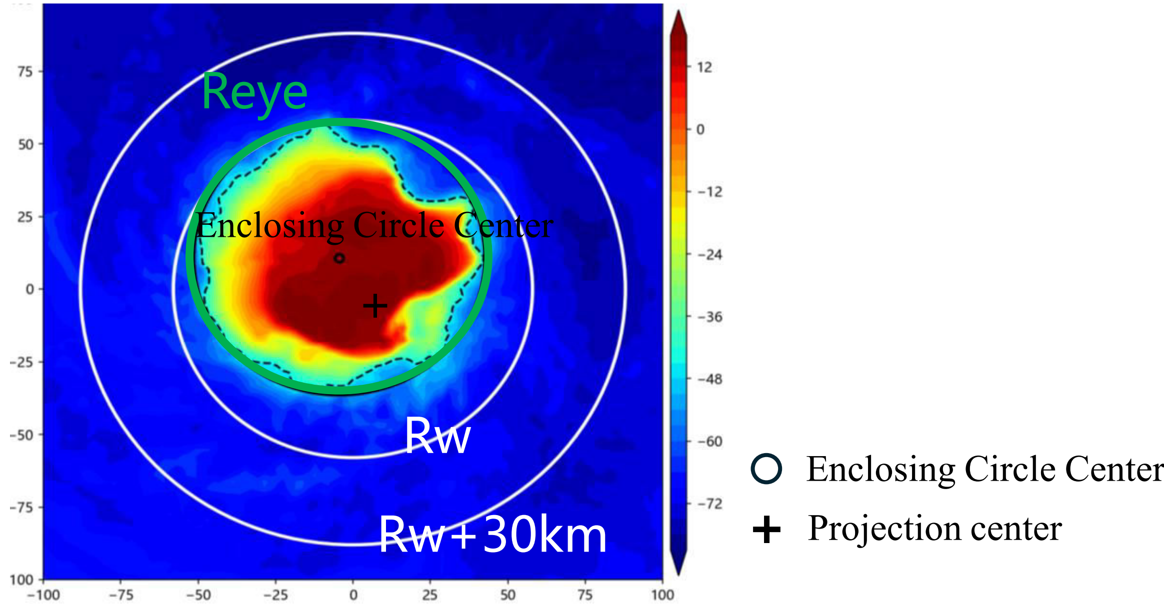
- **Determine the eye temperature threshold T_{th}:**

$$T_{\rm th} = \begin{cases} -45^\circ C, & T_{\rm top} \le -50^\circ C \\ (1-c)T_{\rm top} + cT_{\rm max}, & T_{\rm top} > -50^\circ C \end{cases}$$

$c = \frac{5^\circ C}{T_{\rm max}+50^\circ C}$; T_{max} is the highest BT over $0 \le r \le R_w$; T_{top} is the average BT over $R_w \le r \le R_w + 30km$.

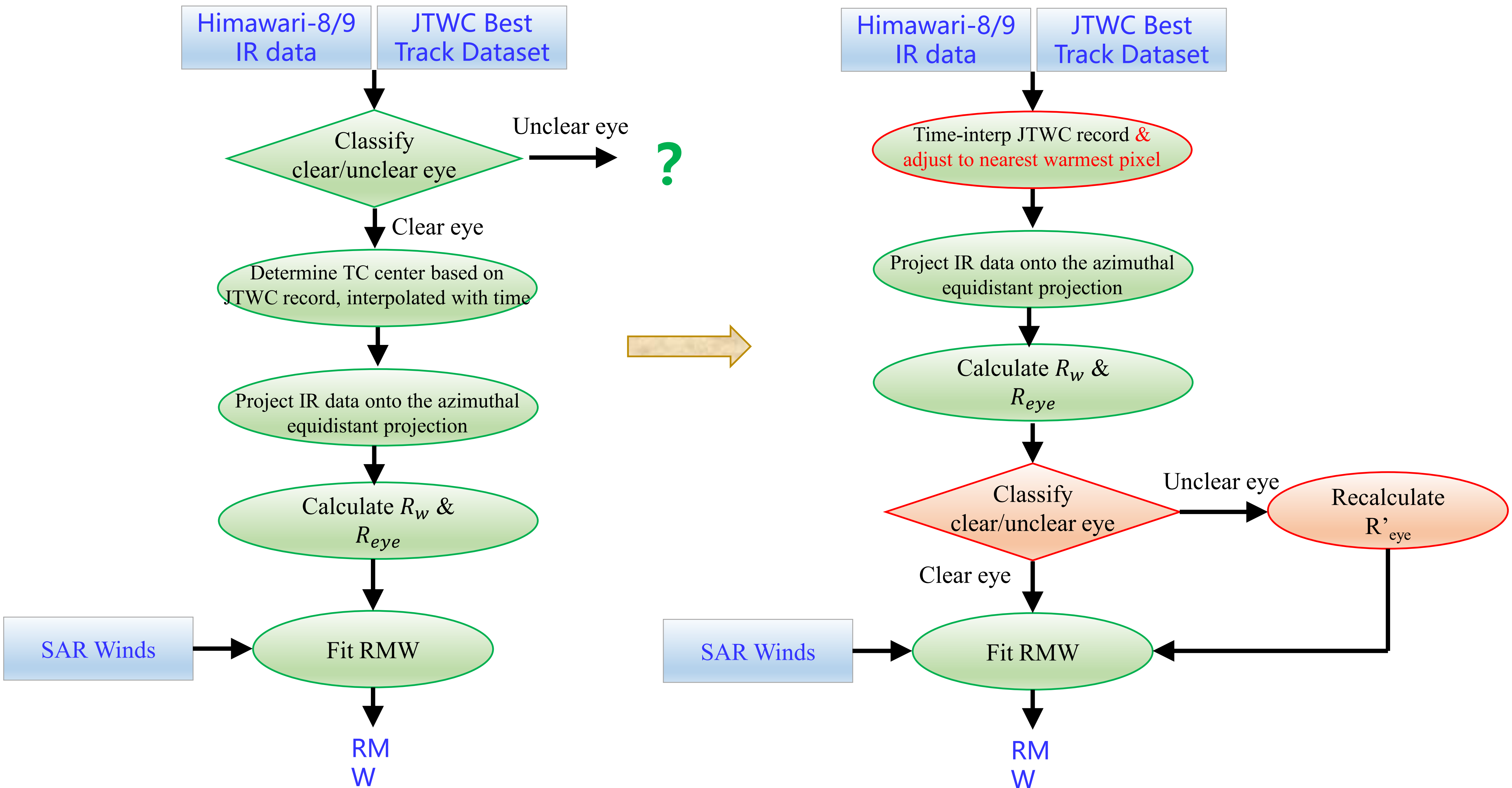
- The eye region is the connected region with $BT \ge T_{th}$ that includes the typhoon center. Reye is defined as the radius of the minimum enclosing circle of the eye region.





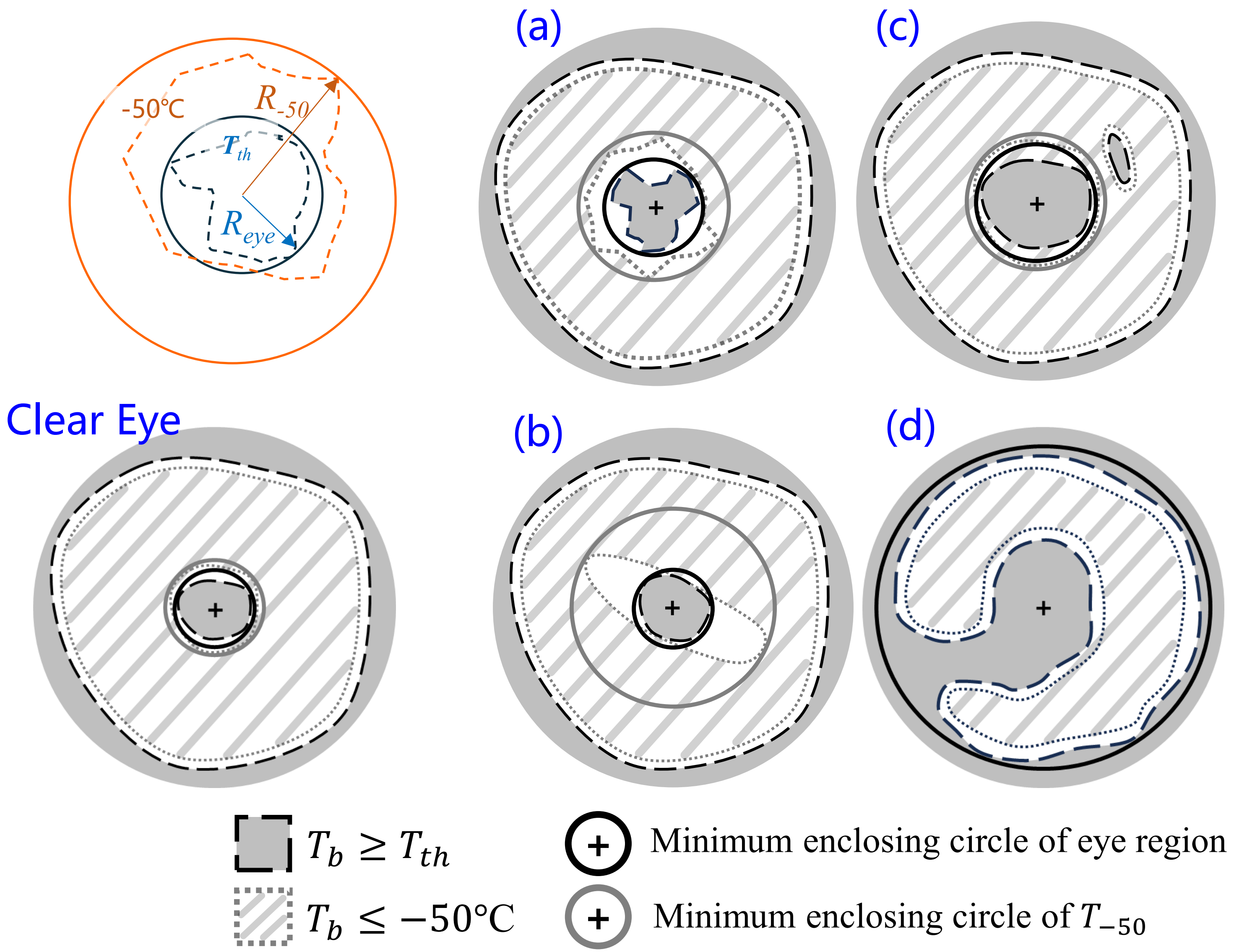
Tsukada & Horinouchi (2023)

Flowchart of RMW algorithm for Eyed Typhoons



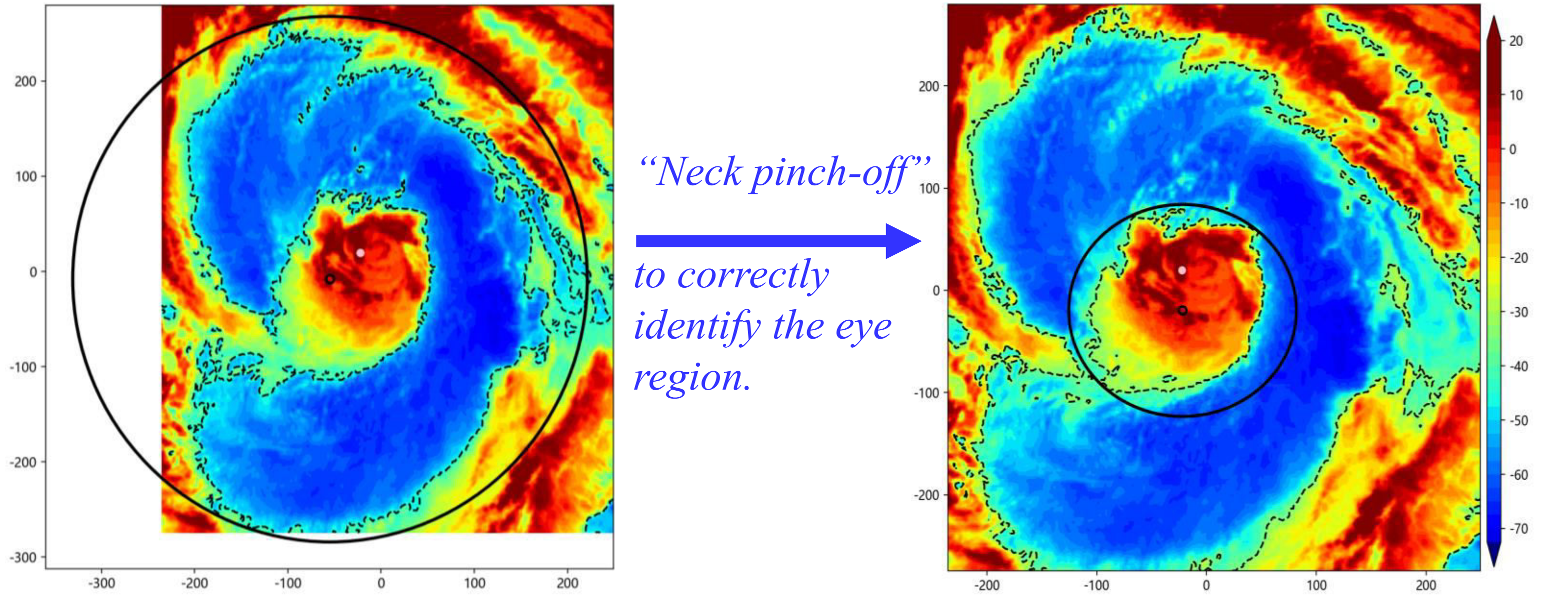
Classify clear/unclear eye

- Eyewall region: The annular region outside the eye region, with a radius of R_{-50} to R_{-50}+15km.
- Warm region: Pixels with BT >-50°C.
- Clear Eye: The eye region is relatively regular in shape; the eyewall region is scarcely intruded by the warm region at any azimuth.
- Unclear Eye: (a) Standardized ellipse fitting deviation D_{rel}>0.14; (b) Transition between the eye and eyewall regions is unnatural, R_{-50}-R_{eye}>10km; (c) The eyewall region contains more than 20 warm pixels in patchy warm areas; (d) Eyewall region severed by warm area; R_{eye}> 200 km. Any of the above conditions met indicates an unclear eye.



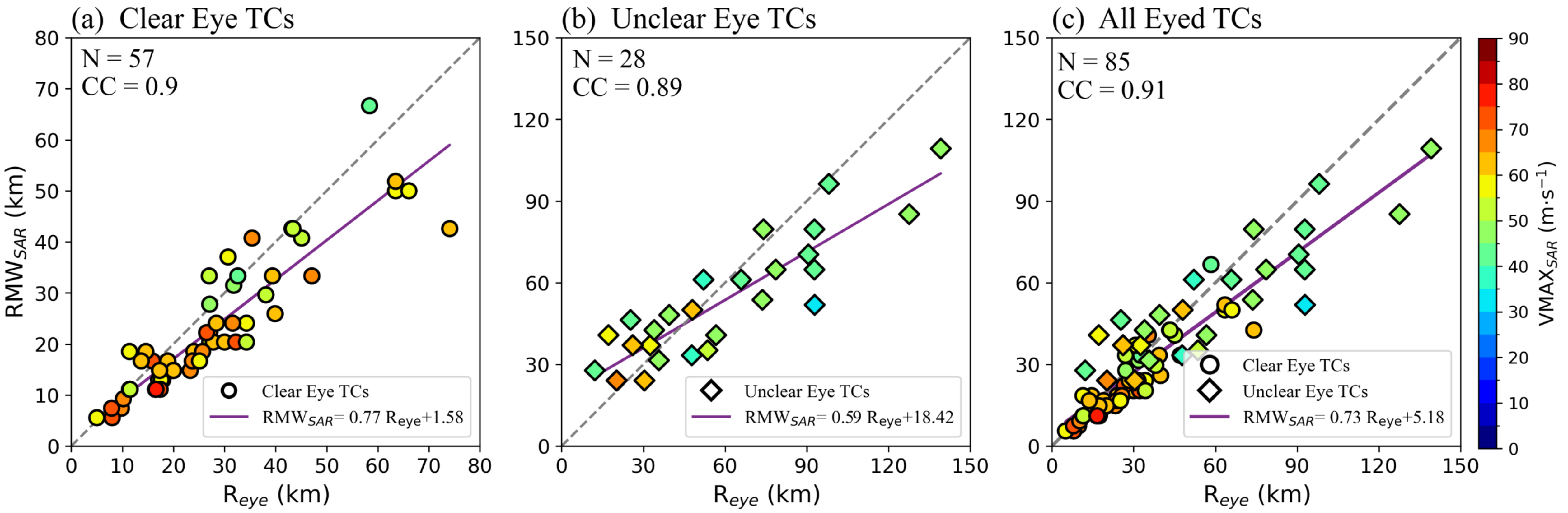
Recalculate R_{eye} for Unclear Eye Cases

- For unclear-eye typhoons, if the proportion of $BT \geq T_{th}$ pixels within $R_w \leq r \leq R_w + 30km$ exceeds 5%, increase T_{top} by 5°C and recalculate T_{th} using the aforementioned equation. Iterate until the proportion falls below 5%.
- The eye region is the connected region with $BT \geq T_{th}$ that includes the typhoon center. R_{eye} is defined as the radius of the minimum enclosing circle of the eye region.



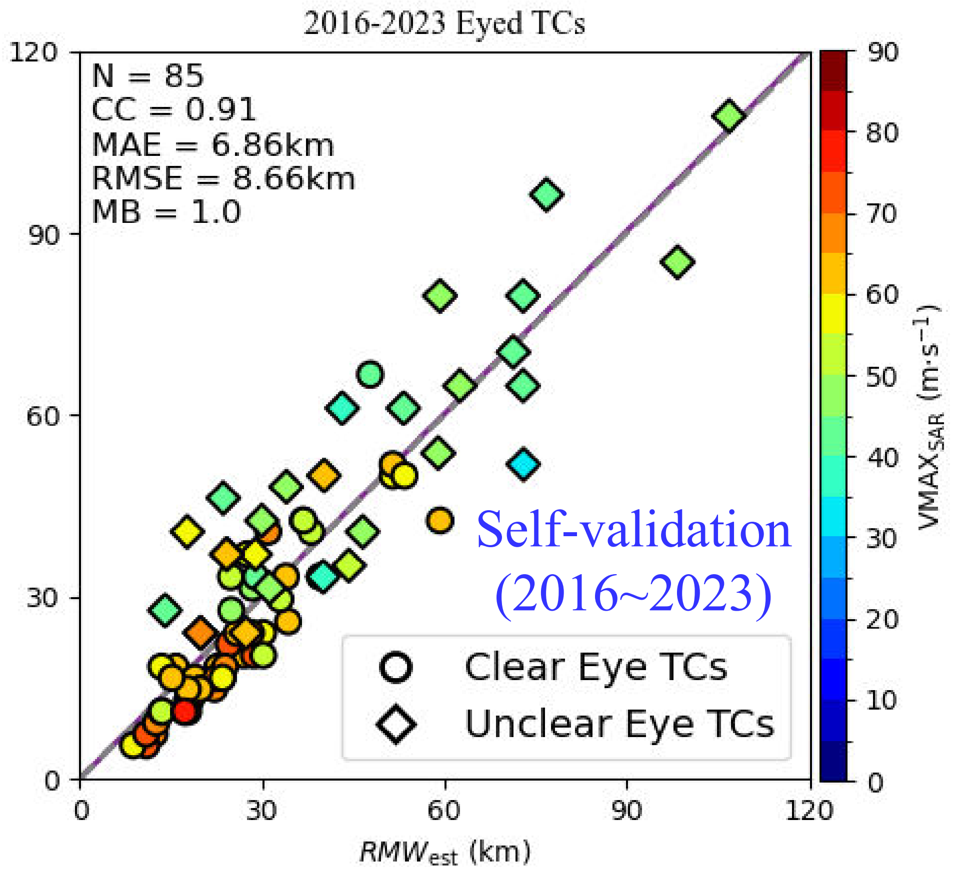
Fit RMW

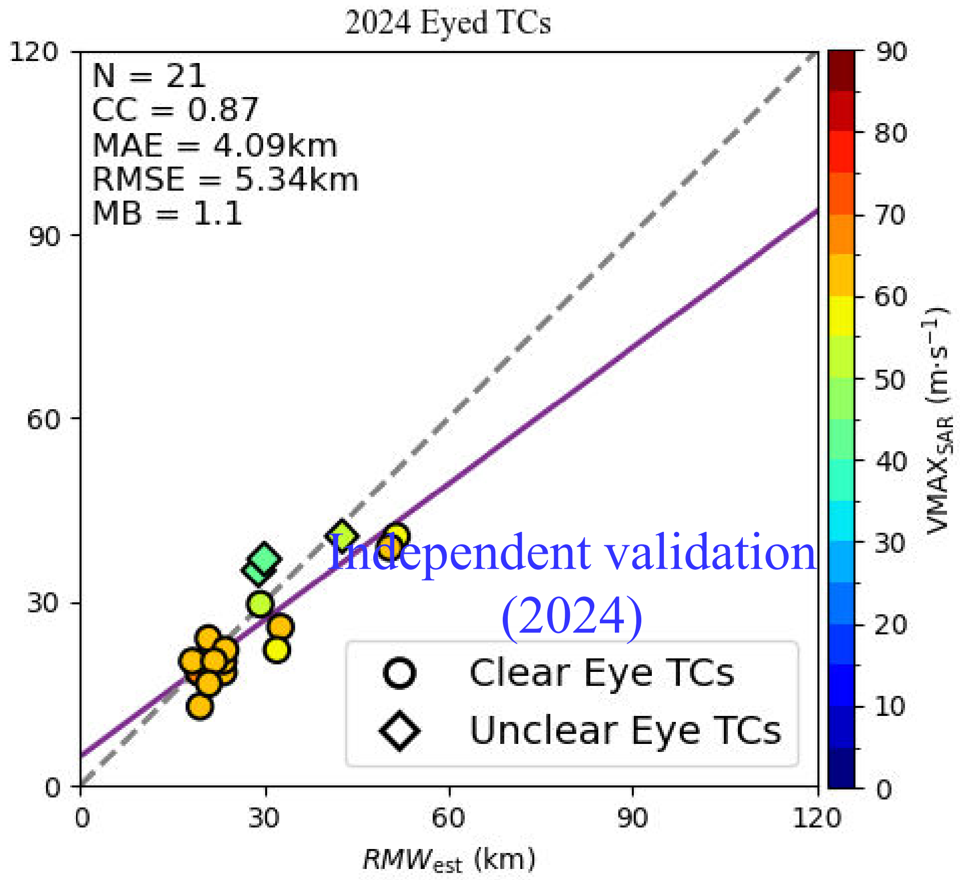
- From 2016 to 2023, there were 85 valid SAR observations of eyed typhoons over WNP, including 57 clear-eye and 28 unclear-eye cases.
- For clear-eye typhoon cases, the correlation coefficient between R_{eye} and RMW_{SAR} is 0.90; for unclear-eye typhoon cases, the correlation coefficient is 0.89; for all eyed typhoon cases, the correlation coefficient is 0.91.



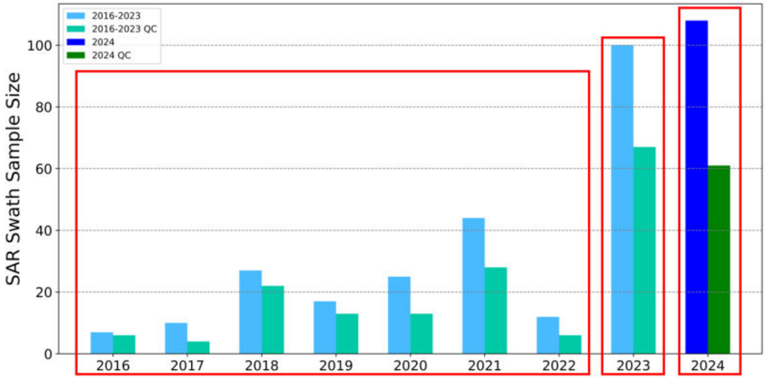
Verification

- Self-validation shows RMW_{est} has a correlation coefficient of 0.91, MAE=6.9km, RMSE=8.7km, when verified with RMW_{SAR}.
- Independent validation demonstrates consistent performance, RMW_{est} has cc=0.87, MAE=4.1km, RMSE=5.3km, when verified with RMW_{SAR}.

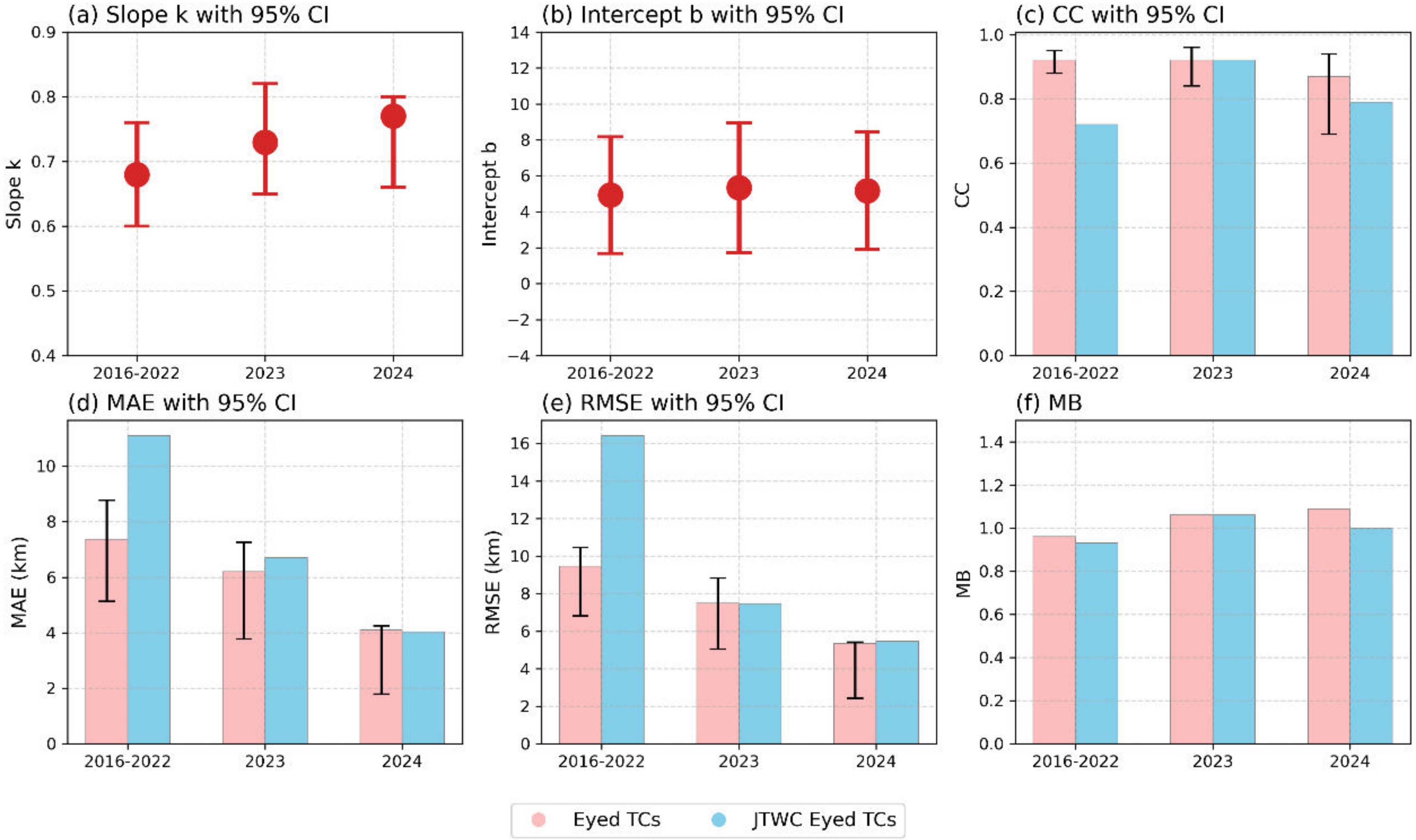




leave-one-year-out cross-validation



- To reduce the influence of year-specific or sample-composition contingencies and to strengthen external validity
- Notably improvement is found for 2016-2022 samples



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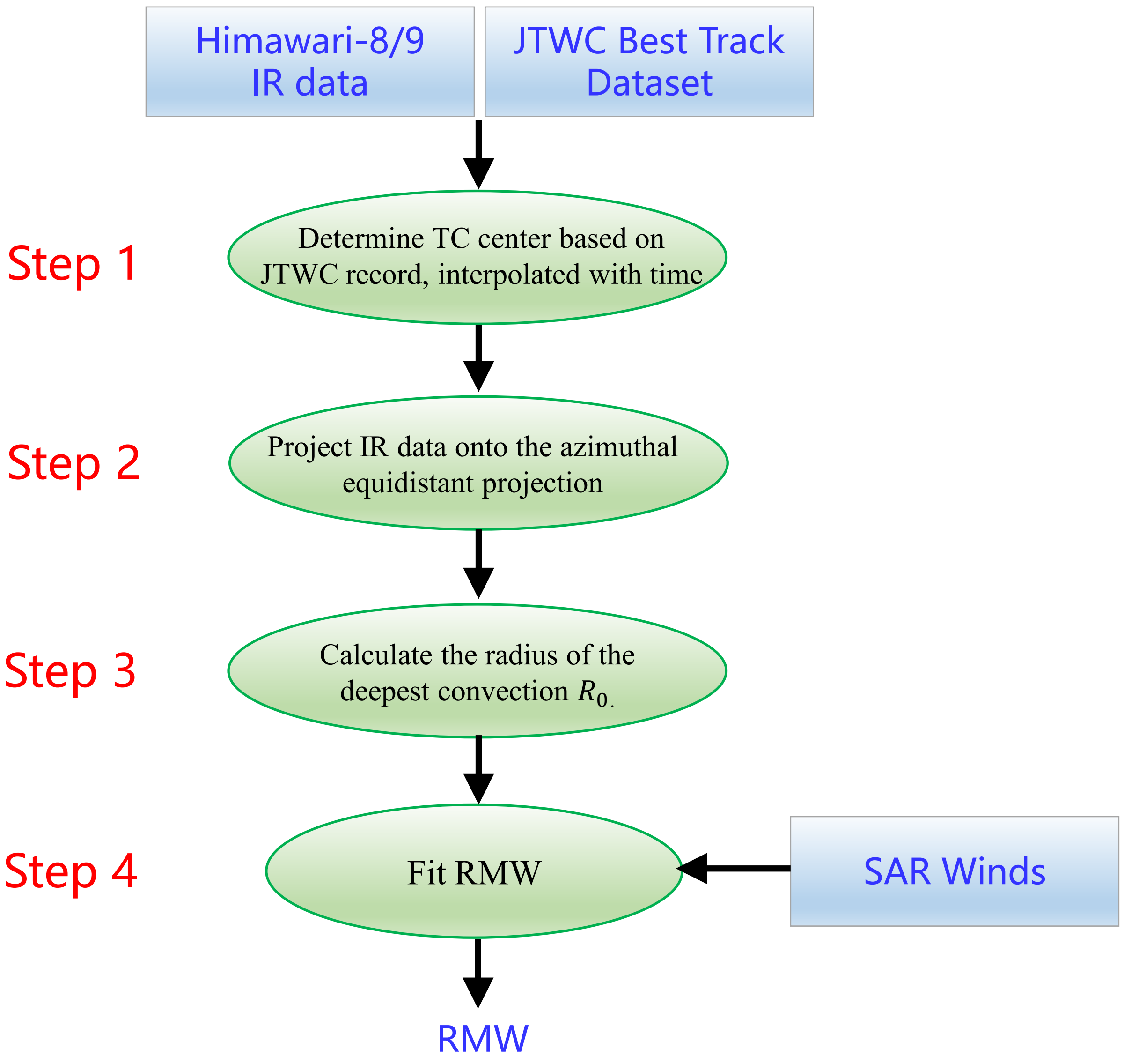
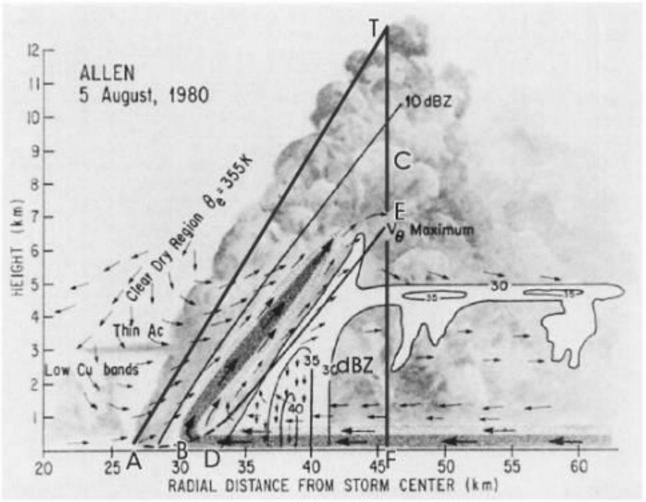
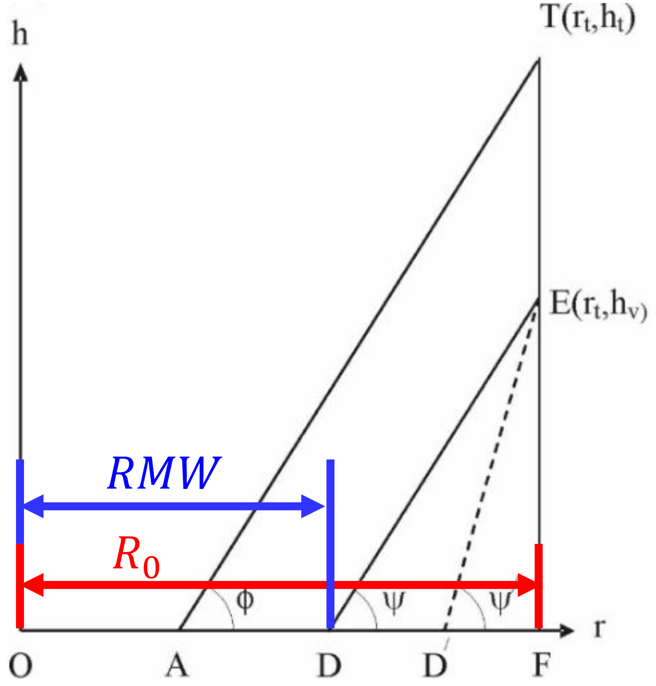
Flowchart of RMW algorithm for Non-Eye Typhoons





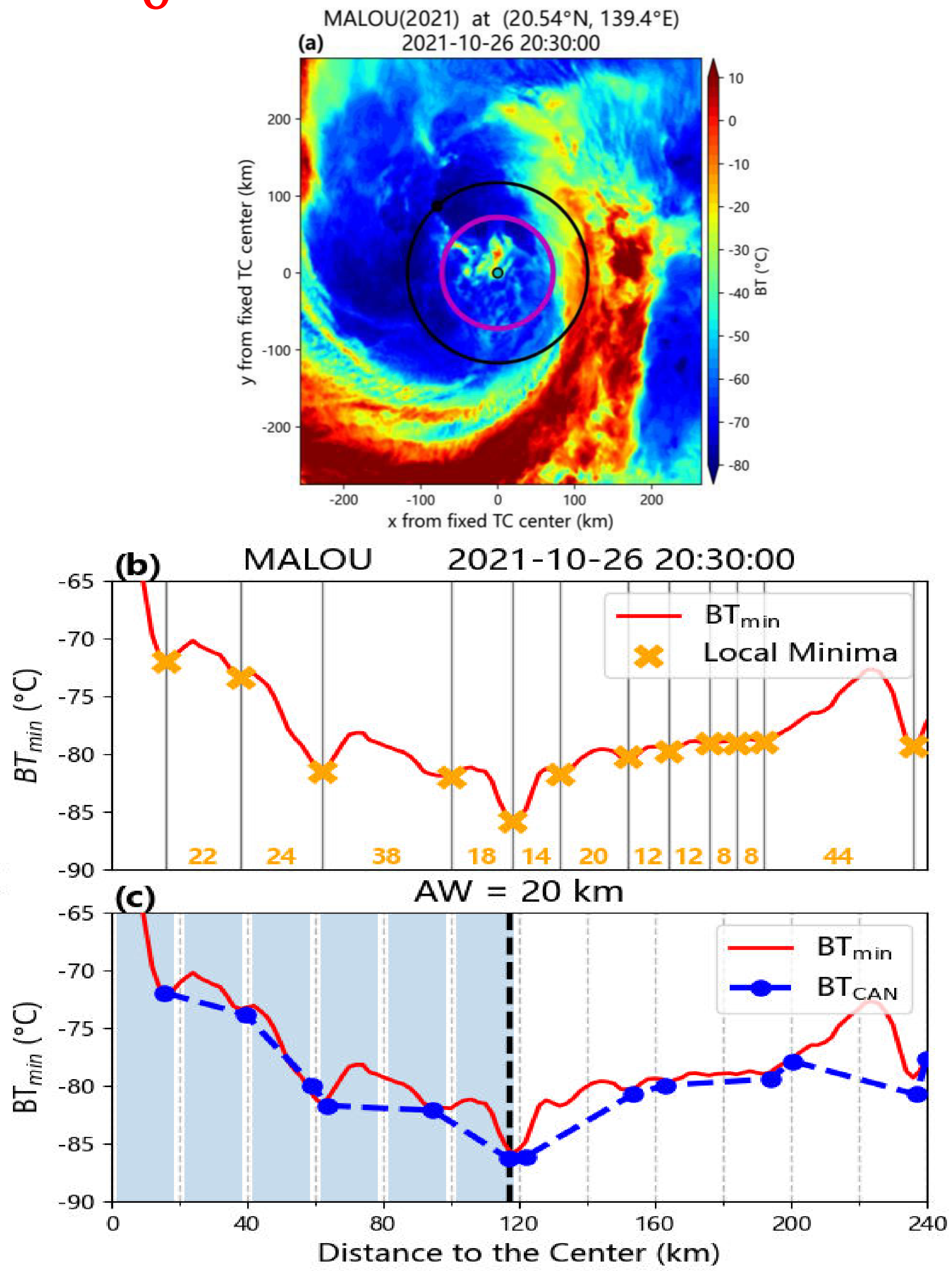


Step 3: Calculate R_0

- **To calculate R_0:** Divide the region within 240 km of the typhoon center into concentric annuli (each with width *AW*), and identify the "valid" coldest pixel (denoted as BT_{CAN}) in each annulus. Then, locate the first local minimum in the BT_{CAN} sequence. The radial distance from this minimum to the typhoon center is defined as R_0.

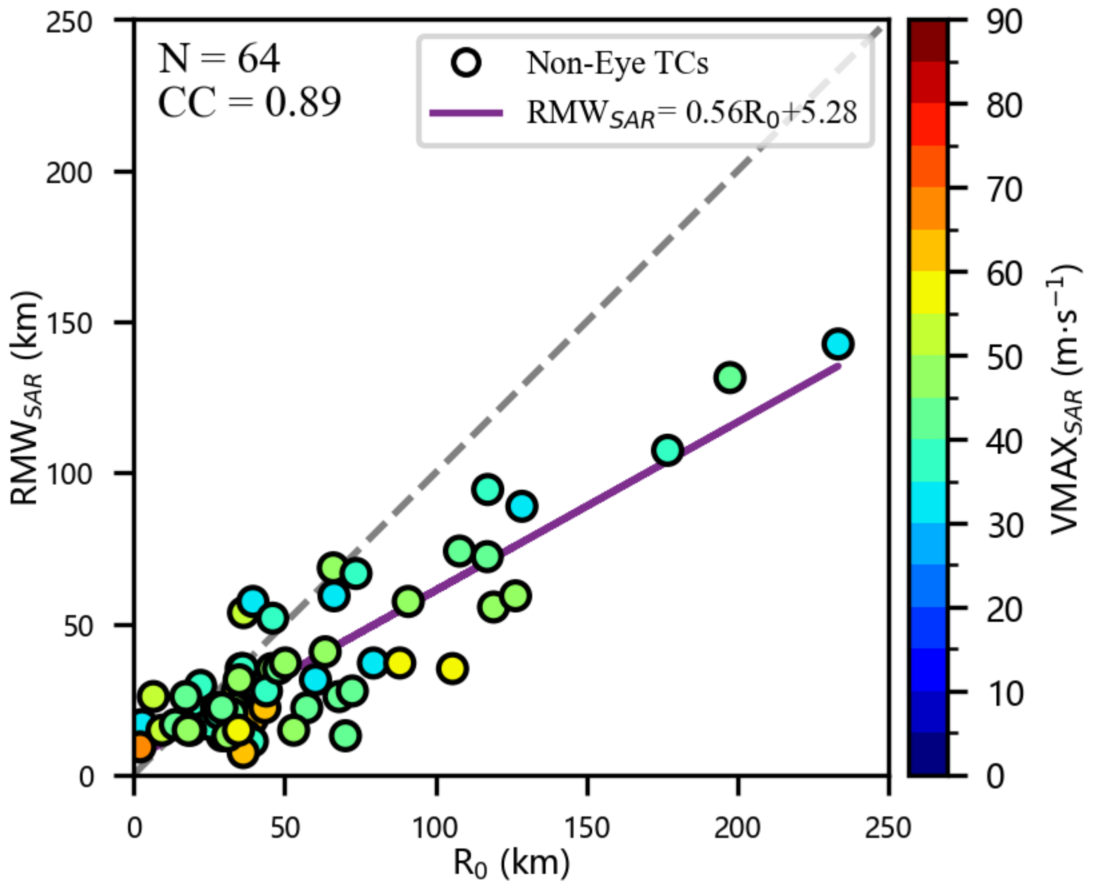
- **Adaptive annulus width (AW):** Within the range 0<*r*≤240 km, radially extract azimuthal minimum of the brightness temperatures and apply a 3-point moving average to form $BT_{min}(r)$. AW is the mean distance between adjacent local minima in $BT_{min}(r)$.

- **"Invalid" coldest pixels:** Cold areas ($BT \leq$ -50°C) on the annulus account for <10%, and the area enclosed by the BT_{CAN}+1 isotherm is <80 km² (i.e., 20 pixels).



Step 4: Fit RMW

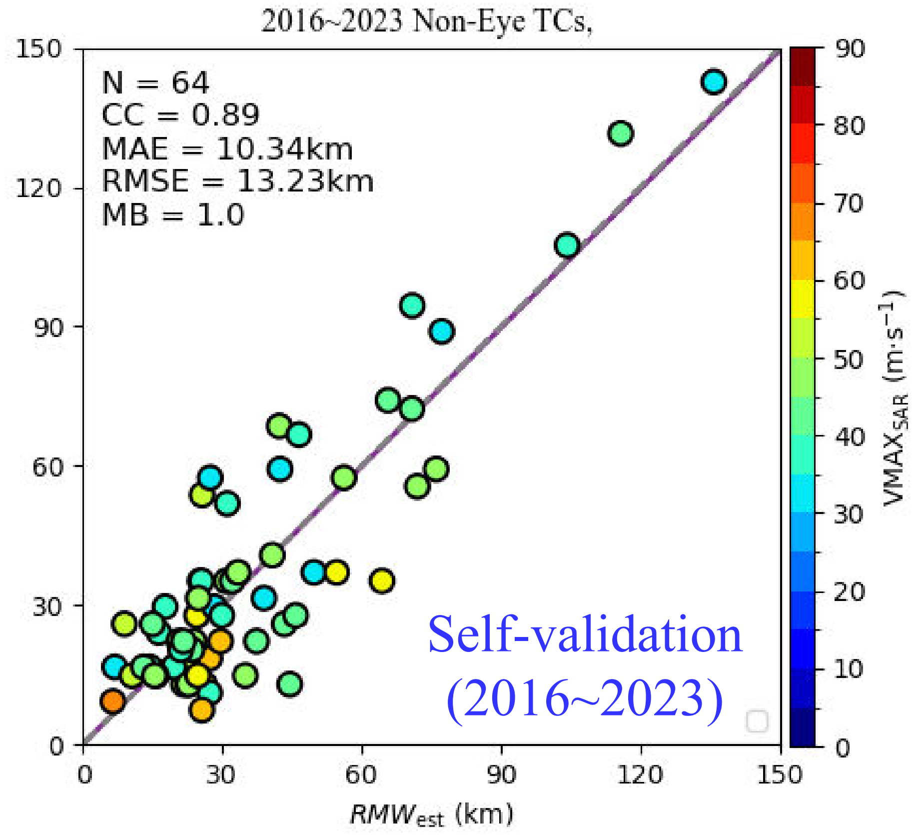
- From 2016 to 2023, there were 64 valid SAR observations of Non-Eye Typhoons with intensity ≥64 kt over WNP
- The correlation coefficient between R_0 and RMW_{SAR} for Non-Eye Typhoons is 0.89.

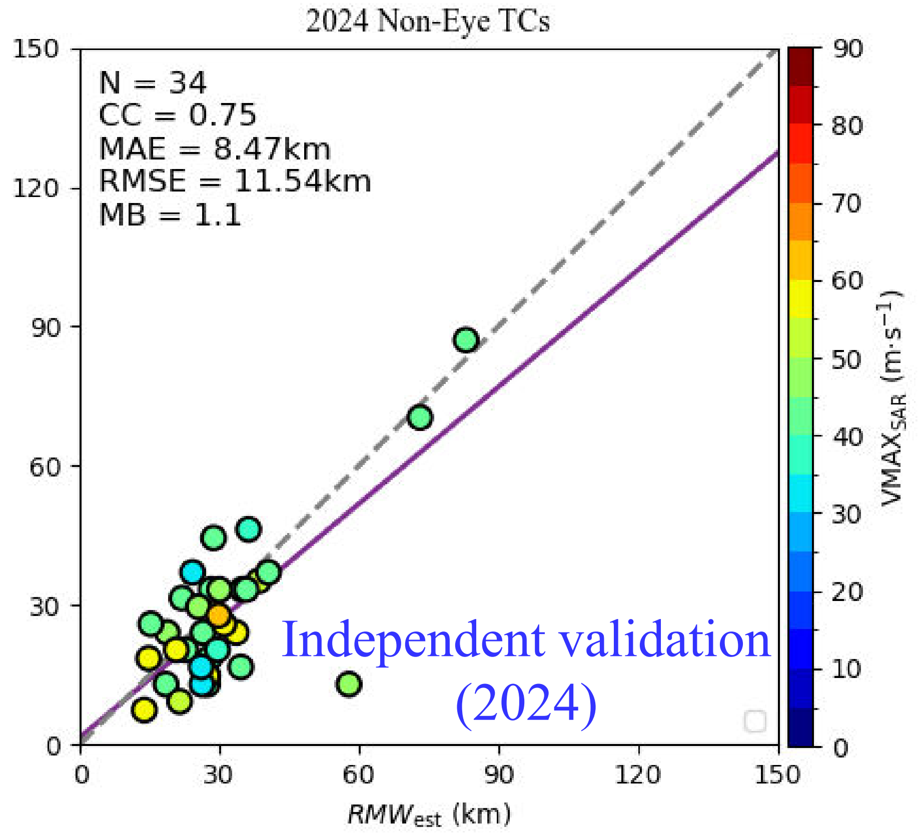


$$RMW_{SAR} = 0.56R_0 + 5.28$$

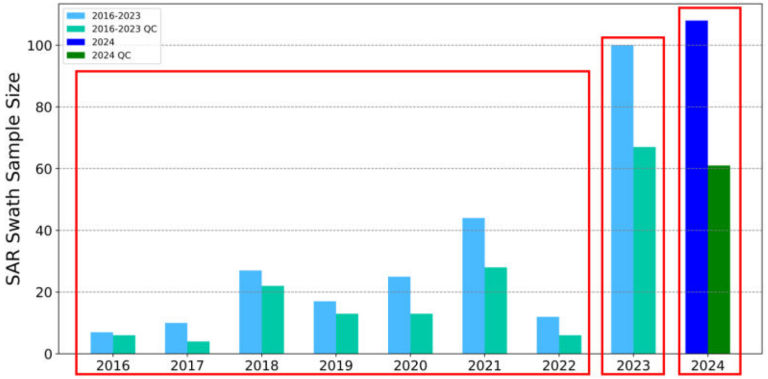
Verification

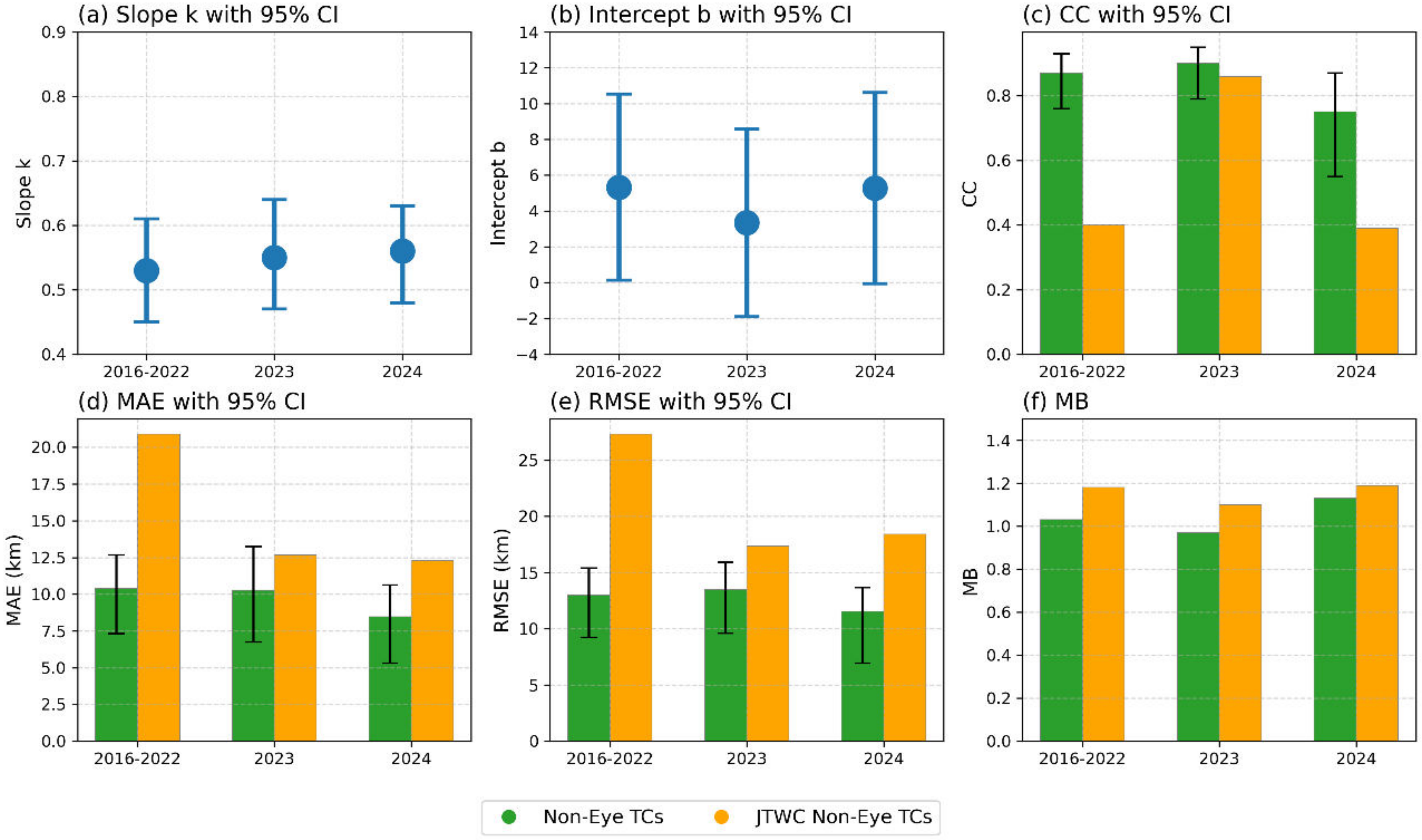
- Self-validation shows RMW_{est} has a correlation coefficient of 0.89, MAE=10.3km, RMSE=13.2km, when verified with RMW_{SAR}.
- Independent validation shows, RMW_{est} has a correlation coefficient of 0.75, MAE =8.5 km, RMSE= 11.5 km, when verified with RMW_{SAR}.





leave-one-year-out cross-validation





- The new method notably reduces RMW estimation errors compared to the JTWC best-track dataset.
- The reduction exceeded 50% for 2016-2022 samples.

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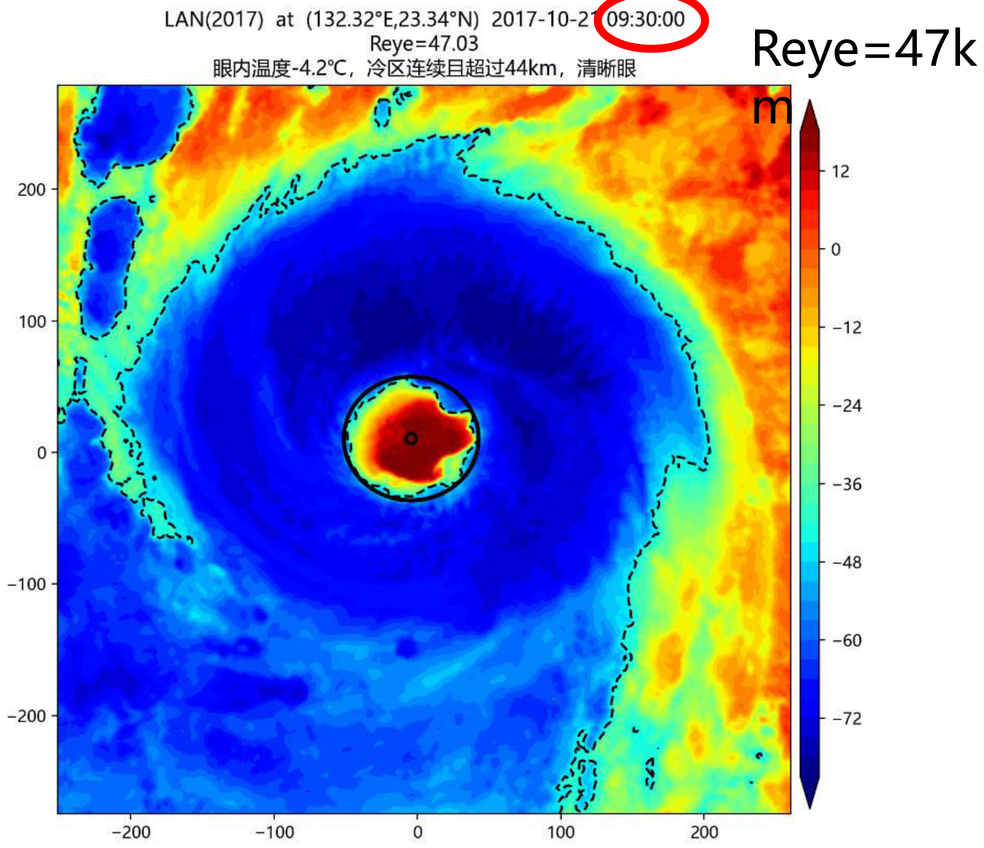
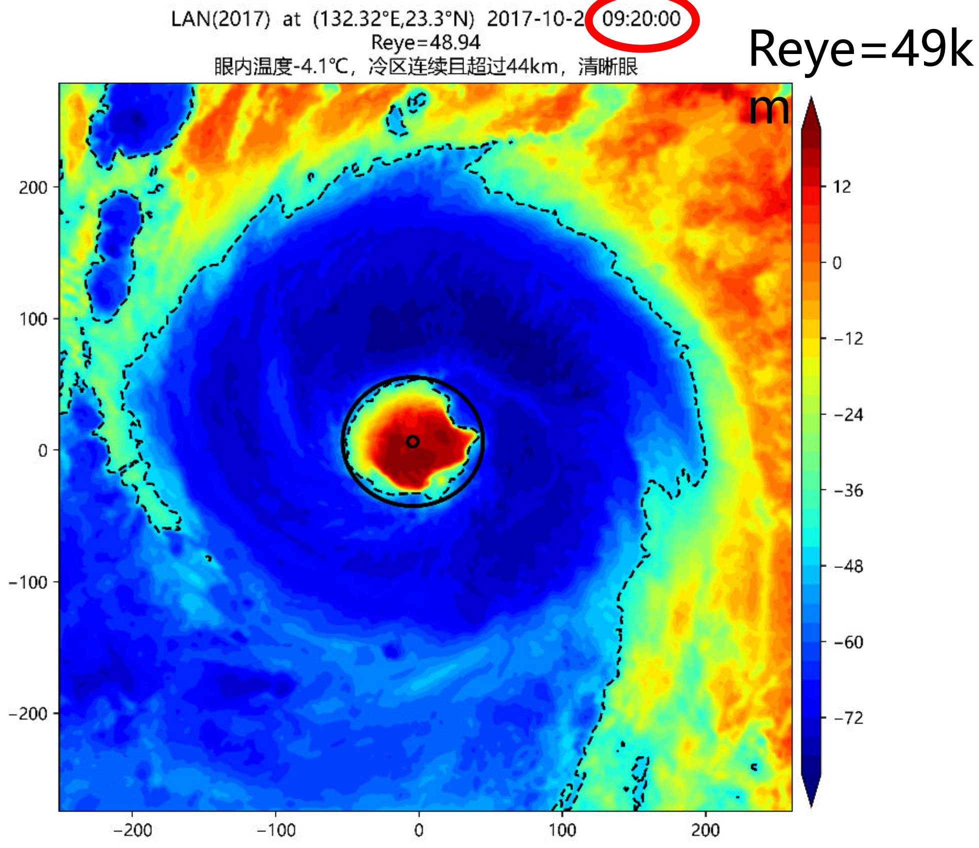
Impacts of Δt between IR and SAR observation

- In reality, R_{eye} and RMW can exhibit non-negligible variations within 10 minutes, potentially affecting the modeling and evaluation results.

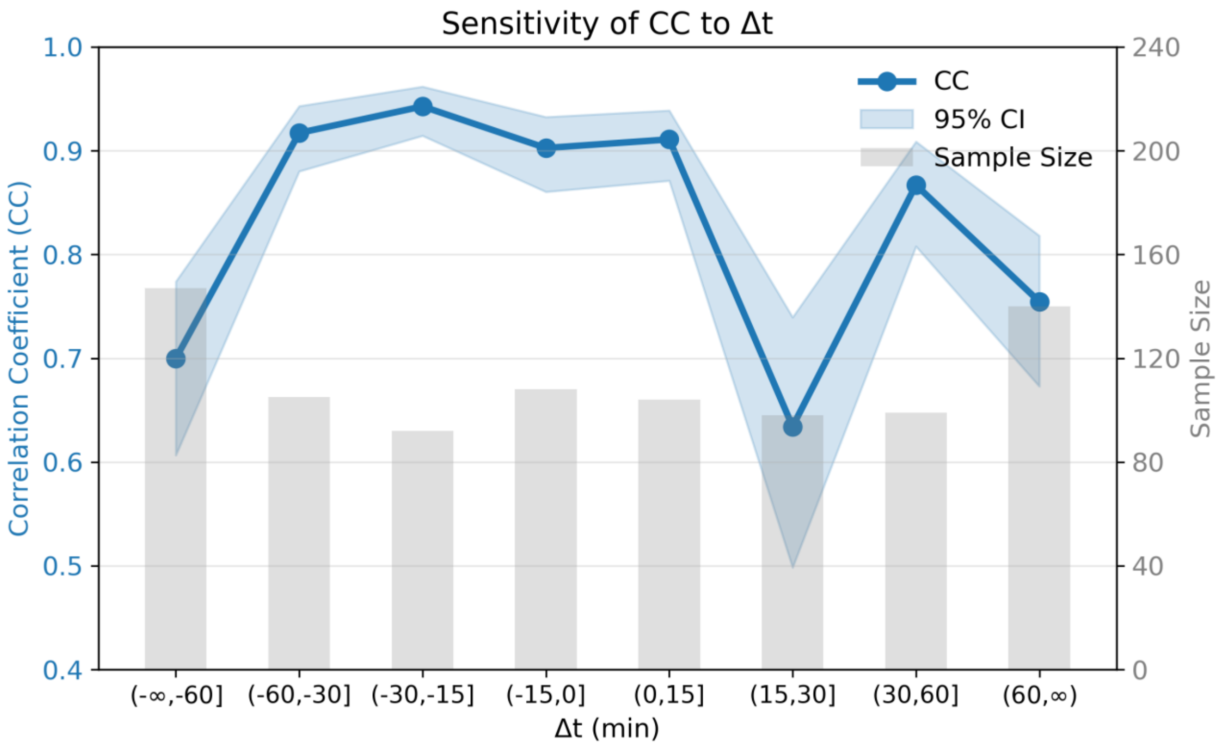




SAR Time：2017-10-21 09:21

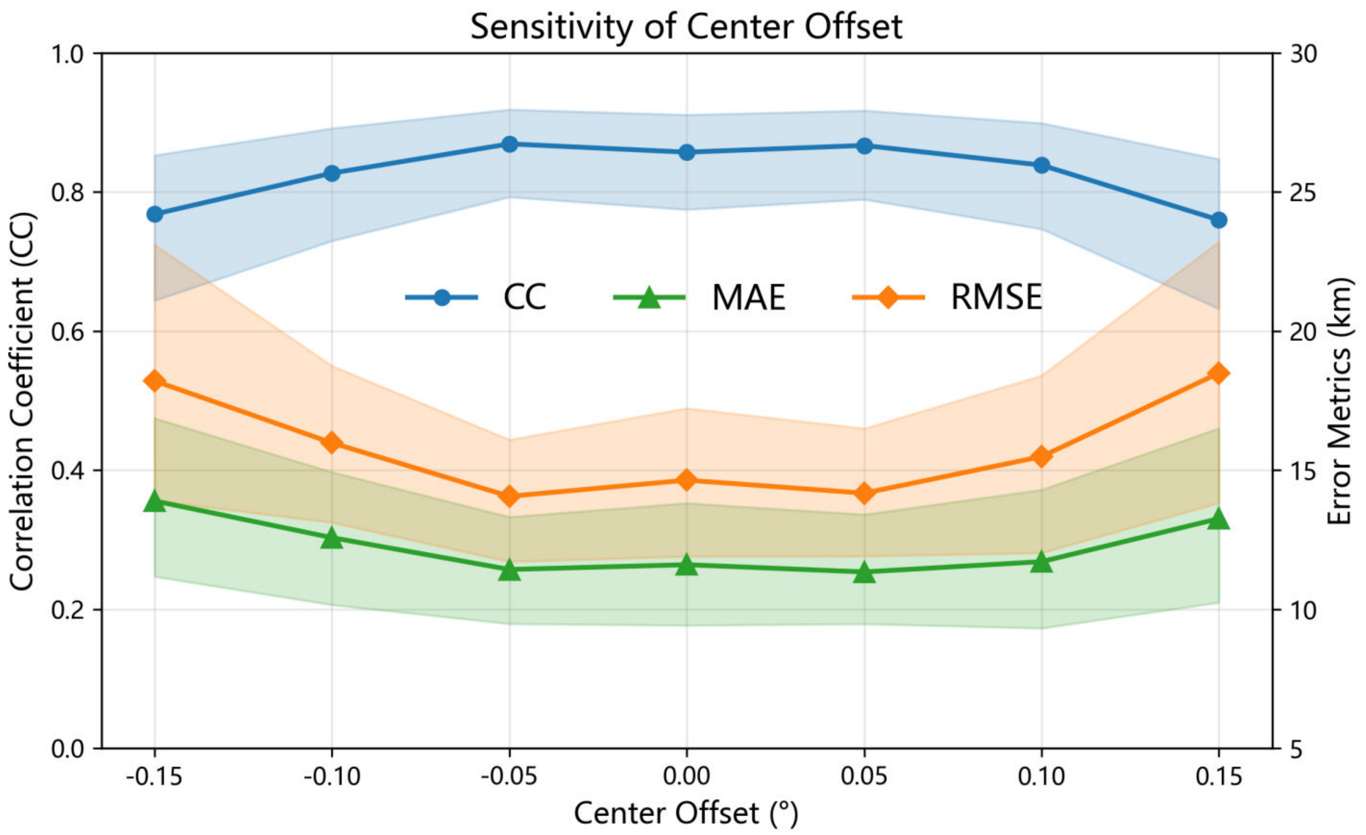
Impacts of Δt between IR and SAR observation

- For eyed typhoons, varying Δt alters sample count and quality.
- Retrieval performance fluctuates when IR lags SAR by >15 min, and uncertainty increases.
- Although the correlation coefficient is largest when IR precedes SAR observation by 15-30 min, it is still recommended to use the nearest-SAR-time IR image to retrieve RMW for method rigor.

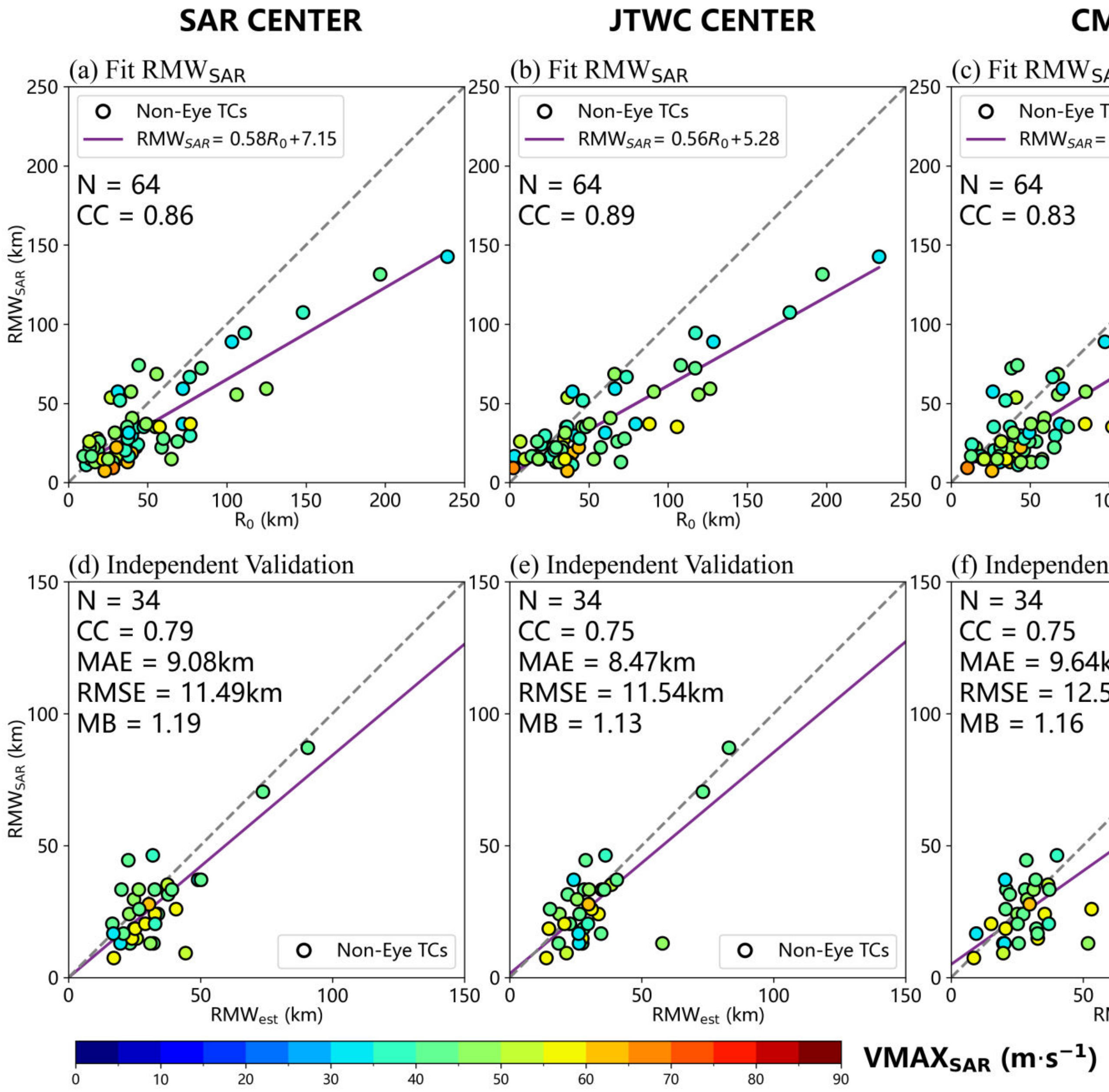


Impacts of positioning accuracy for non-eye typhoons

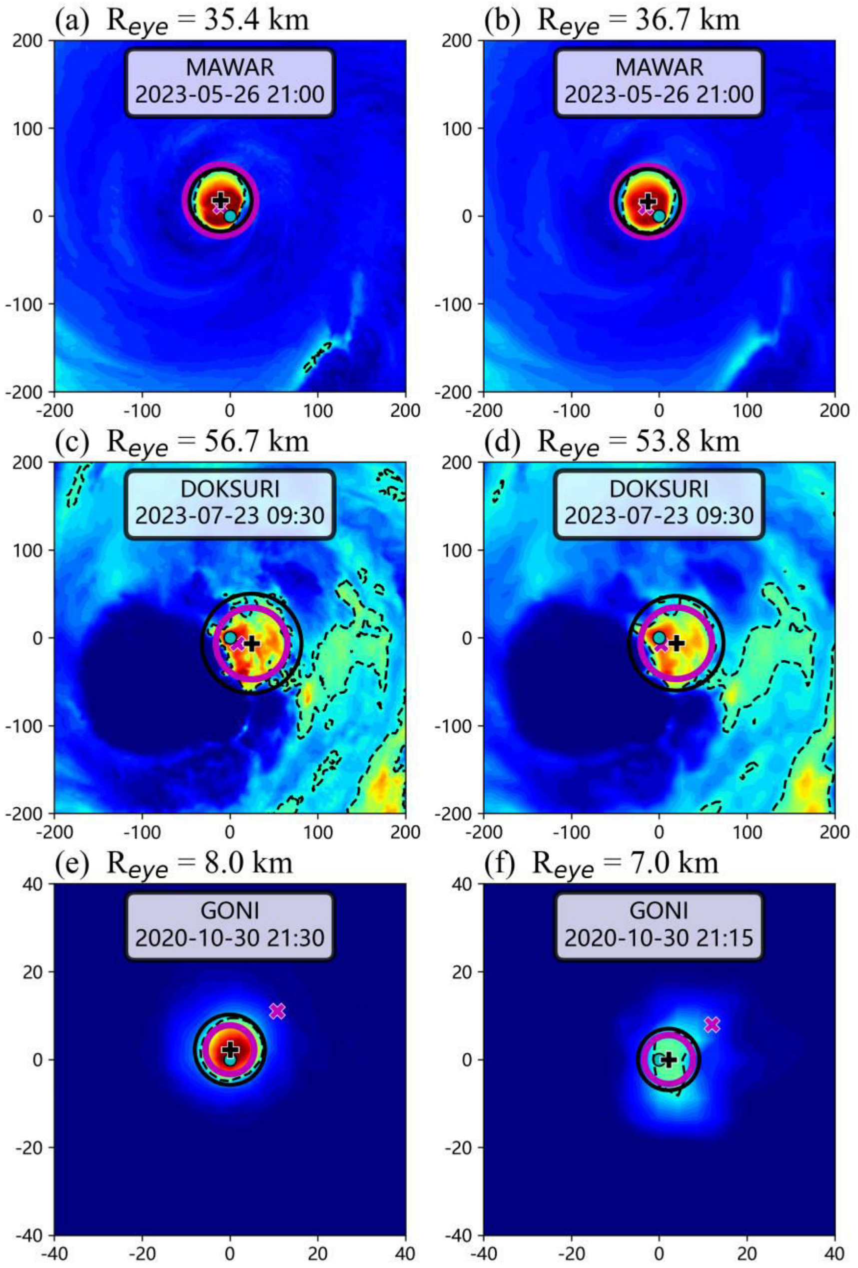
- Randomly shift the SAR-derived typhoon center (by ±0.15°, ±0.1°, ±0.05°, and no offset) to discuss the impact of center offset on RMW estimation for non-eye typhoons.
- Results show that algorithm performance remains good with small offsets (within ±0.05°).



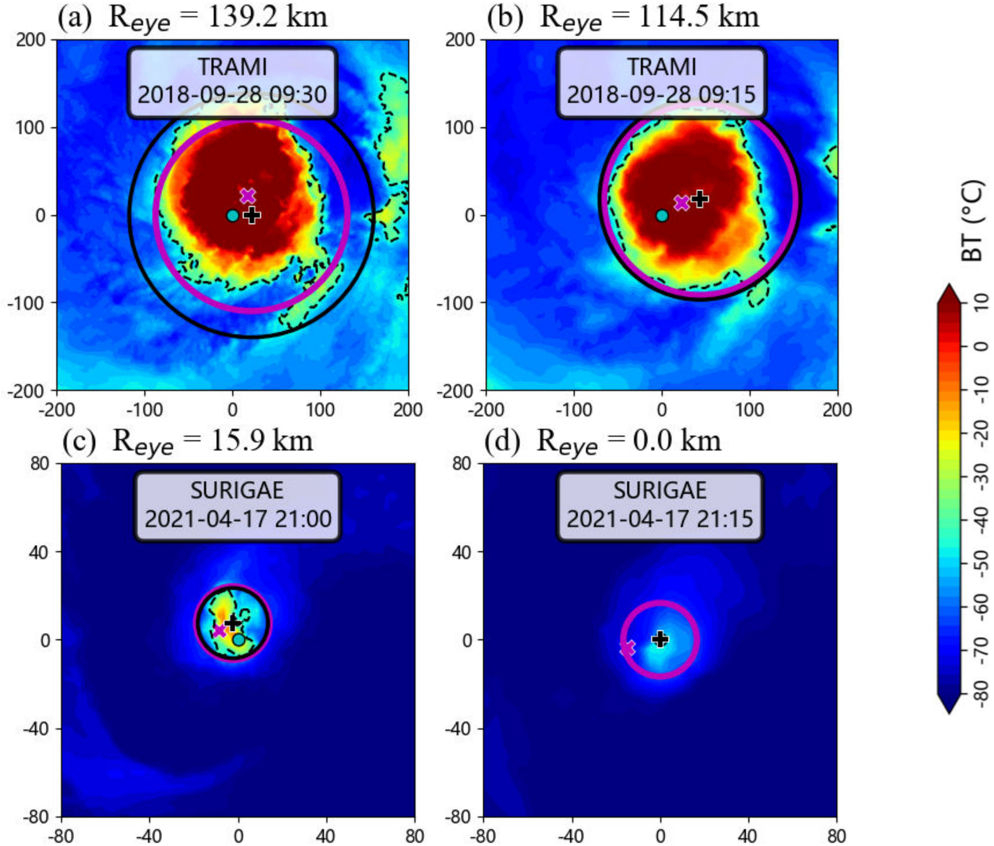
Impacts of positioning accuracy for non-eye typhoons



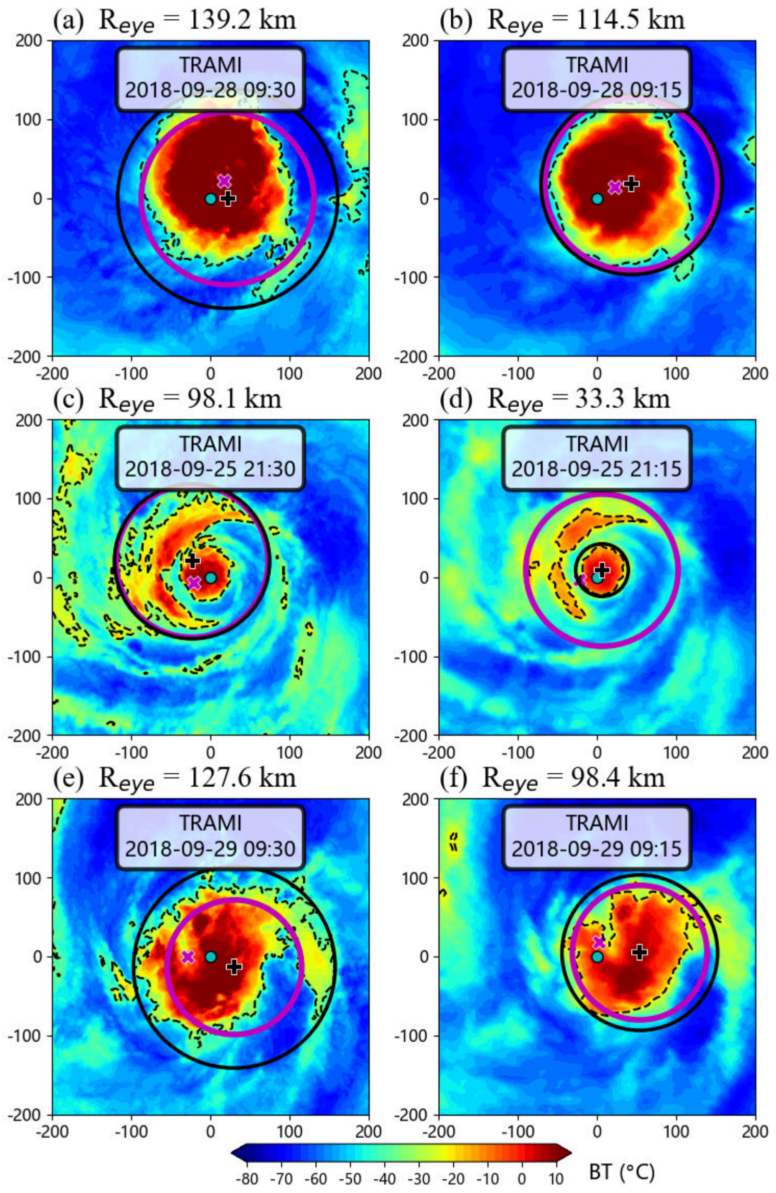
Impacts of different Geo. satellite data

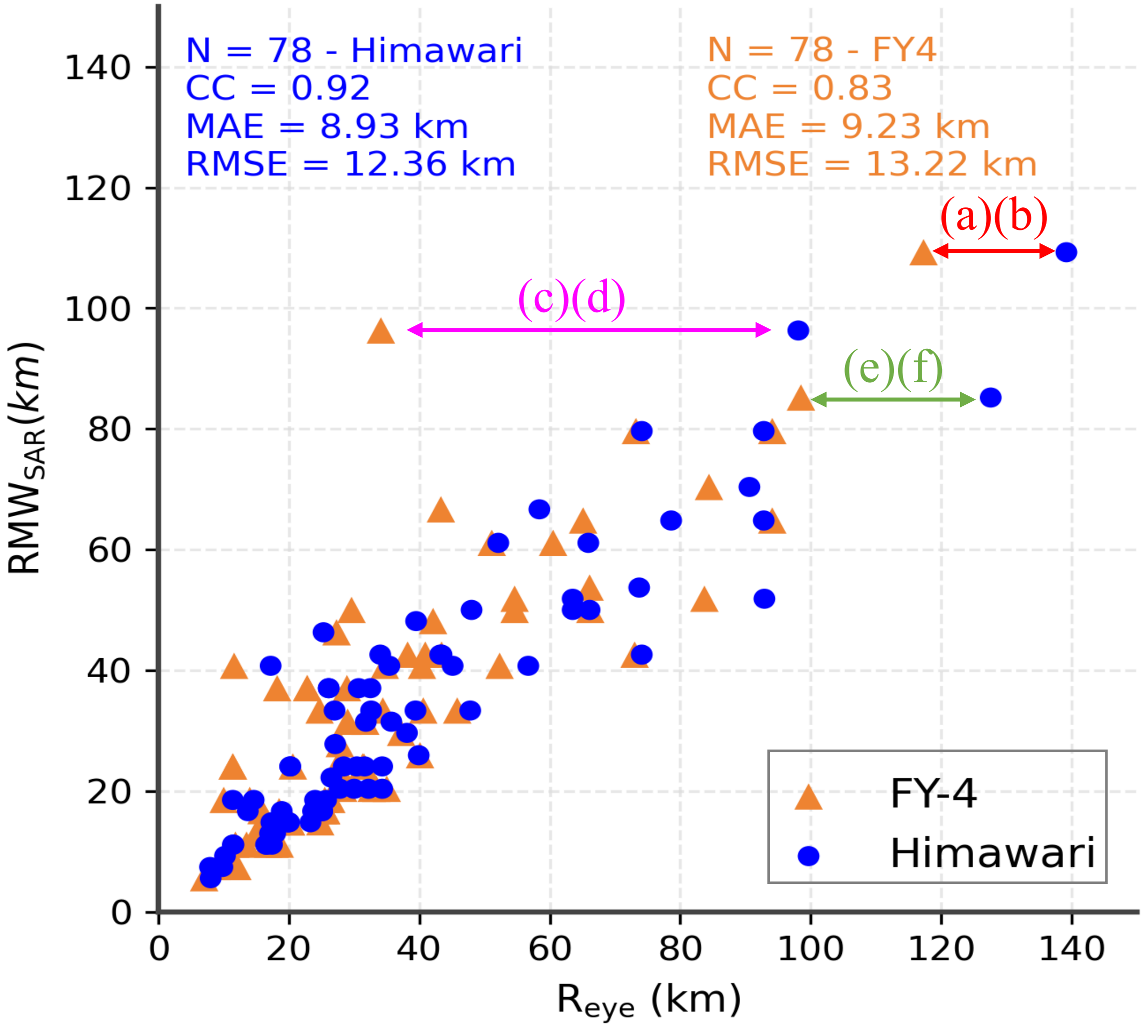


Satellite Name	Spatial resolution	Sub-satellite Lon.
Himawari-8/9	2 km	140.7° E
FY-4A/4B	4 km	104.7/133/105° E



Impacts of different Geo. satellite data





Outline

- Backgrounds
- Error Analysis of JTWC Best Track Dataset
- RMW Retrieval for Eyed Typhoons
- RMW Retrieval for Non-Eye Typhoons
- Potential Error Sources of Current Algorithms
- Summary

Summary and Outlook

(1) Algorithms for estimating the RMW values were developed separately for eyed typhoon and non-eye typhoons (≥64 kt). For eyed typhoons, RMW is estimated by fitting the eye radius R_{eye}; for non-eye typhoons, RMW is estimated by fitting the radius of the deepest convection R_0.

(2) For non-eye typhoons, the new algorithms reduce bias (MAE and RMSE) by over 40% compared to the JTWC best-track dataset.

(3) While operationally viable, the algorithm requires two human-assisted inputs: (1) TC center position, (2) eye presence flag.

(4) Enhancing the spatiotemporal resolution of infrared imagery and improving TC positioning accuracy would further refine the RMW estimation algorithms' precision.

(5) We also establish a typhoon inner-core size dataset (2016–2024; 0.5-h Resolution) for research purpose.

Variables in Typhoon Inner-core Size Dataset

Short Name	Long Name	Assigned value or unit
Name	TC name	-
Intl_ID	International TC number	-
ISO_Time	Observation time in ISO forma	YYYY-MM-DD hh:mm:ss
*_Vmax	TC intensity (wind) provided by JTWC, RSMC, CMA	knots
*_Lat / *_Lon	TC center position provided by JTWC, RSMC, CMA	° N / ° E
Eye_Type	Eye type	0=Non-Eye; 1=Clear eye; 2=Unclear eye; -99=Unknown
R0	Radius of strongest convection for Non-eye TC	km
Reye	Eyewall radius for eyed TC	km
RMW	RMW estimated	km
EC_Lat / EC_Lon	Minimum enclosing circle center for eyed TC	° N / ° E
L45_BT / U45_BT	Temperatures for eyewall slope estimation for eyed TC	℃
L45_R / U45_R	Radii for eyewall slope estimation for eyed TC	km
Obs_Quality	Satellite observation data quality	0=Normal; 1=All observation missing; 2=Infrared observation missing; 3=Infrared observation quality issue
RMW_Uncertainty	RMW estimation uncertainty	0=Normal; 1=TC centers from 3 datasets vary greatly; 2=JTWC_Vmax<64 kt; 3=Scene Transitional phase

Results handling at eye-non-eye transition phase

The continuous RMW series may exhibit abrupt changes during the transition between eye and non-eye scenes. We then perform post-processing smoothing on significant jumps in RMW values.

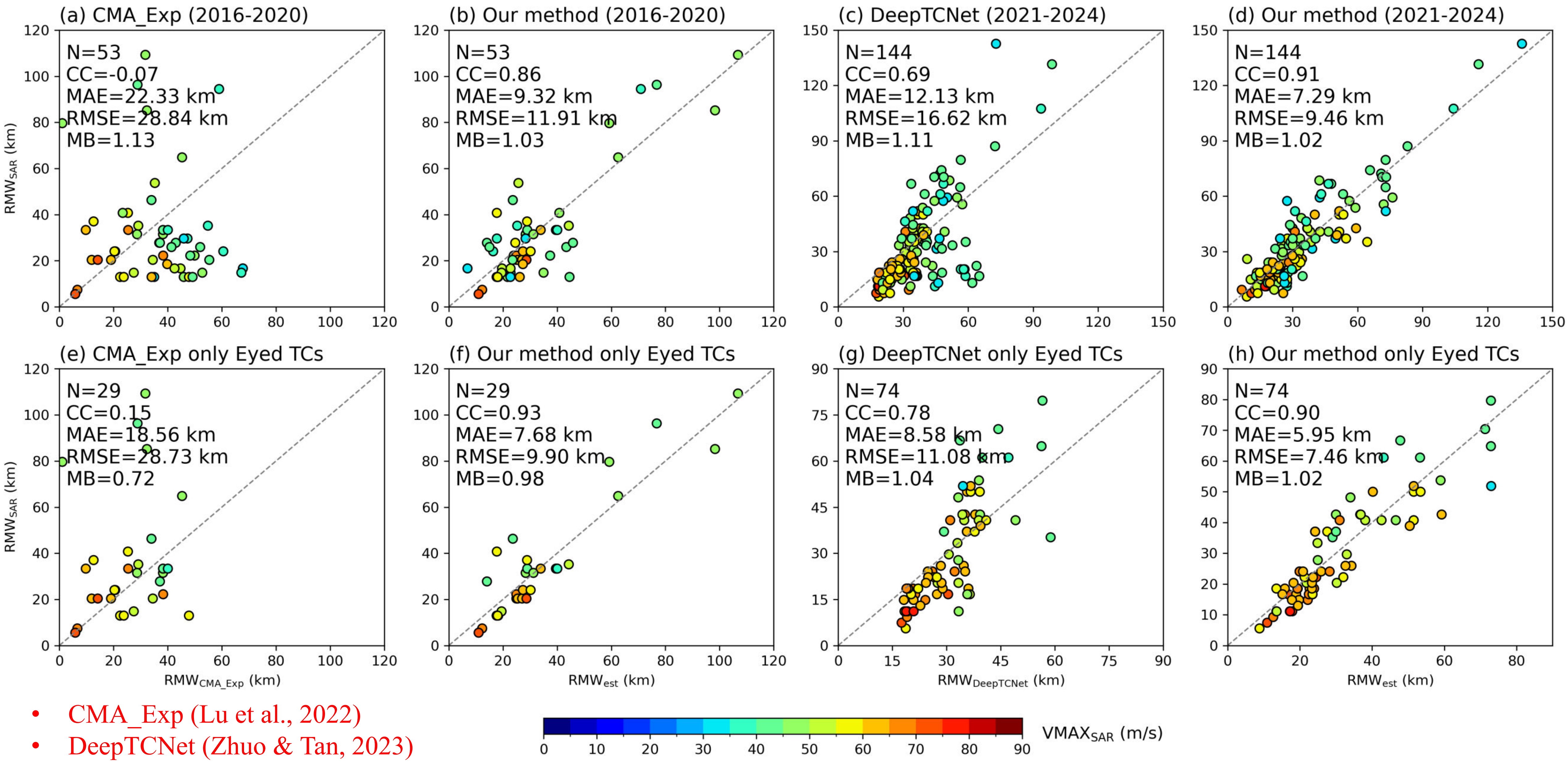
- Three-point smoothing for Point #1: $\mathrm{RMW_t} = \frac{RMW_{t-1}+RMW_t+RMW_{t+1}}{3}$ =31
- Three-point smoothing for Point #2: $\mathrm{RMW_{t+4}} = \frac{RMW_{t+3}+RMW_{t+4}+RMW_{t+5}}{3}$ =37.7

Time	EYE_TYPE	RMW Value
t-2	Non-eye	60
t-1	Non-eye	55
t	Unclear eye	20 → 31
t+1	Clear eye	18
t+2	Clear eye	16
t+3	Clear eye	17
t+4	Non-eye	50 → 37.7
t+5	Non-eye	46

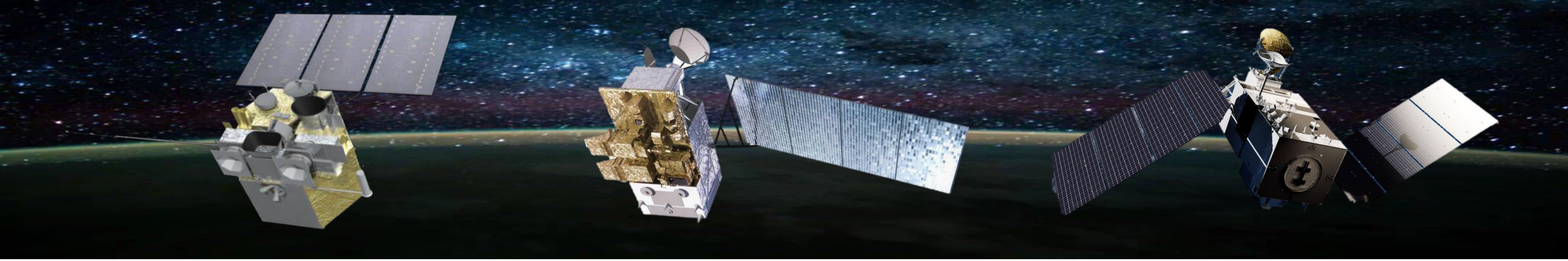
Point #1

Point #2

Compared with AI-based datasets from peers



- CMA_Exp (Lu et al., 2022)
- DeepTCNet (Zhuo & Tan, 2023)



Retrieval of Tropical Cyclone Inner-core Size from Geostationary Satellite Infrared Imagery

Thank you for your attention!

AMS

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