Estimation of Tropical Cyclone Intensity Using Satellite Passive Microwave Observations: Year 2 Update

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Project Overview

Passive Microwave Intensity Estimation (PMW-IE) Model:

- Task 1: Model development
  - Proof-of-Concept & initial model development using TRMM data
  - Initial model development & implementation using current available PMW sensors: GMI, AMSR2, and SSMIS
- Task 2: Real time testing & post-season evaluations
  - AL basin: 2018 hurricane season
  - Post-season analysis & model refinement
  - AL and EP basins: 2019 hurricane season

Motivation of the Project

- **Currently TC intensity is almost exclusively estimated by Dvorak technique (Dvorak 1975, 1984;** Objective Version ODT**: Velden et al. 1998;** ADT **Olander and Velden 2007)** except when sometime aircraft recon data are available in the AL basin**.**
- **The Dvorak technique is based on both visible and IR satellite images**, which only show the cloud top structure of a TC and cannot measure the detailed rainfall and convective structure at lower levels.
- **The advantage of passive microwave (PMW)** channels is that they allow penetration into precipitating clouds, therefore providing information about precipitation and convective structure that are better correlated with TC intensity (**Cecil and Zipser 1999**).
- In recent years, **inter-calibration of different PMW radiometers has been done by NASA. The era has arrived where timely observations from PMW sensors can be incorporated into real-time TC monitoring and forecasting**.

Past, Current, & Future
Passive Microwave Satellite Sensors

Sensor	85-91 GHz Frequency	Spatial Resolution at 85-91 GHz	Swath Width	Year
SSM/I (F15)	85.5 GHz	15 x 13 km^2	1400 km	1987-present
SSMIS (F16, 17,18,19)	91 GHz	14 x 13 km^2	1700 km	2003-present
AMSR-E	89 GHz	6 x 4 km^2	1450 km	2002-2011
AMSR2	89 GHz	5 x 3 km^2	1450 km	2012-present
TMI	85.5 GHz	7x5 (before boost) /8x6 (after boost) km^2	760 km (before boost) 878 km /(after boost)	1997-2014
GMI	89 GHz	7.2x4.4 km	900 km	2014-present
TROPICS	91 GHz	17 x 17 km^2	2025 km	2020-??

Initial Model Development Using TMI data

- **16-yr TMI data (1998-2013):** 2326 overpasses over 503 TCs
- Developed **a stepwise multiple linear regression** model using 1998-2010 (13-yr) cases as the dependent sample
- **Model verification:** 2011-2013 (3-yr) cases as the independent sample
- **Develop AL and EP/CP models separately; Estimate both Vmax & 6-h future Vmax.**
- This algorithm will be referred to as the **Passive Microwave Intensity Estimation (PMW-IE) model**.
- **Aircraft-recon-based independent samples yield a MAE of 9.6 kt and best track-based samples yield a MAE of 9 kt**.
- Results published in:

Jiang, H., C. Tao, and Y. Pei, 2019: Estimation of Tropical Cyclone Intensity in the North Atlantic and North Eastern Pacific Basins Using TRMM Satellite Passive Microwave Observations. *J. Appl. Meteor. Climatol.,* **58**, 185–197, https://doi.org/10.1175/JAMC-D-18-0094.1.

Comparison of MAE & RMSE with other methods

TABLE 9. Comparison of the error statistics (MAE and RMSE) of TC intensity Vmax (or MSLP in hPa converted to Vmax in kt) of this study (PMW-IE) and other satellite-based TC intensity estimation methods.

Methods	Sensors	Verification against	MAE	RMSE	Reference(s)
Dvorak technique	Visible, IR	Within 2-h aircraft-reconnaissance-based best track	5–11 kt[a] (avg ~8 kt)	6–14 kt[a] (avg ~10 kt)	Knaff et al. (2010)
Deep convolutional neutral network	IR	Aircraft-reconnaissance dataset[b]	—	9–16 kt (avg = 11.7 kt)	Pradhan et al. (2018)
Feature analogs in satellite imagery	IR	Within 12-h aircraft-reconnaissance-based best track	10.9 kt	12.7 kt or 9.8 hPa	Fetanat et al. (2013)
Advanced Dvorak technique	IR	Within 1-h aircraft-reconnaissance-based best track	9.2 hPa (~10.9 kt[c])	12.5 hPa (~14.9 kt[c])	Olander and Velden (2007)
Multivariate regression	IR	Within 3-h aircraft-reconnaissance-based best track	13.2 kt	16.7 kt	Kossin et al. (2007)
Deviation angle variance	IR	Best track	—	12–15 kt	Ritchie et al. (2012, 2014)
Warm-core anomaly	AMSU	Best track	10.8 kt	14 kt	Demuth et al. (2004, 2006)
Feature-based *k*-nearest-neighbor	SSM/I	Best track	14–16 kt	18.1–19.8 kt	Bankert and Tag (2002)
PMW-IE combined model for $t = 6$ h	TMI	Best track/within 3-h aircraft-reconnaissance-based best track	9/9.6 kt	12/12.6 kt	This study

Table taken from Jiang et al. (2019)

Variables Selected for the PMW-IE Model

Table below: List of variables in the inner core having correlation coefficients with Vmax significant at the 99.99% level.

Variables	Description	Units
85 GHz		
1) MEANPCT	Mean 85 GHz PCT	K
2) FRAC275	Fractional area covered by 85 GHz PCT≤ 275K	%
3) FRAC250	Fractional area covered by 85 GHz PCT≤ 250K	%
4) FRAC225	Fractional area covered by 85 GHz PCT≤ 225K	%
5) FRAC200	Fractional area covered by 85 GHz PCT≤ 200K	%
Rain		
1) U_RR	Unconditional mean rain rate	mm/hr
2) C_RR	Conditional mean rain rate	mm/hr
3) L_RR	Mean light rain (rain rate between 0-5 mm/hr) rate	mm/hr
4) H_RR	Mean heavy rain (rain rate ≥ 5 mm/hr) rate	mm/hr
5) RA	Fractional area covered by rain	%
6) L_RA	Fractional area covered by light rain	%
7) H_RA	Fractional area covered by heavy rain	%

2018 Real-Time Testing Using GPM-constellation 1C/2A Data

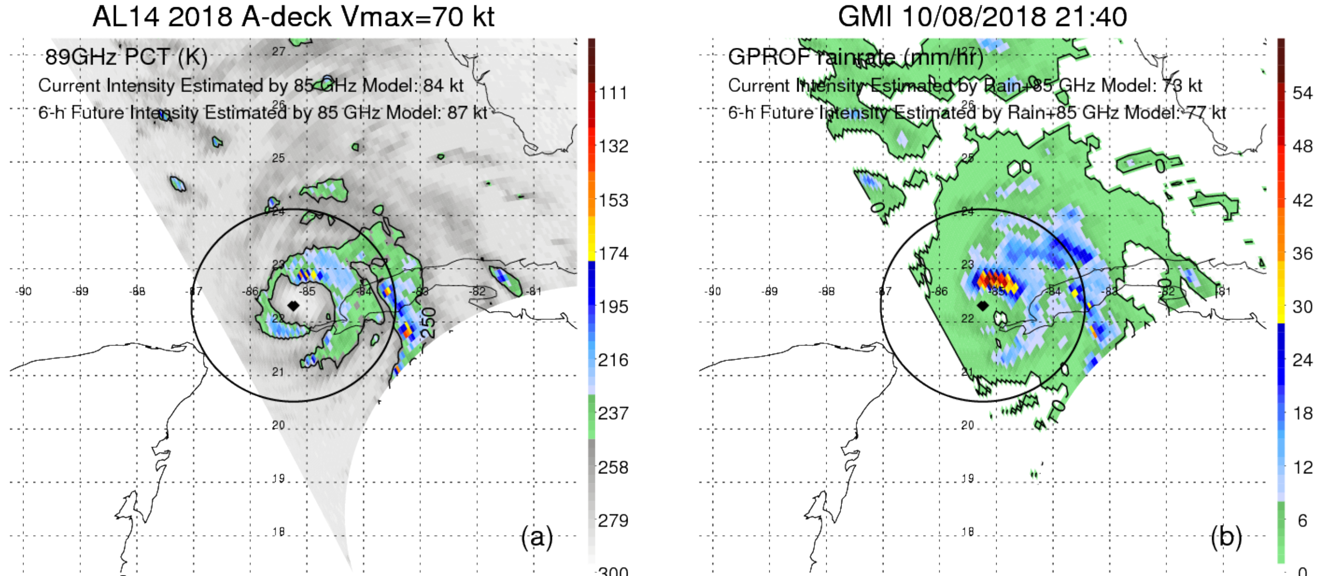
- Use TMI-trained stepwise model for GMI, AMSR2 and SSMIS data
- In real-time, the 85-91 GHz Tb observations will be available through the **GPM 1C-constelation near-real-time product**, which includes the inter-calibrated brightness temperatures from GMI, ASMR2, and SSMIS.
- The microwave rain retrievals will be from the GPM **2A-GPROF-constellation near-real-time product**, which contains the rain rates retrieved from GMI, AMSR2, and SSMIS using the NASA GPROF algorithm (Kummerow et al. 1996).
- **Latencies:**
  - GMI 1C/2A: **about 20 to 30 minutes**
  - AMSR2 & SSMIS 1C/2A: **about 2 to 3 hours**
  - Therefore, in real-time, the rain variables may or may not be available for estimating Vmax at the current synoptic time. But we can still estimate the current Vmax using the regression model for the 6-h future Vmax.

AL (EP/CP) 2018 Real-Time Testing

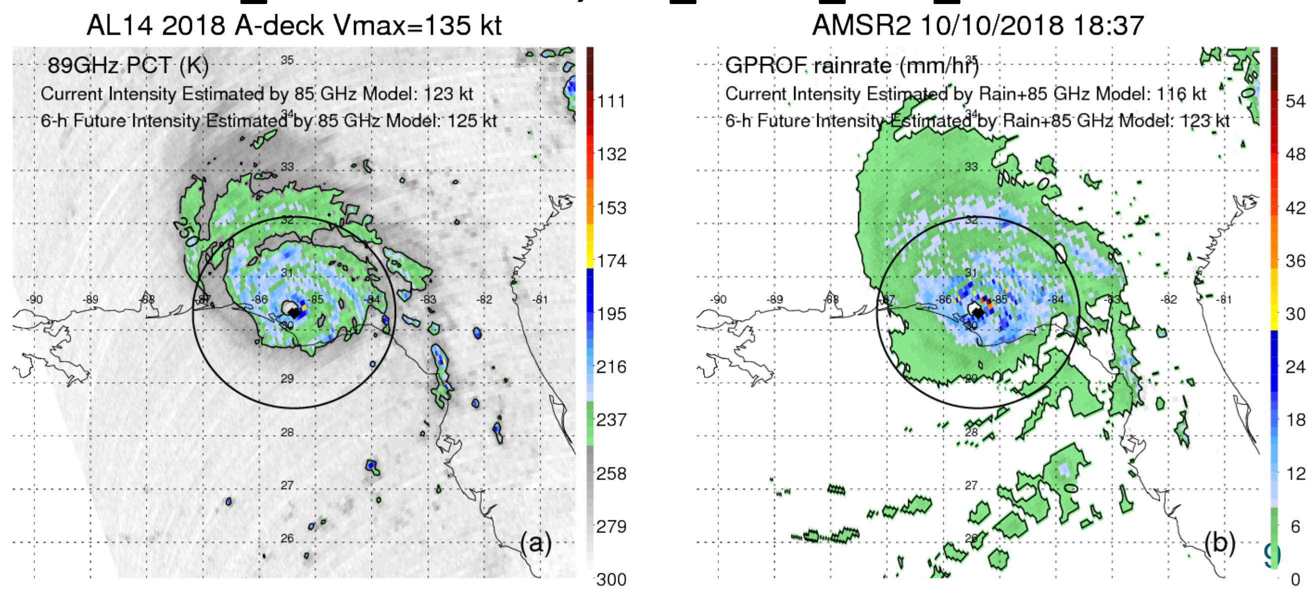
- **Online Output**: **http://tcpf.fiu.edu/JHT/Figures/**
  3 Folders:
  /AL2018
  /EP2018
  /CP2018

- **Hurricane Micheal 2018 Example:** http://tcpf.fiu.edu/JHT/Figures/AL2018/AL14/

Btrk Vmax=70 & 75 kt at 10/08 18Z & 10/09 00Z; GMI @21:40Z
Est. Vmax_85GHz=84 kt; Est_Vmax_rain_85GHz=73 kt



10/10: Btrk Vmax=135 kt at 18Z; AMSR2 @18:37Z
Est. Vmax_85GHz=123 kt; Est_Vmax_rain_85GHz=116 kt



Real-time PMW Satellite Coverage for 2017-2018 TCs in AL & EP/CP

2017-2018	AL	EP/CP	Total
6-h Best Track Data Points	1256	1451	2707
GMI coverage	396 (32%)	399 (27%)	795 (29%)
AMSR2 coverage	622 (50%)	585 (40%)	1207 (45%)
Total High-Res. GMI+AMSR2	**822 (65%)**	**795 (55%)**	**1617 (60%)**
Low-Res. SSMIS	**1108 (88%)**	**1094 (75%)**	**2202 (81%)**
Overall Total	**1184 (94%)**	**1213 (84%)**	**2397 (89%)**

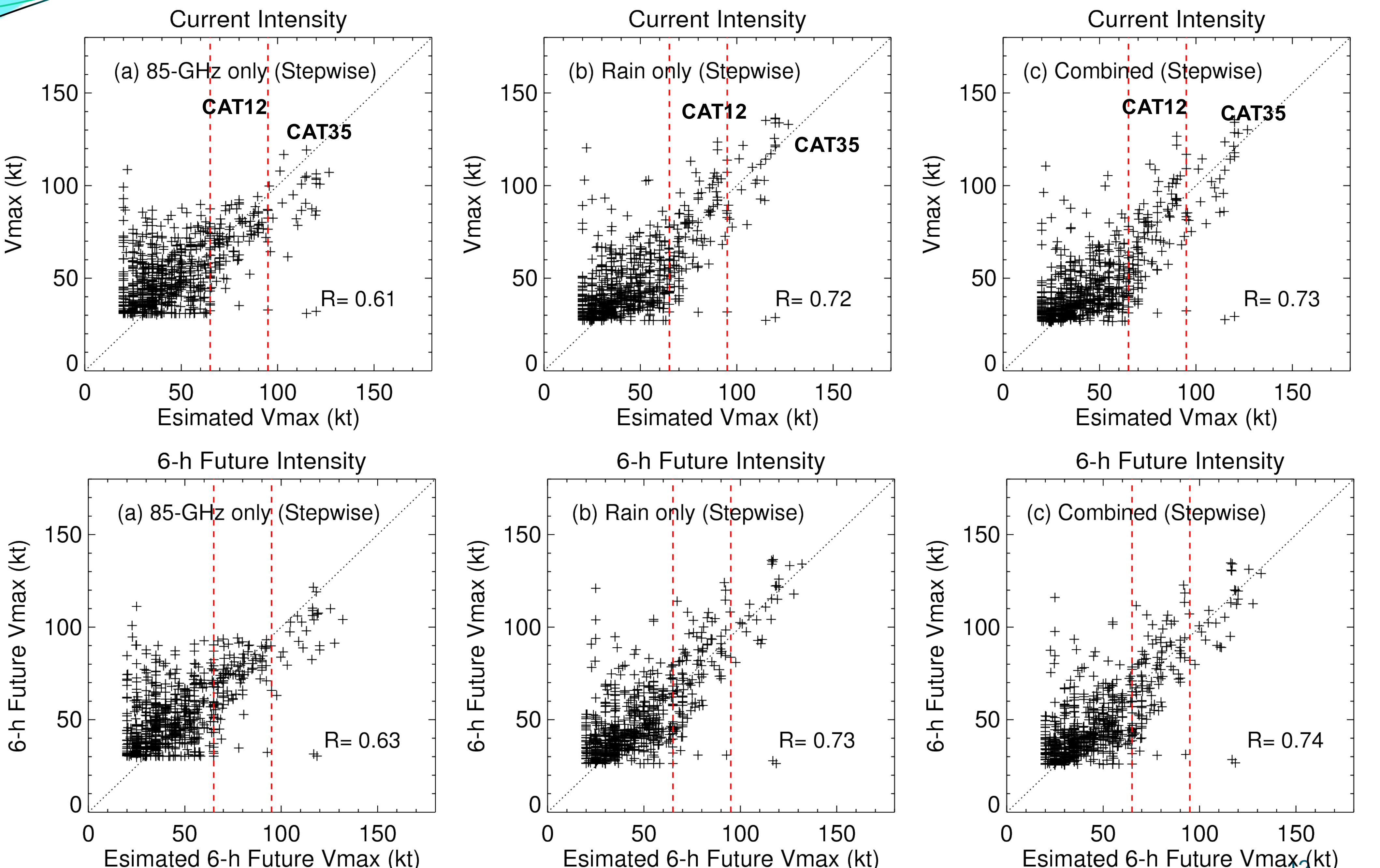
2018 Real-time Testing Statistical Evaluation Against Best Track

Error Analysis

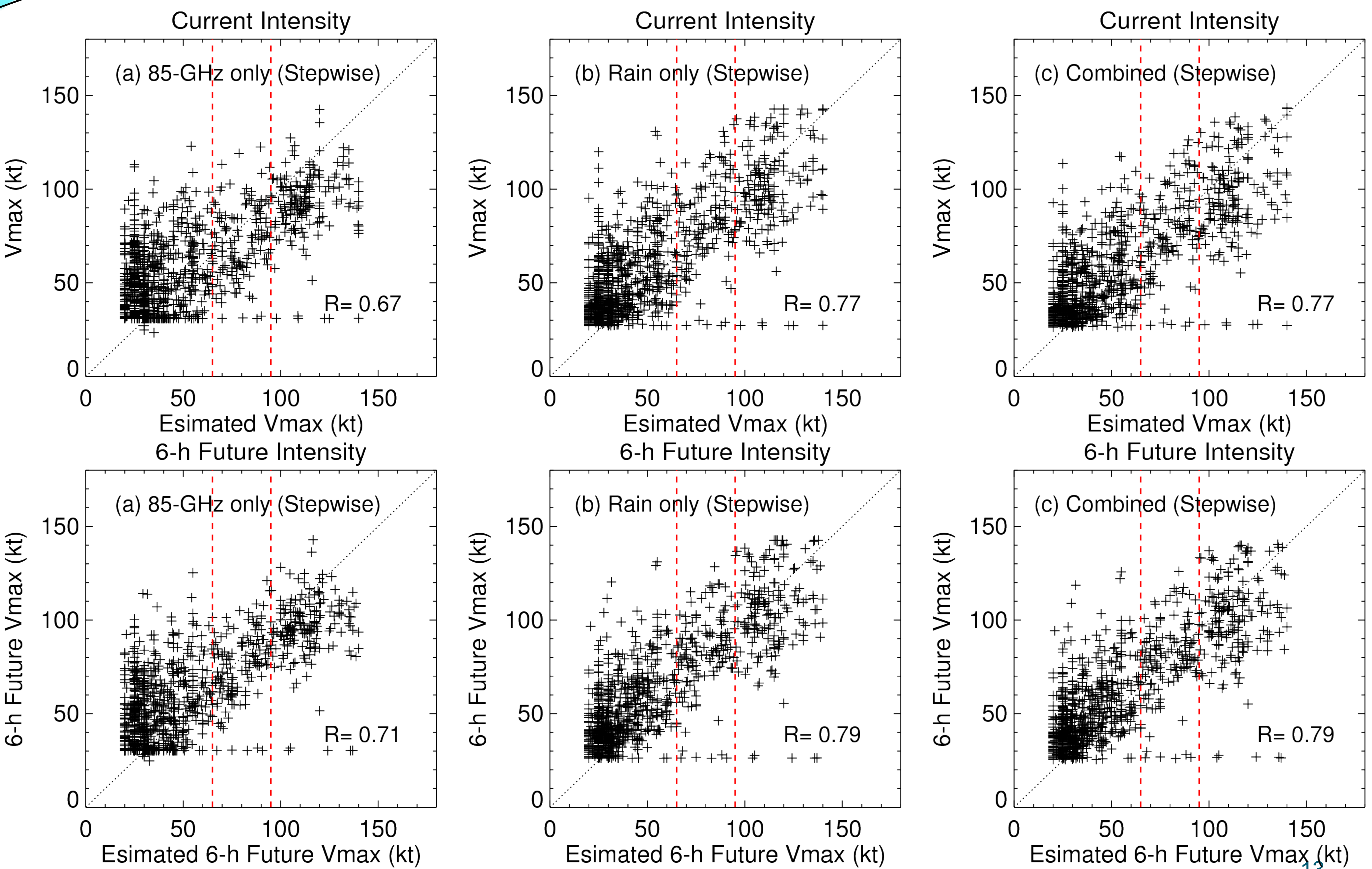
		85-GHz only		Rain only		Combined		Non-stepwise
		t=0 h	t=6 h	t=0 h	t=6 h	t=0 h	t=6 h	
AL (758 samples)	r^2 (%)	0.38	0.41	0.53	0.54	0.54	0.55	0.61
	MAE (kt)	13.96	13.50	11.59	11.34	11.19	10.79	10.43
	RMSE (kt)	18.91	18.77	16.46	16.40	15.83	15.73	14.56
EP/CP 1024 samples	r^2 (%)	0.45	0.51	0.59	0.62	0.60	0.63	0.70
	MAE (kt)	19.71	18.33	16.82	16.58	15.94	15.76	13.56
	RMSE (kt)	25.27	24.34	22.49	22.06	21.42	21.15	18.15

- Results are slightly better when using regular multiple linear (non-stepwise) regression.
- Subjective Dvorak Mean Absolute Error (MAE) is ~8 kt, Root Mean Square Error (RMSE) is ~10 kt (Knaff et al. (2010).
- The AMSU-based MAE is 10.8 kt and RMSE is 14.0 kt (Demuth et al. 2006).
- The SSM/I-based MAE is 14-16 kt, and RMSE is 18.1-19.8 kt (Bankert and Tag 2002).
- Jiang et al. (2019) PMW-IE TMI-based MAE 9 kt, RMSE 9.6 kt.

2018 Real-time Evaluation (AL)



2018 Real-time Evaluation (EP/CP)



Post-Season Model Refinement

- Stepwise versus non-stepwise regressions
- Separate high (GMI/AMSR2) and low-resolution (SSMIS) sensors
- 4 (AL high-res; AL low-res; EP/CP high-res; EP/CP low-res) X 6 (85 GHz, rain, and combined for Vmax at t=0 and 6h)=24 separate models

Sample Size

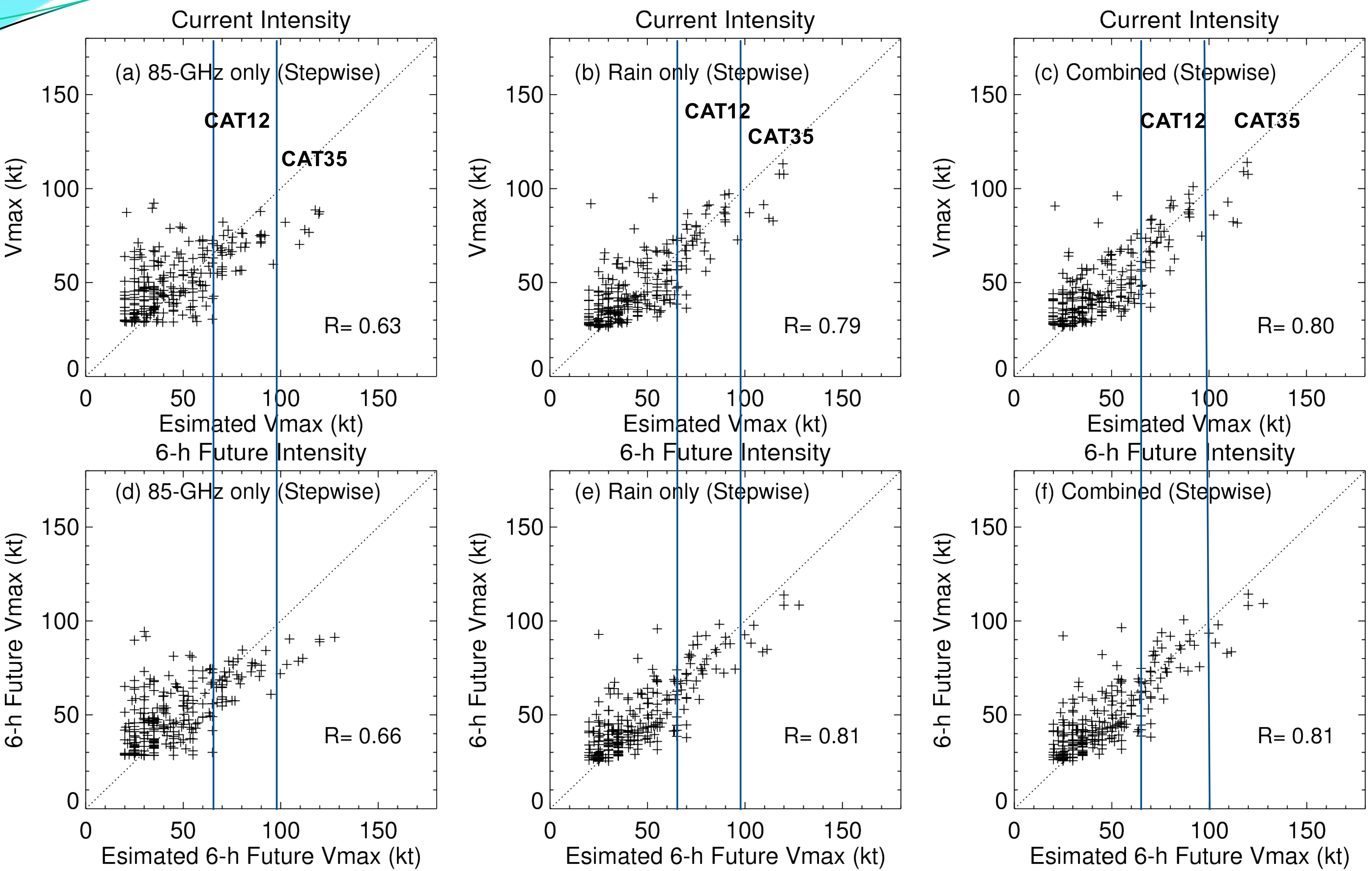
	AL		EP/CP	
# of orbits (# of TCs)	Dependent 1998-2017	Independent 2018	Dependent 1998-2017	Independent 2018
High-Res (TMI, GMI, AMSR2)	1980 (300)	251 (15)	2284 (358)	345 (23)
Low-Res (SSMIS)	1485 (55)	507 (15)	2458 (95)	697 (23)

Refined Model Verification Against Best Track

Error Analysis for 2018 Independent Sample

		85-GHz only		Rain only		Combined		No stepwise
		t=0 h	t=6 h	t=0 h	t=6 h	t=0 h	t=6 h	
AL High	r^2 (%)	0.40	0.44	0.63	0.66	0.64	0.67	0.68
	MAE (kt)	13.27	12.61	9.94	9.30	9.87	9.24	9.09
	RMSE (kt)	17.46	16.96	13.37	12.77	13.23	12.67	12.37
AL Low	r^2 (%)	0.44	0.48	0.60	0.61	0.60	0.61	0.60
	MAE (kt)	12.70	12.12	10.49	10.24	10.39	10.14	10.29
	RMSE (kt)	16.86	16.13	14.19	13.86	14.07	13.84	14.08
EP/CP High	r^2 (%)	0.53	0.60	0.64	0.69	0.66	0.69	0.72
	MAE (kt)	17.62	16.19	14.61	13.35	14.31	13.29	12.70
	RMSE (kt)	22.22	20.78	18.90	17.97	18.55	17.87	16.99
EP/CP low	r^2 (%)	0.49	0.54	0.60	0.62	0.60	0.62	0.70
	MAE (kt)	18.73	17.40	15.75	14.66	15.70	14.72	14.15
	RMSE (kt)	24.57	23.18	21.86	20.87	21.89	20.91	18.90

Independent Verification (AL High-Res)



Summary

- The PMW-IE model's performance is similar to other objective satellite-based TC intensity estimate methods (all worse than the subjective Dvorak Technique).
- However, the PMW-IE estimates are independent of visible, IR, and microwave sounder observations. Because of this independence, the PMW-IE method will be able to provide additional information for TC forecasters who can utilize different methods to achieve more accurate intensity estimates.

Next-Step Work

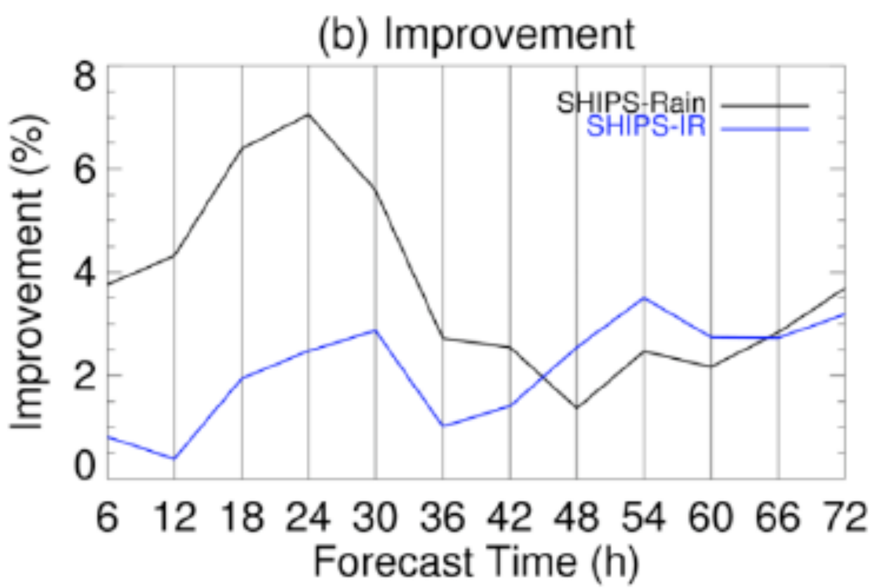
- **Year 2:**
  - Mar-Jun, 2019: Implement the refined model for real-time testing for AL & EP/CP basins in 2019 season
- **Year 3 (no-cost extension):**
  - Jun-Nov, 2019: real-time testing to be continued
  - Nov 2019-Jun 2020: post-season analysis
- **Year 4 (more no-cost extension??):**
  - Apply the method to JTWC basins

Future Work: Enhancement of SHIPS Using Passive Microwave Rainfall Features

- **Add rainfall structural parameters**
- **Model development using 16-yr TMI samples**

Table 2. List of rain variables derived from the TMI 2A-GPROF product

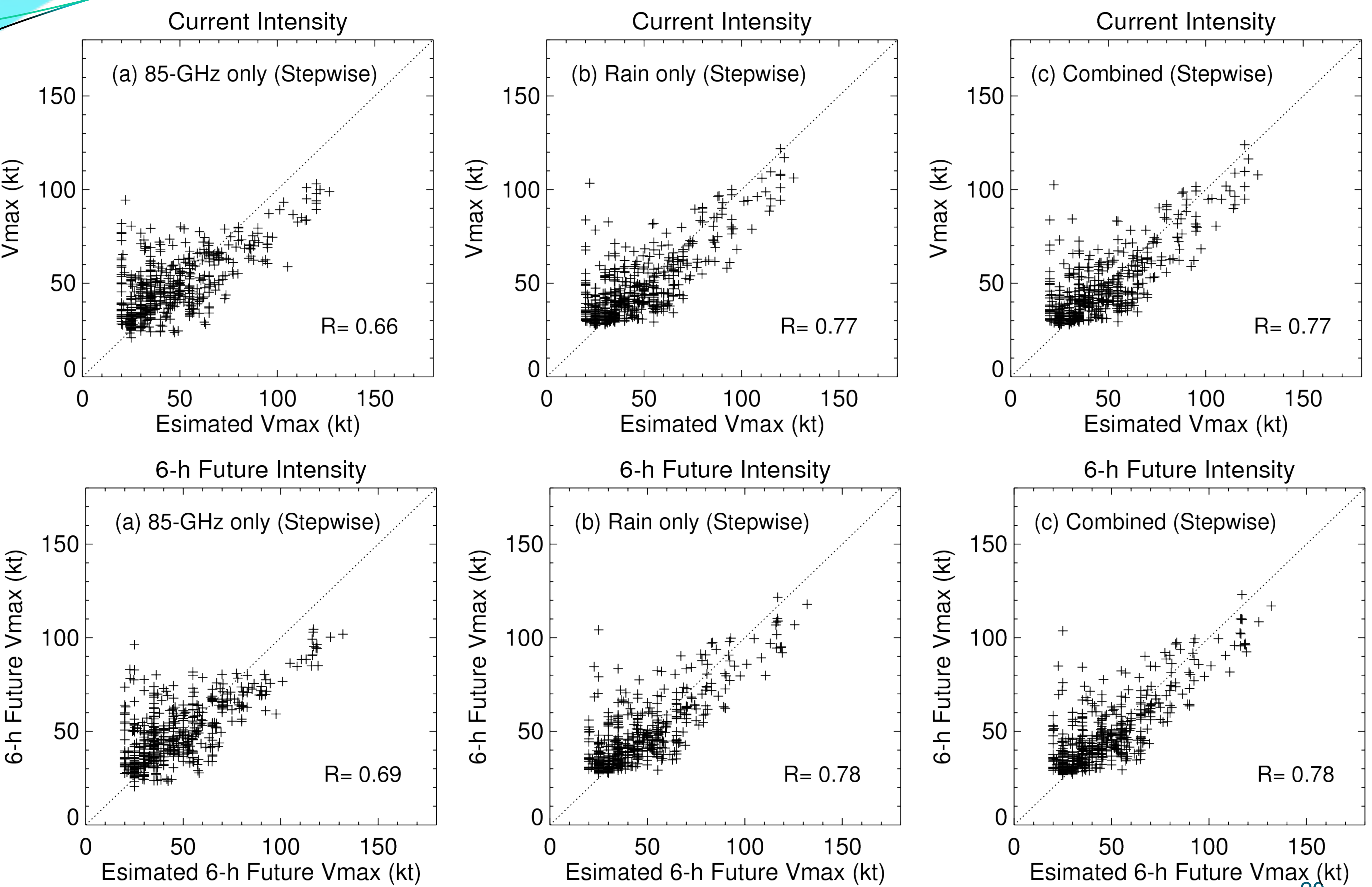
Predictors	Description	Units
RMR	Radius of maximum azimuthal mean rainfall	km
AXIS	Axisymmetry of rainfall structure within 100, 100-250, or 250 km radius	%
UMEAN	Unconditional mean rain rate within 100, 100-250, or 250 km radius	mm/hr
CMEAN	Conditional mean rain rate within 100, 100-250, or 250 km radius	mm/hr
LMEAN	Mean light rain (rain rate between 0-5 mm/hr) rate within 100, 100-250, or 250 km radius	mm/hr
HMEAN	Mean heavy rain (rain rate $\geq$ 5 mm/hr) rate within 100, 100-250, or 250 km radius	mm/hr
RA	Fractional area covered by rain within 100, 100-250, or 250 km radius	%
LRA	Fractional area covered by light rain within 100, 100-250, or 250 km radius	%
HRA	Fractional area covered by heavy rain within 100, 100-250, or 250 km radius	%



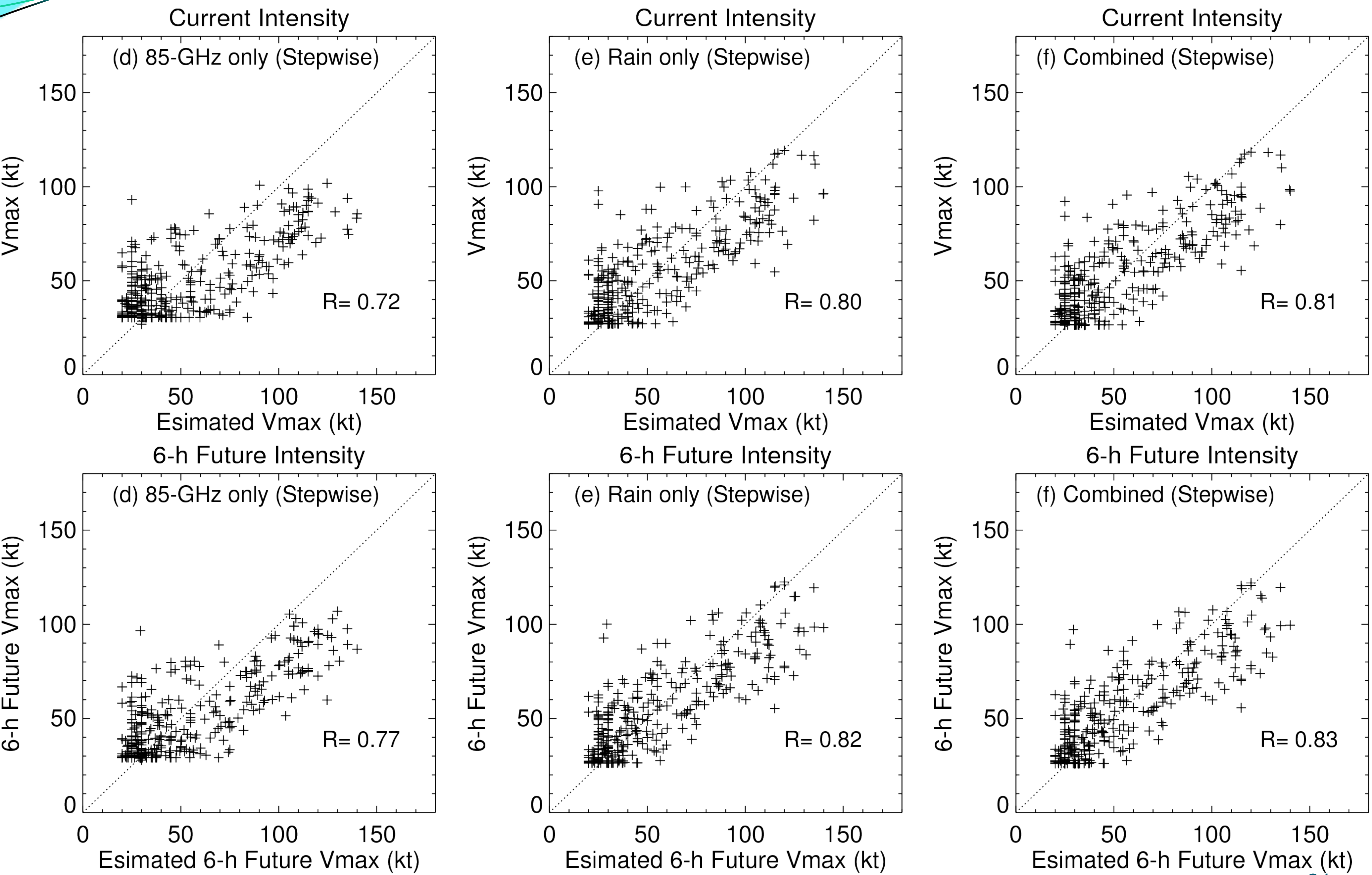
Max. improvement is ~7% at 24-h future against SHIPS-Base.

Thanks for your attention!

Independent Verification (AL Low-Res)



Independent Verification (EP/CP High-Res)



Independent Verification (EP/CP Low-Res)