The Simulation Studies of Potential Influence of Future Long-term Climate Change on Super Typhoon Precipitation Cases in Western North Pacific

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Introduction

- Many researches indicate TC rainfall increases under global warming. According to Tsou et al. (2016), rainfall rate in 200 km radii of TC circulation increases 22% under RCP 8.5 scenario in HiRAM model. Knutson et al. (2020) also indicates the precipitation rate of TCs would increase ~14%.
- Wang et al. (2015) used high-resolution Cloud-Resolving Storm Simulator (CReSS) on modeling Typhoon Sinlaku (2008) and Jangmi (2008), and found that TC precipitation under current scenario may increase in comparison to the environment of few decades ago.
- In particular to more hazardous TCs, Thean (2021) has made attribution of C4/C5 TC intensity changes in warming scenarios. However, the details of precipitation changes in these strong TC cases need more clarification and analysis. Thus, by high-resolution modeling, we want to find out how rainfall structure changes and how much precipitation would occur if these super typhoons form in warming future.

Data & Method

Super typhoon cases for analysis

1. MEGI (2010) 2. HAIYAN (2013) 3. MERANTI (2016)

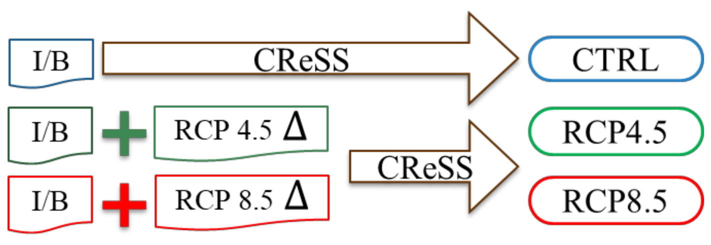
Grid data

1.NCEP GFS 0.5° 2.NCEP FNL 0.25° 3.HYCOM+NCODA 0.08° 4.CMIP5 2° climate data

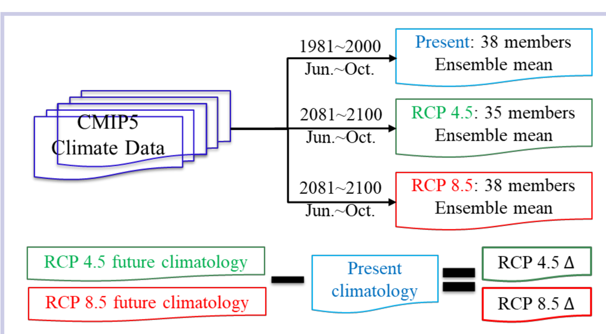
Method

1. 2.5-km high resolution downscaling model: Cloud-Resolving Storm Simulator (CReSS) v3.4.3
2. Experiment: Control Run (CTRL) & Pseudo Global Warming (PGW) Run (RCP 4.5/8.5)

	Megi (2010)	Haiyan (2013)	Meranti (2016)
Horizontal resolution	2.5 km (0.025˚)		
I/B condition	NCEP GFS 0.5°	NCEP GFS 0.5°	NCEP FNL 0.25°
SST data	HYCOM GLBu 19.1	HYCOM GLBv 53.X	HYCOM GLBv 57.2
Domain	3.70065~33.5074˚N; 112.237~149.989˚E	2.11391~22.306˚N; 109.791~150.305˚E	6.50141~39.6123˚N; 110.203~150.607˚E
Initial time	2010/10/15 00 UTC	2013/11/6 00 UTC	2016/9/10 12 UTC
Simulating length	4 days (96 h)	3 days (72 h)	4 days (96 h)
Cloud microphysics	Bulk cold rain microphysics		



▲ Schematic diagram of simulation process in this study.



▲ Process of producing future climate difference (Δ)

1) CMIP5 data
2) TC season (Jun.~ Oct.) monthly composite
3) Present cli.: 1981-2000, 38 members ensemble mean
4) Future cli.: 2081-2100, 35(38) members ensemble mean in RCP 4.5 (RCP 8.5)
5) Δ = future - present climatology

3. Water budget equation (Trenberth and Guillemot, 1995)

$$\frac{\partial w}{\partial t} + P = -\boxed{\nabla\cdot\int_0^\infty \rho_w \vec{V}\,dz} + E + R$$

① ② ③ ④ ⑤ — LHS: sink; RHS: source

$$\nabla\cdot\int_0^\infty \rho_w \vec{V}\,dz = \int_0^\infty \rho_w\left(\nabla\cdot\vec{V}\right)dz + \int_0^\infty \vec{V}\cdot\left(\nabla\cdot\rho_w\right)dz$$

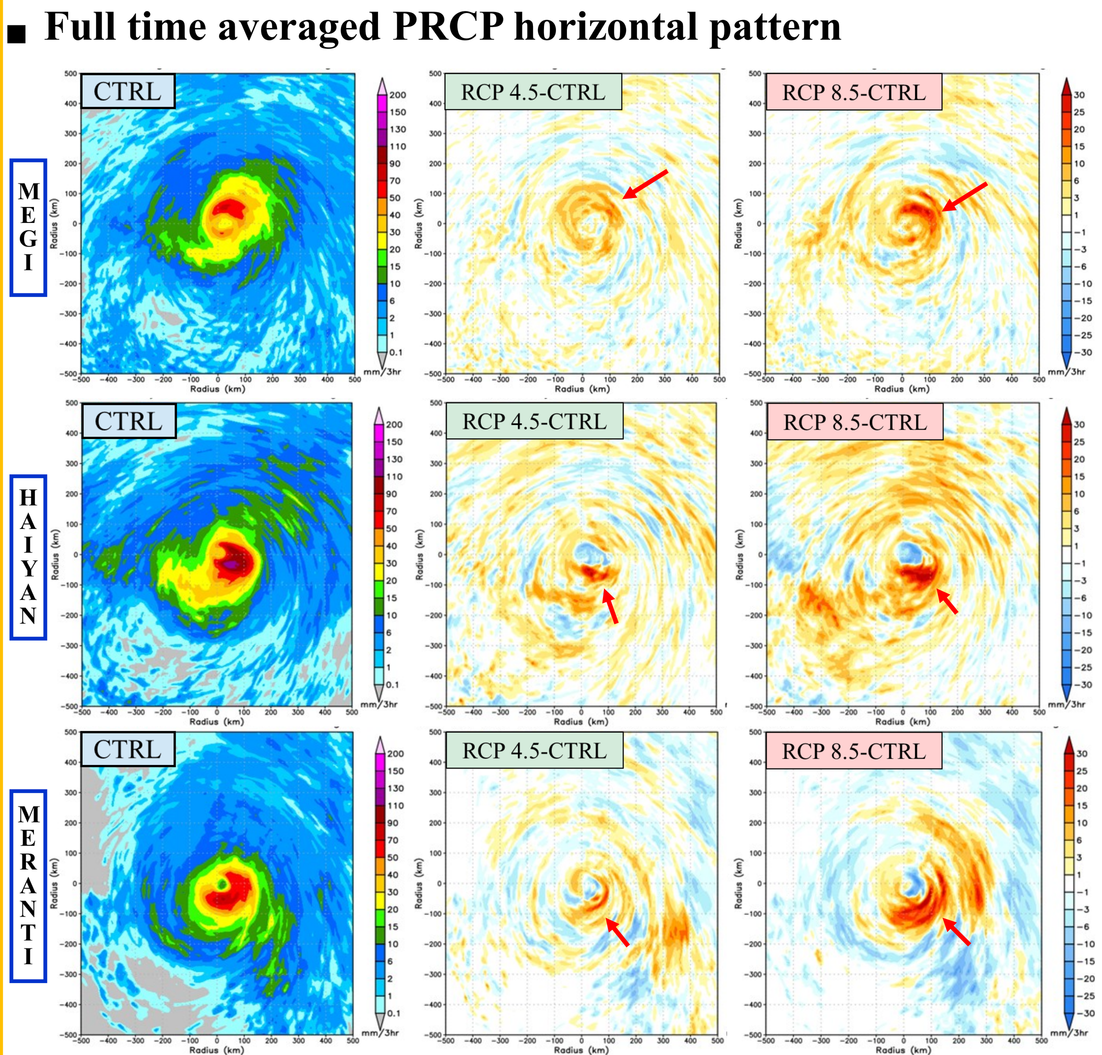
③ ⑥ ⑦

Each term in water budget equation:

① Absolute humidity change
② Precipitation
③ Density flux divergence (**without "-" sign!**)
④ Surface evaporation
⑤ Residual
⑥ Density divergence
⑦ Density advection

Result: Changes of Precipitation

Full time averaged PRCP horizontal pattern



200/400 km quantitation

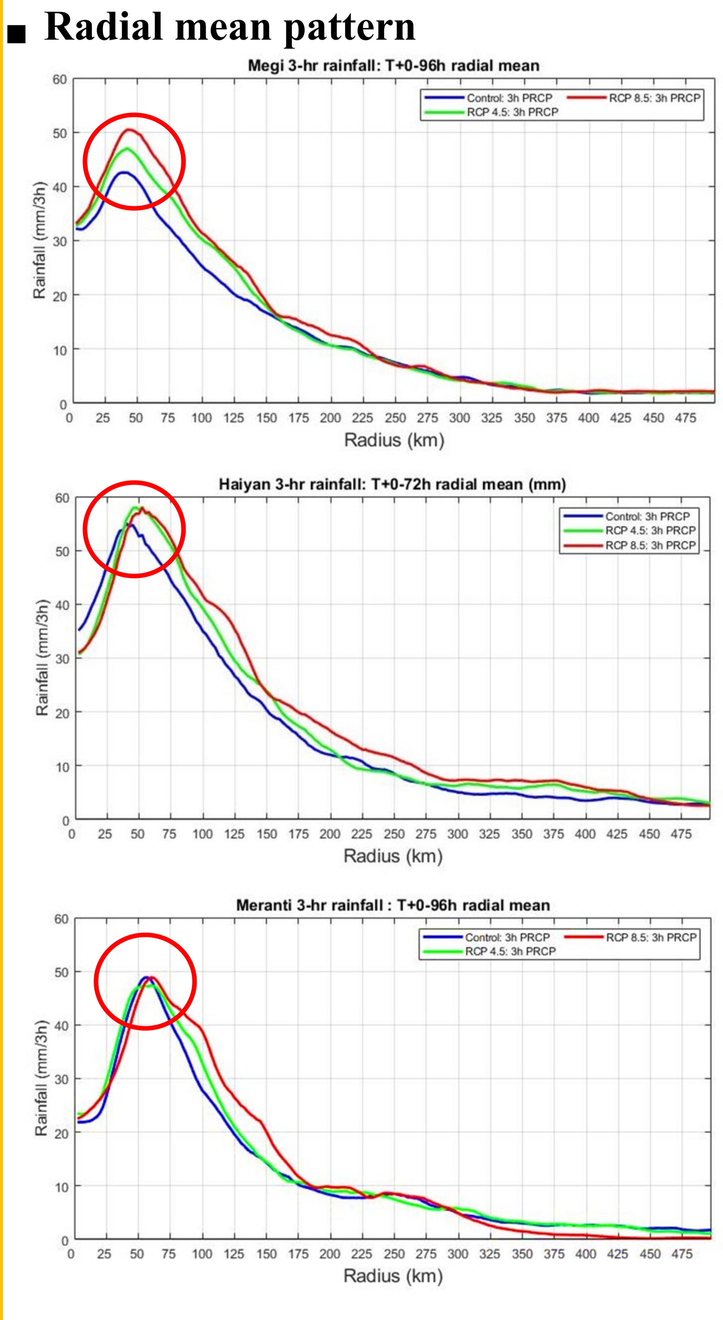
MEGI 2010 precipitation		
Radii	0~200 km	0~400 km
CTRL	20.583 mm	8.701 mm
RCP 4.5	22.846 mm (+11.00%)	9.227 mm (+6.04%)
RCP 8.5	24.698 mm (+19.99%)	9.819 mm (+12.85%)

HAIYAN 2013 precipitation		
Radius	0~200 km	0~400 km
CTRL	26.185 mm	11.043 mm
RCP 4.5	28.914 mm (+10.42%)	12.461 mm (+12.85%)
RCP 8.5	31.274 mm (+19.43%)	14.312 mm (+29.60%)

MERANTI 2016 precipitation		
Radius	0~200 km	0~400 km
CTRL	20.143 mm	8.727 mm
RCP 4.5	21.334 mm (+5.92%)	9.131 mm (+4.63%)
RCP 8.5	24.087 mm (+19.58%)	9.277 mm (+6.30%)

1. More rainfall under RCP 4.5/ RCP 8.5 scenario than CTRL, especially in inner core (red arrow in left figures).
2. PRCP quantitation under global warming brings more rain in each case. RCP 8.5 has more increase than RCP 4.5 (upper tables).

Radial mean pattern



Student's T-test for variation significance

Megi (2010) (Sample=32)	Radius (km)								Confidence	One-tail t_α
RCP 4.5-CTRL	0~50	0~100	0~150	0~200	0~250	0~300	0~350	0~400	99.9%	3.375
Mean	3.623	4.759	4.243	2.319	1.405	0.875	0.660	0.529	99.5%	2.744
SD	9.647	8.155	4.928	2.530	1.272	0.971	0.867	0.623	99%	2.453
t-value	2.124	3.301	4.871	5.183	6.249	5.100	4.306	4.805	95%	1.696
RCP 8.5-CTRL	0~50	0~100	0~150	0~200	0~250	0~300	0~350	0~400	90%	1.309
Mean	6.113	7.673	6.222	4.170	2.965	2.112	1.503	1.126	Note: Shading on T-value = Confidence level	
SD	11.678	8.293	5.165	3.064	1.989	1.411	1.142	0.942		
t-value	2.961	5.234	6.814	7.700	8.432	8.464	7.443	6.761		

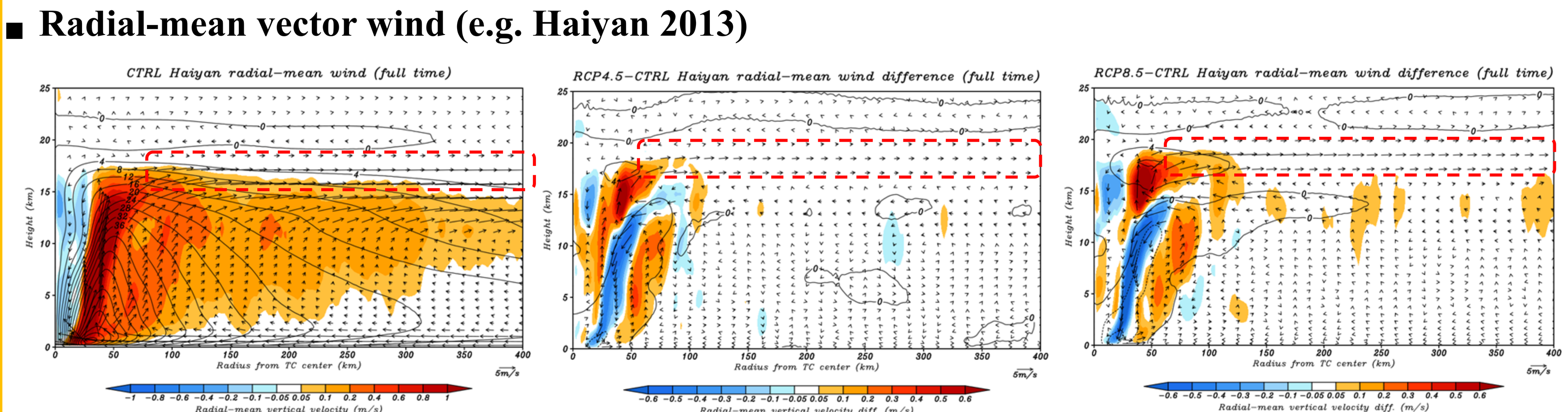
Haiyan (2013) (Sample=24)	Radius (km)								Confidence	One-tail t_α
RCP 4.5-CTRL	0~50	0~100	0~150	0~200	0~250	0~300	0~350	0~400	99.9%	3.485
Mean	-1.291	3.471	3.386	2.774	1.549	1.191	1.252	1.415	99.5%	2.807
SD	10.063	7.042	4.731	3.161	2.461	1.801	1.338	1.206	99%	2.500
t-value	-0.629	2.414	3.505	4.298	3.084	3.240	4.586	5.746	95%	1.714
RCP 8.5-CTRL	0~50	0~100	0~150	0~200	0~250	0~300	0~350	0~400	90%	1.320
Mean	-3.036	4.211	5.664	5.105	4.361	3.752	3.415	3.279		
SD	10.877	8.769	7.704	4.849	3.476	2.601	2.048	1.637		
t-value	-1.368	2.352	3.602	5.158	6.146	7.067	8.169	9.810		

Meranti (2016) (Sample=32)	Radius (km)								Confidence	One-tail t_α
RCP 4.5-CTRL	0~50	0~100	0~150	0~200	0~250	0~300	0~350	0~400	99.9%	3.375
Mean	2.103	2.308	1.962	1.205	0.950	0.467	0.496	0.411	99.5%	2.744
SD	10.636	4.815	2.763	1.725	1.393	1.196	0.987	0.900	99%	2.453
t-value	1.119	2.711	4.018	3.951	3.859	2.207	2.842	2.585	95%	1.696
RCP 8.5-CTRL	0~50	0~100	0~150	0~200	0~250	0~300	0~350	0~400	90%	1.309
Mean	-1.329	3.154	5.513	4.006	2.849	2.075	1.272	0.580		
SD	12.266	6.867	4.592	3.908	2.957	2.219	1.824	1.390		
t-value	-0.613	2.598	6.791	5.799	5.450	5.290	3.945	2.359		

1. 3-h rainfall peak under warming scenario is more severe (except for Meranti); RCP 8.5 is more significant (red circle area).
2. It seems that the peak in future scenarios is more away from TC center (red circle area).
3. T-test (Null hypothesis H_0: 3-h PRCP has no increase under warming) shows 3-h precipitation in these studying cases has significant increase with high confidence (>95%).
4. Inner core (0~50 km) couldn't pass the t-test probably due to some factors: 3-h TC tracking error, dry area in TC eye, or some simulative uncertainties, etc..

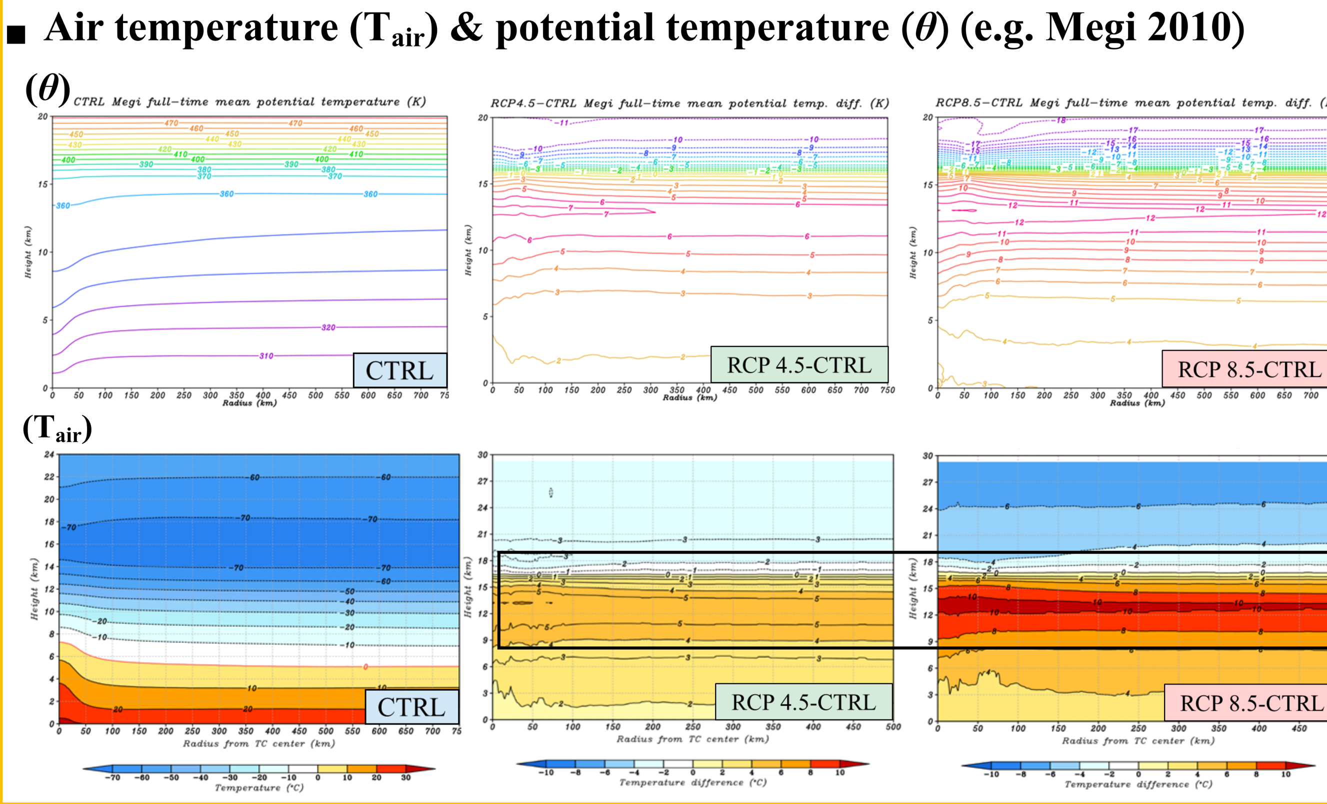
Result: Changes of TC Environment

Radial-mean vector wind (e.g. Haiyan 2013)



1. 0~100 km vertical updraft/downdraft motion (shading area) difference is more significant under RCP 4.5/8.5, bringing about stronger convection in inner core. (Other cases are not shown but similar)
2. Tangential wind (contour) and low-level inflow (vector) do not change much in the future; however, the higher troposphere outflow significantly ascent to higher level (red dashed line), indicating the strengthening of convection.

Air temperature (T_{air}) & potential temperature (θ) (e.g. Megi 2010)



1. θ increases in future, sustaining warm-core and enhancing thermal effect.
2. RCP 8.5 has more increase of T_{air} than RCP 4.5.
3. Surface T_{air} slightly increase under warming, and higher troposphere has greater enhancement >> More stable!
4. 0°C melting level is higher under warming.

Result: Water Budget Analysis

Water budget quantitation

Considering the accuracy and uncertainty of simulations, time range and radius of water budget calculation are adjusted in each case based on the least residual.

Megi 0~350 km 3hr water budget (time average: T=6-90 h)

Term ($kg/m^2\cdot 3h$)	Equation LHS: Sink		Equation RHS: Source				
	Precipitation	Abs. humidity change	Evaporation	Flux divergence	Density divergence	Density advection	Residual
CTRL	10.79	0.21	1.41	-9.4035	-12.23	2.83	0.19
RCP 4.5	11.48	0.25	1.46	-10.3120	-13.23	2.92	-0.04
RCP 8.5	12.47	0.29	1.54	-11.2489	-14.70	3.45	-0.02
Difference and growing rate (%)							
RCP 4.5 - CTRL	0.69 (+6.4%)	0.03 (+15.7%)	0.05 (+3.2%)	-0.91 (+9.7%)	-1.00 (+8.2%)	0.10 (+3.4%)	-0.23
RCP 8.5 - CTRL	1.68 (+15.6%)	0.08 (+35.5%)	0.12 (+8.7%)	-1.85 (+19.6%)	-2.47 (+20.2%)	0.63 (+22.2%)	-0.21

Haiyan 0~250 km 3hr water budget (time average: T=24-72 h)

Term ($kg/m^2\cdot 3h$)	Equation LHS: Sink		Equation RHS: Source				
	Precipitation	Abs. humidity change	Evaporation	Flux divergence	Density divergence	Density advection	Residual
CTRL	19.16	0.15	1.80	-15.94	-19.28	3.34	1.57
RCP 4.5	21.48	0.19	1.84	-17.13	-20.60	3.47	2.70
RCP 8.5	23.75	0.29	2.03	-19.45	-23.51	4.07	2.57
Difference and growing rate (%)							
RCP 4.5 - CTRL	2.32 (+12.1%)	0.04 (+24.2%)	0.05 (+2.6%)	-1.18 (+7.4%)	-1.32 (+6.8%)	0.13 (+4%)	1.12
RCP 8.5 - CTRL	4.59 (+23.9%)	0.14 (+94%)	0.23 (+12.8%)	-3.50 (+22%)	-4.23 (+22%)	0.73 (+21.8%)	0.99

Meranti 0~300 km 3hr water budget (time average: T=6-90 h)

Term ($kg/m^2\cdot 3h$)	Equation LHS: Sink		Equation RHS: Source				
	Precipitation	Abs. humidity change	Evaporation	Flux divergence	Density	Density	Residual
CTRL	13.36	0.13	1.52	-11.27	-14.06	2.79	0.70
RCP 4.5	14.03	0.15	1.59	-12.65	-15.69	3.04	-0.06
RCP 8.5	15.49	0.24	1.56	-15.72	-19.80	4.07	-1.55
Difference and growing rate (%)							
RCP 4.5 - CTRL	0.67 (+5.0%)	0.02 (+11.6%)	0.07 (+4.3%)	-1.38 (+12.3%)	-1.64 (+11.6%)	0.25 (+9.1%)	-0.76
RCP 8.5 - CTRL	2.13 (+15.9%)	0.11 (+80%)	0.04 (+2.2%)	-4.45 (+39.5%)	-5.74 (+40.8%)	1.28 (+46.0%)	-2.25

1. Main source of water budget: density convergence (negative pattern of divergence)
2. All terms in water budget significantly enhance under warming scenarios, indicating the water transport would be larger, and the rainfall would be more extreme.
3. (Not shown) For hydrometers, water vapor (qv) dominates density divergence and absolute humidity change, and precipitable hydrometeors (qp, including rain, snow and graupel) dominate the density advection term.

0~5.5 km precipitable water (PW) & integrated horizontal convergence (IHC)

Megi (2010) Radii	100 km	200 km	350 km	Haiyan (2013) Radii	100 km	250 km	400 km	Meranti (2016) Radii	100 km	200 km	300 km
PRCP	+14.22 %	+11 %	+6.17 %	PRCP	+7.83 %	+7.4 %	+12.85 %	PRCP	+6.51 %	+5.92 %	+3.64 %
PW	+12.99 %	+12.94 %	+12.76 %	PW	+12.97 %	+13.25 %	+13 %	PW	+13.7 %	+13.37 %	+12.96 %
IHC	+8.8 %	+2.52 %	-3.04 %	IHC	-0.76 %	-4.98 %	+8.22 %	IHC	+2.67 %	+2.93 %	-0.16 %
PRCP	+22.63 %	+19.99 %	+13.9 %	PRCP	+9.66 %	+21.16 %	+29.6 %	PRCP	+9.44 %	+19.58 %	+15.66 %
PW	+23.9 %	+24.02 %	+23.83%	PW	+24.95 %	+24.97 %	+24.47 %	PW	+26.77 %	+25.96 %	+25.76 %
IHC	+16.83 %	+5.24 %	-1.5 %	IHC	-1.78 %	+0.73 %	+9.38 %	IHC	+1.34 %	+19.18 %	+8.4 %

1. Background PW in 3 cases: RCP 4.5 increases by 12~13%; RCP 8.5 increases by 24~26% (red square)
2. Increasing/decreasing IHC can enhance/weaken the convection.
3. Positive IHC under global warming would bring more significant increase of super typhoon rainfall; negative IHC would weaken the increase, but the enhancement of PW sustains positive growing of PRCP.

∴ For the future increase of strong TC precipitation, PW can be seen as essential and sufficient condition; IHC can be seen as sufficient condition.

Summary

- 1. By simulation, super typhoon precipitation would increase in future, especially in the eyewall or inner core. The rainfall peaks under warming scenarios are more away from the center of typhoon, implying the possibility of bigger growth of TC eye.
- 2. Temperature of troposphere increases, and upper troposphere has more enhancement. Also, PW would increase under global warming. Thus, strong TC may obtain more advantageous thermal condition for moisture convection under warming scenarios, in spite of the stability of developing environment would increase.
- 3. Water budget shows all terms enhance in warming climate, so more precipitation is expectable, and the dominant effect that brings about precipitation increase is density convergence.
- 4. By diagnosing PW and IHC, we find out the interaction between both factors are different in different scenarios and different cases. Nevertheless, either PW or IHC would be the sufficient condition of future super typhoon precipitation enhancement.

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QR code