1. A Tale of Two Rapidly-Intensifying Super-typhoons: Hagibis (2019) and Haiyan (2013)

I-I Lin* (NTUAS), Robert F. Rogers* (NOAA/HRD), Hsiao-Ching Huang, Yi-Chun Liao, Derrick Herndon (CIMSS/Wisconsin), Jin-Yi Yu (UC Irvine), Ya-Ting Chang, Jun A. Zhang (NOAA/HRD), Christina M. Patricola (Univ. of Iowa/Lawrence Berkeley Lab), Iam-Fei Pun (NCU), & Chun-Chi Lien

In Press 2021, Bulletin of the American Meteorological Society

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2. The Association of Typhoon Intensity Increase with Translation Speed Increase in the South China Sea

Ya-ting Chang, I-I Lin*, Hsiao-Ching Huang, Yi-Chun Liao and Chun-Chi Lien (NTUAS)

Sustainability, 2020

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3. ENSO, Tropical Cyclone, and Global Warming – A Review

I-I Lin (NTUAS), Suzana J. Camargo (Columbia Uni.), Christina M. Patricola (Lawrence Berkeley Lab/Uni. of Iowa), Johnny C L Chan (City Univ. of Hong Kong), Julien Boucharel (LEGOS, Uni. of Toulouse, France), Savin Chand (Federation University, Australia), Phil Klotzbach (CSU), Bin Wang (Uni. of Hawaii), Ping Chang (Texas A&M Uni.), Tim Li (Uni. of Hawaii), Fei Fei Jin (Uni. of Hawaii)

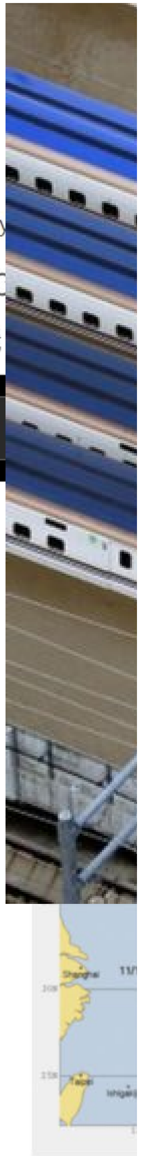
Chap. 17, AGU 100th Celebration Monograph, 2020

Typhoon Hagibis: Japan postpones Emperor Naruhito's enthronement parade

BBC

18 October 2019

Typhoon Hagibis



The foreca

The Economist

World politics | Business & finance | Economics | Science & technology | Culture | Blogs | Debate | Multimedia

Cat. ‘6’, Haiyan: 170kts!

Typhoon Haiyan

Print edition

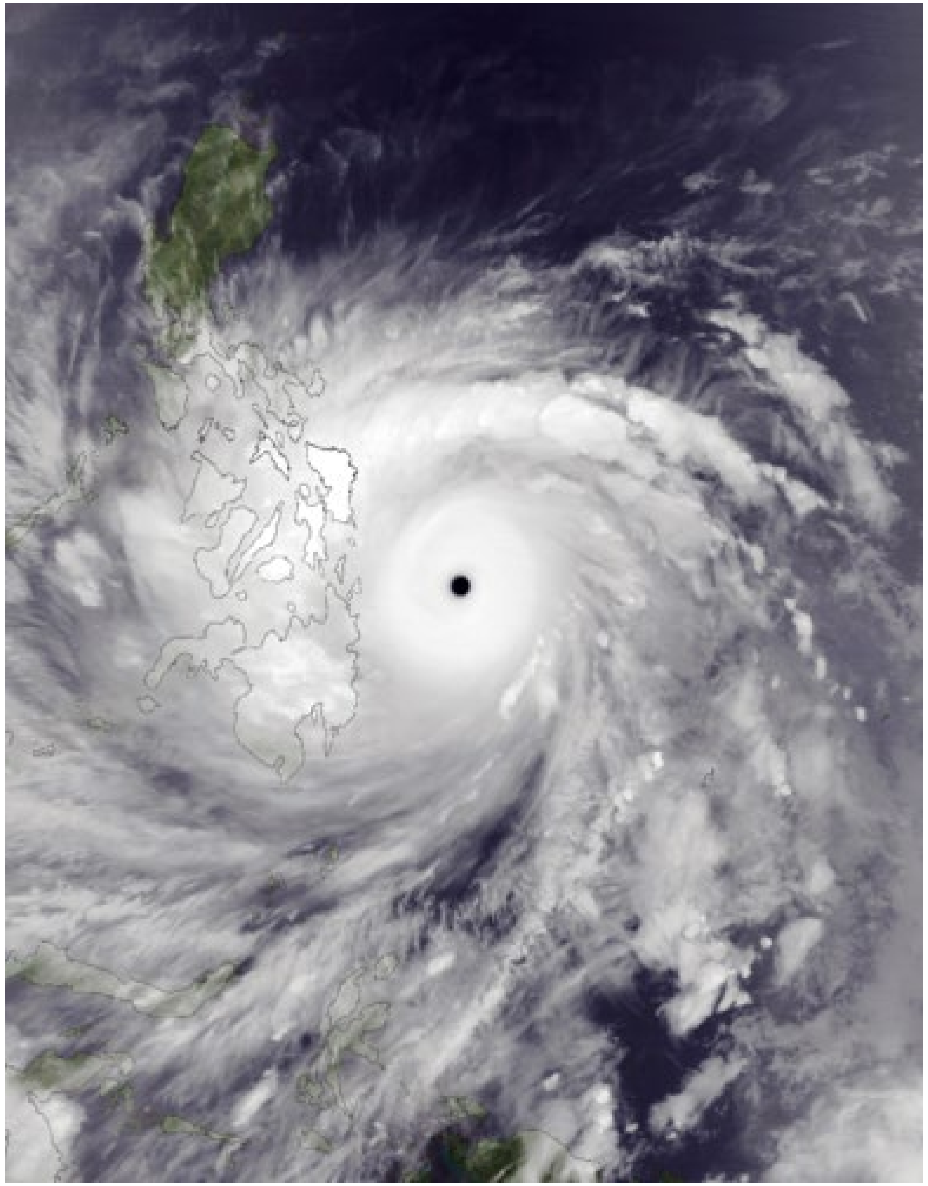
Worse than hell

Lin et al. 2014;
Lagmay et al. 2015

One of the strongest storms ever recorded has devastated parts of the Philippines, and relief is slow to arrive

Nov 16th 2013 | CEBU, HANOI AND MANILA | From the print edition

Timekeeper | Like | Tweet



Death: 6300; Injured: 28689;

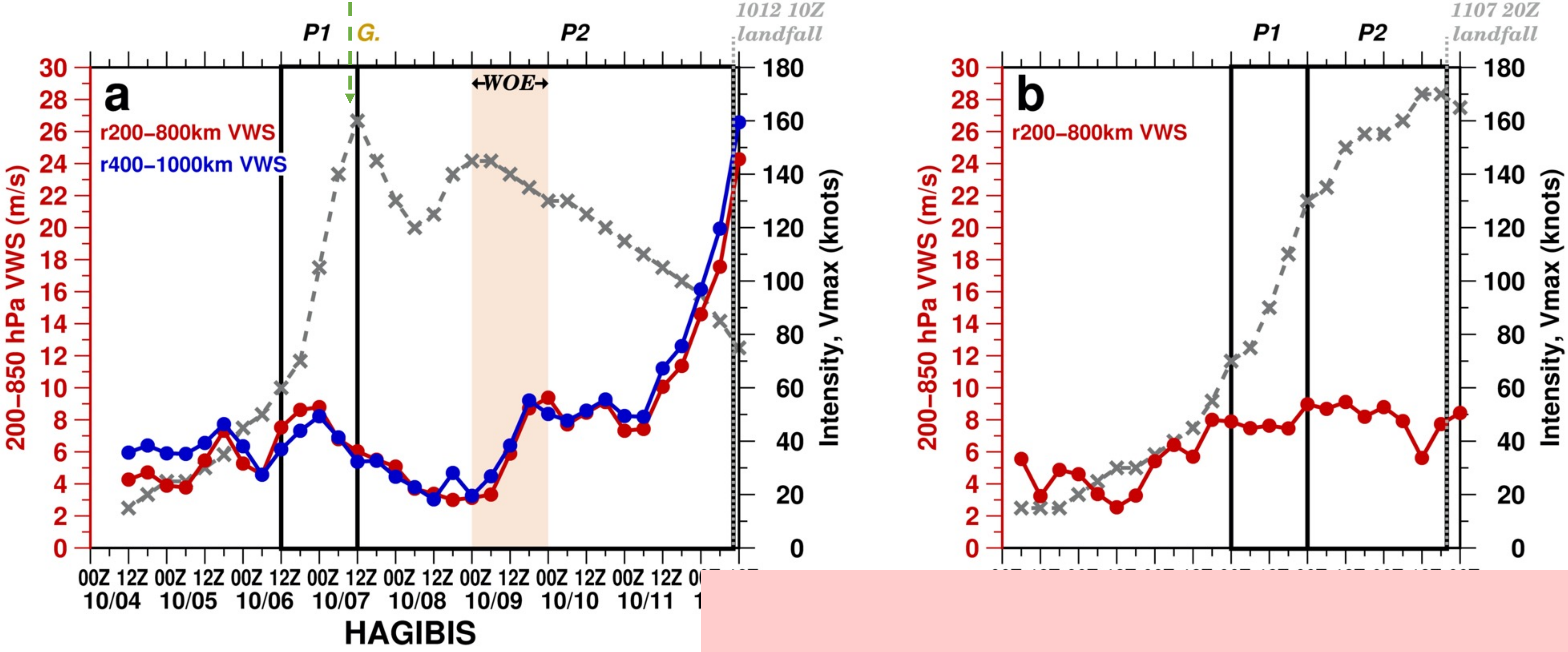
Damage : US $ 2,051,710,653 (2 billion)

http://en.wikipedia.org/wiki/Typhoon_Haiyan

100 kt RI in 24h (Explosive RI,
333% of the RI Threshold!, Kaplan & DeMaria 2003)
.vs. Patricia's 105 kt RI in 24h (Rogers et al. 2017)

LMI: 170kts

60 kt RI in 24h for Haiyan



Holliday and Thompson 1979; Kaplan a…
Rogers et al. 2017; Chang and Wu 2017

Scientific Questions for P1 and P2

Lin et al. GRL 2014

Category		Winds (knots)	V^2 (fcn. of ACE, k. energy)		V^3 (fcn. of PDI, destructiveness)	
1		64-82	4,096		262,144	
2	19	83-95	6,889	x1.7	571,787	x2.2
3	13	96-113	9,216	x1.3	884,736	x1.5
4	18	114-135				
5 (Katrina)	22	>135 - 159				
'Cat 6'	25	>=160 (170)	28,900		4,913,000	

Hagibis: 60 to 160kt (TS to C6) in 24h!

.vs.

Haiyan 70-130kt (C1 to C4) in 24h

Data and Method

Co-Existing Multiple Factors:

Ocean: Surface and Subsurface, Pre-TC SST/OHC, and During-TC Air-Sea Interaction (e.g., during-TC SST, Fluxes)

Atmosphere: Wind Shear, Rh

TC Structure and Attributes: Size, Uh, Convective feature, Eyewall Replacement Cycle

3DPWP: TC wind, size, Uh, ocean T/S profiles, Transit Time

Data and Method

1. **Large-Scale Atmospheric Environment (e.g., DeMaria et al. 2005; Knaff et al. 2018): Vertical Wind Shear (VWS) & RH (Relative Humidity); 200-800km Ring/400-1000km Ring**

2. **Large-Scale, Pre-TC Ocean (SST, Ocean Heat Content (OHC)) and During-TC, Local-Scale Air-Sea Interaction (During-TC Cooling and Air-Sea Sensible and Latent Heat Fluxes (Lin et al. 2005; 2009; 2013; Wu et al. 2007; Goni et al. 2009; Lin et al. 2009; 2013; Chih and Wu 2020).**

3. **Vortex-Scale TC Properties & Convective-Scale Features (Chavas and Emanuel 2010; Rogers et al. 2013; 2017; Pun et al. 2018; Molinari et al. 2019; Peng and Wu 2020; Shen et al. 2021): Uh (Translation Speed), Size (RMW, R64, R50, R34], Eyewall Replacement Cycle (ERC, Kuo et al. 2009; Wimmers and Velden 2016; Huang et al. 2018), Convective-Scale Features (Radial Location of Deep Convection)**

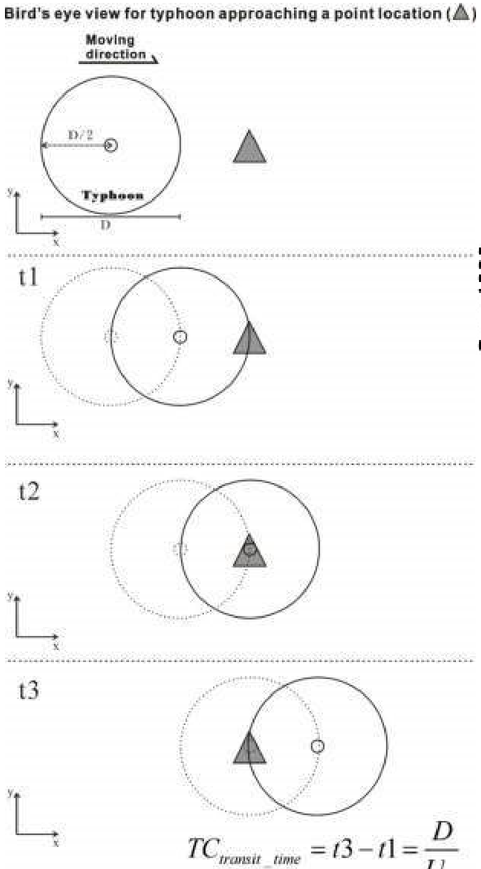
Observational Data:

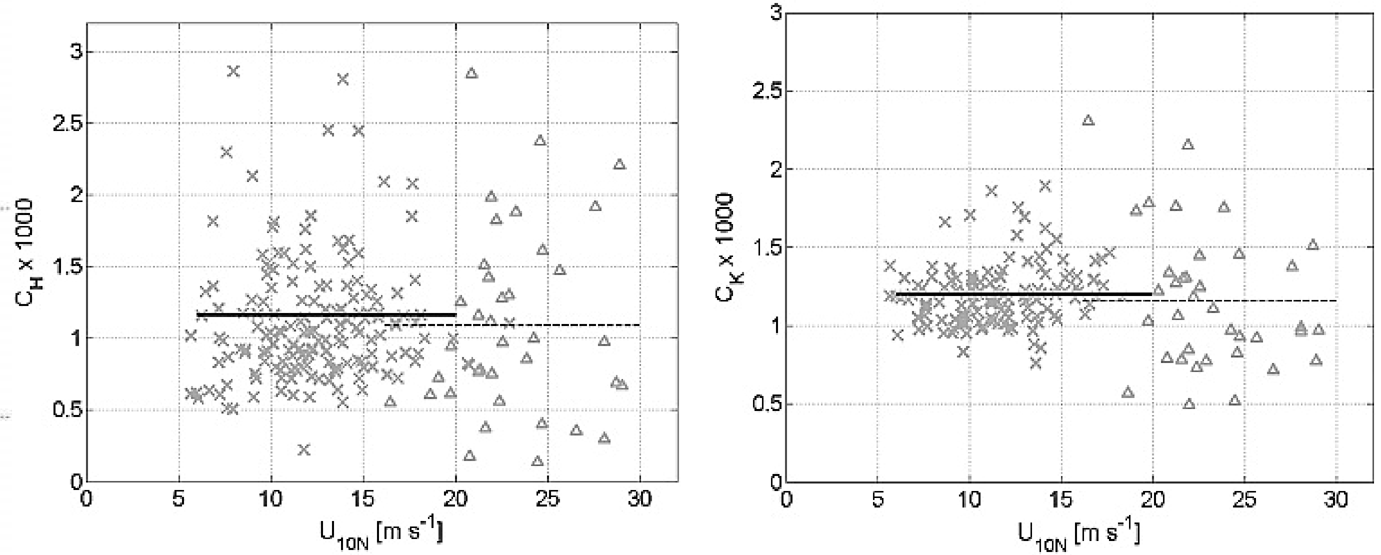
NCEP-CFSR/6hrly, JTWC Best Track (including track, RMW, size, intensity, Uh), ASCAT wind, Satellite Altimetry SSHA (Sea Surface Height Anomaly), Microwave Sea Surface Temperature (SST), Argo in situ floats (pre, and during-TC), NRL microwave imagery, ARCHER ((Automated Rotational Center Hurricane Eye Retrieval)/MPERC (Microwave-based Probability of Eyewall Replacement Cycle)/MIMIC (Morphed Integrated Microwave Imagery at CIMSS), IR Tb imagery (NRL), NCEP near surface Ta and q: converting from Sigma 995 level (~40m) to 10m

Data & Method-2 : Numerical Simulations & Air-Sea Flux Estimation

3-D PWP (Price-Weller-Pinkel, Price et al. 1986; 1994) Ocean Model
Drag Coefficient: high wind Cd, Powell et al. 2013
TC's Transit Time (Size in D50/Uh) at each 6hrly point.
Input: pre-TC Argo T/S profiles and JTWC max. intensity and wind profile shape

6 Experiments: 2 Observational + 4 Sensitivity Experiments (for Uh, Size, Uh+Size, Salinity)





From CBLAST Exp. Zhang, Black et al. GRL 2008

During-TC SST (Pre-TC minus cooling)

$$Q_S = C_H W (T_s - T_a) \rho_a C_{pa}$$

$$Q_L = C_E W (q_s - q_a) \rho_a L_{va}$$

Fcn. of during-TC SST

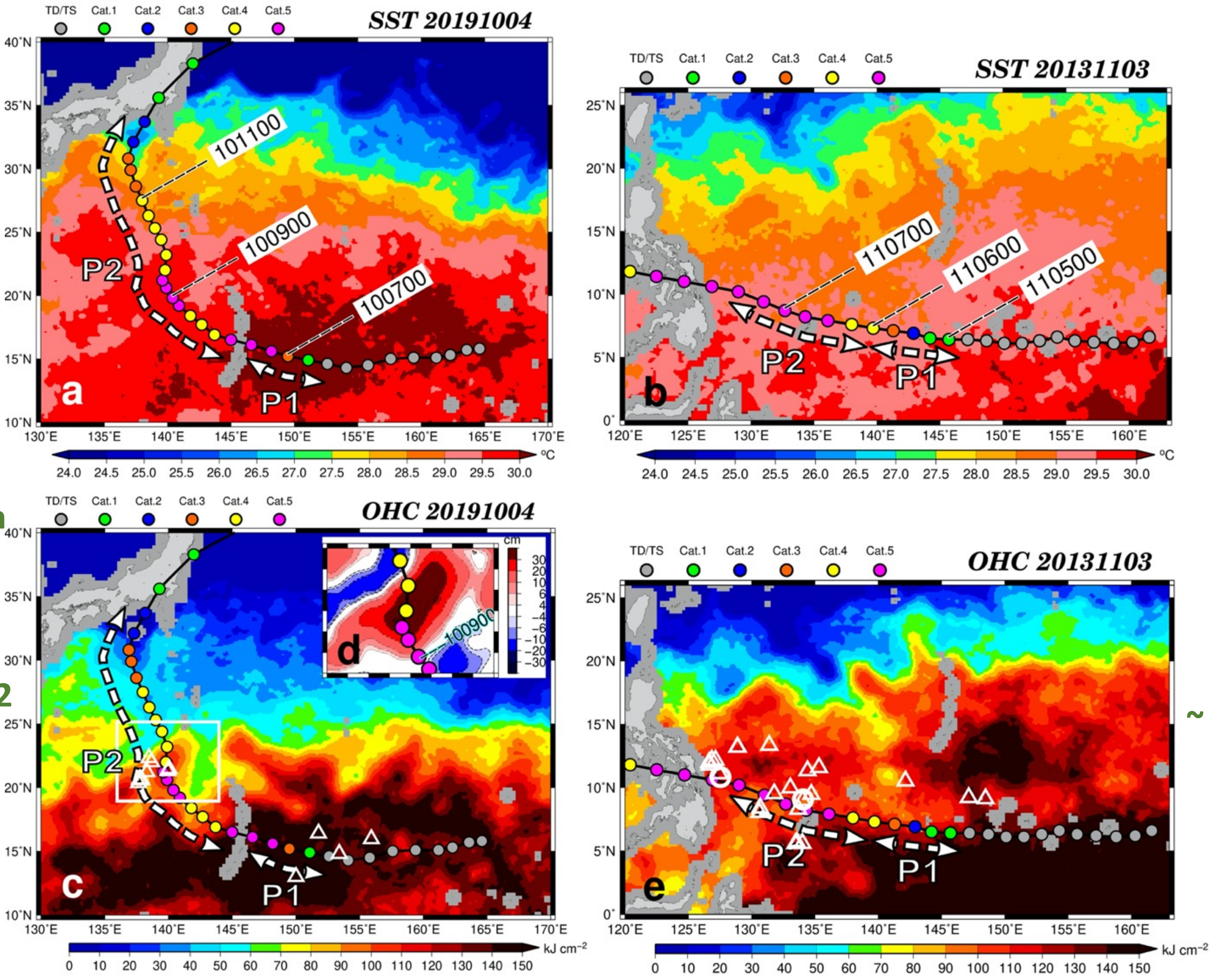
Lin et al. MWR 2008; JGR 2012, GRL 2013; Huang, Lin et al. Nature Comm. 2015

P1

~ 30-30.5° C
Pre-TC SST

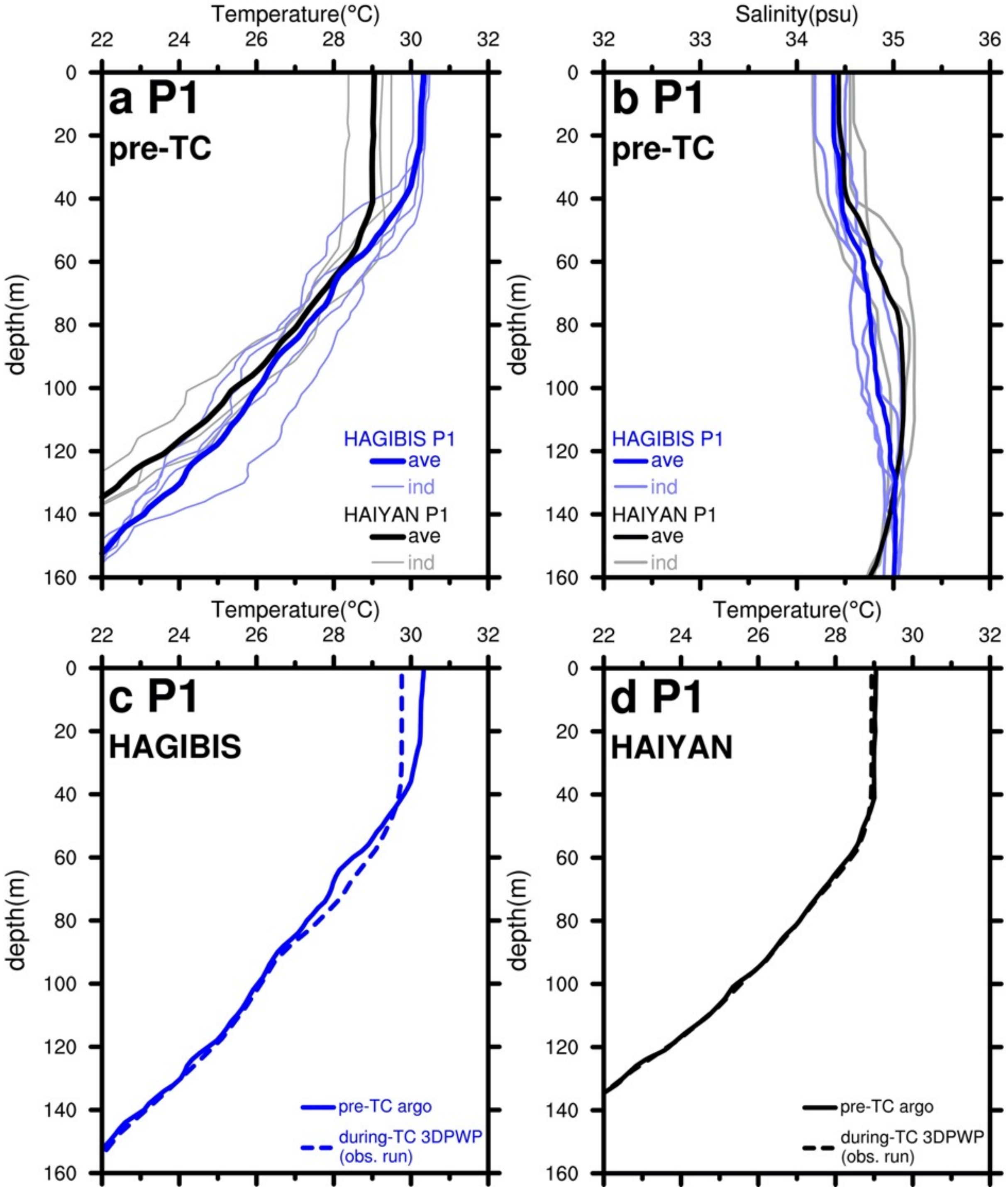
One of the best ever observed. Even better than Haiyan

~ 140-160 kJ/cm2
Pre-TC OHC



~ 29-29.5° C
Pre-TC SST

~ 115-135 kJ/cm2
Pre-TC OHC



Temperature(°C)
a P1
pre-TC
depth(m)
HAGIBIS P1
ave
ind
HAIYAN P1
ave
ind
Salinity(psu)
b P1
pre-TC
depth(m)
HAGIBIS P1
ave
ind
HAIYAN P1
ave
ind
Temperature(°C)
c P1
HAGIBIS
depth(m)
pre-TC argo
during-TC 3DPWP
(obs. run)
Temperature(°C)
d P1
HAIYAN
depth(m)
pre-TC argo
during-TC 3DPWP
(obs. run)

a. P1 (Obs. run)	Input TC Size in D50 (km)	Input TC U_h (m s^{-1})	SST_{preTC} (°C) [from Argo]	$SST_{duringTC}$ (°C) [3DPWP output]	Cooling (°C)
Hagibis obs. run	266.8 ±91.2	7.7 ±0.6	30.33 ±0.20 [4 Argo]	29.76 ±0.30	0.57 ±0.30
Haiyan obs. run	157.4 ±53.2	7.8 ±0.5	29.05 ±0.59 [3 Argo]	28.94 ±0.05	0.11 ±0.05

a. P1 (Obs. run)	$SST_{duringTC}$ (°C) [3DPWP]	T_a (°C) [CFS]	q_s (g kg^{-1}) [$SST_{duringTC}$]	q_a (g kg^{-1}) [CFS]	△T (°C)	△q (g kg^{-1})	SHF (W m^{-2})	LHF (W m^{-2})	Total Flux (W m^{-2})
Hagibis obs. run	29.76 ±0.30	28.42 ±0.35	25.74 ±0.31	19.33 ±0.28	1.34 ±0.60	6.42 ±0.25	82 ±23	1169 ±433	1250 ±433
Haiyan obs. run	28.94 ±0.05	27.78 ±1.11	24.61 ±0.16	19.37 ±0.23	1.15 ±1.10	5.24 ±0.09	69 ±65	853 ±212	923 ±240

Concentrated area of deep convection strategically located at center, with a tiny eye

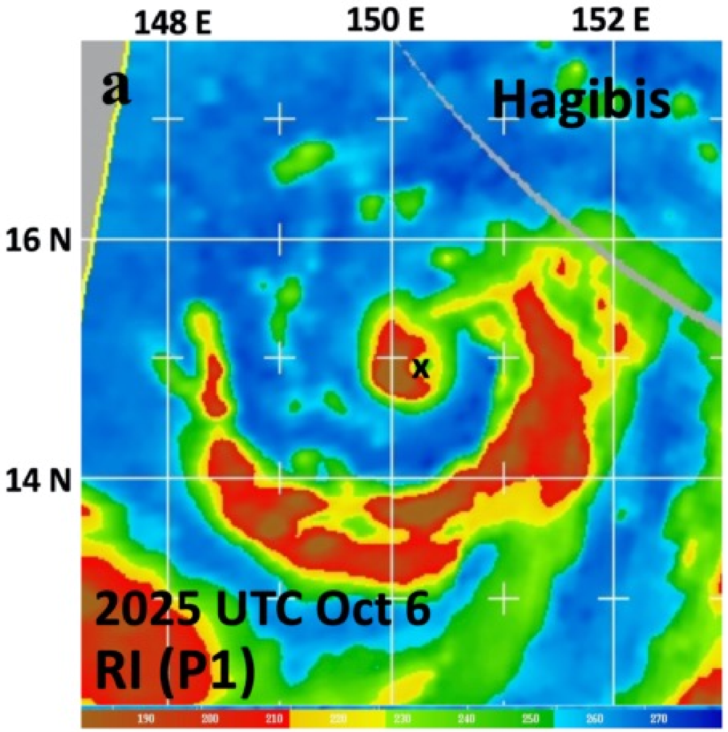
Rapid eyewall contraction 30km to 10km in 6h

Deep convection at TC center: linking with intensification due to peak diabatic heating being preferentially located within a region of high inertial stability (Pendergrass and Willoughby 2009; Vigh and Schubert 2009; Rogers et al. 2013)

&

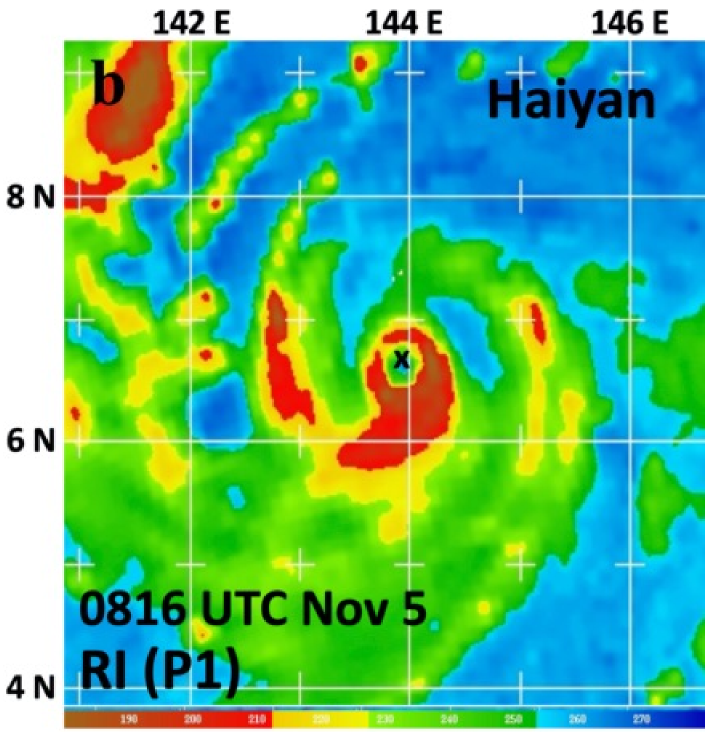
More likely to cause inward transport of angular momentum and rapid eyewall contraction (Smith and Montgomery 2016; Chen et al. 2018)

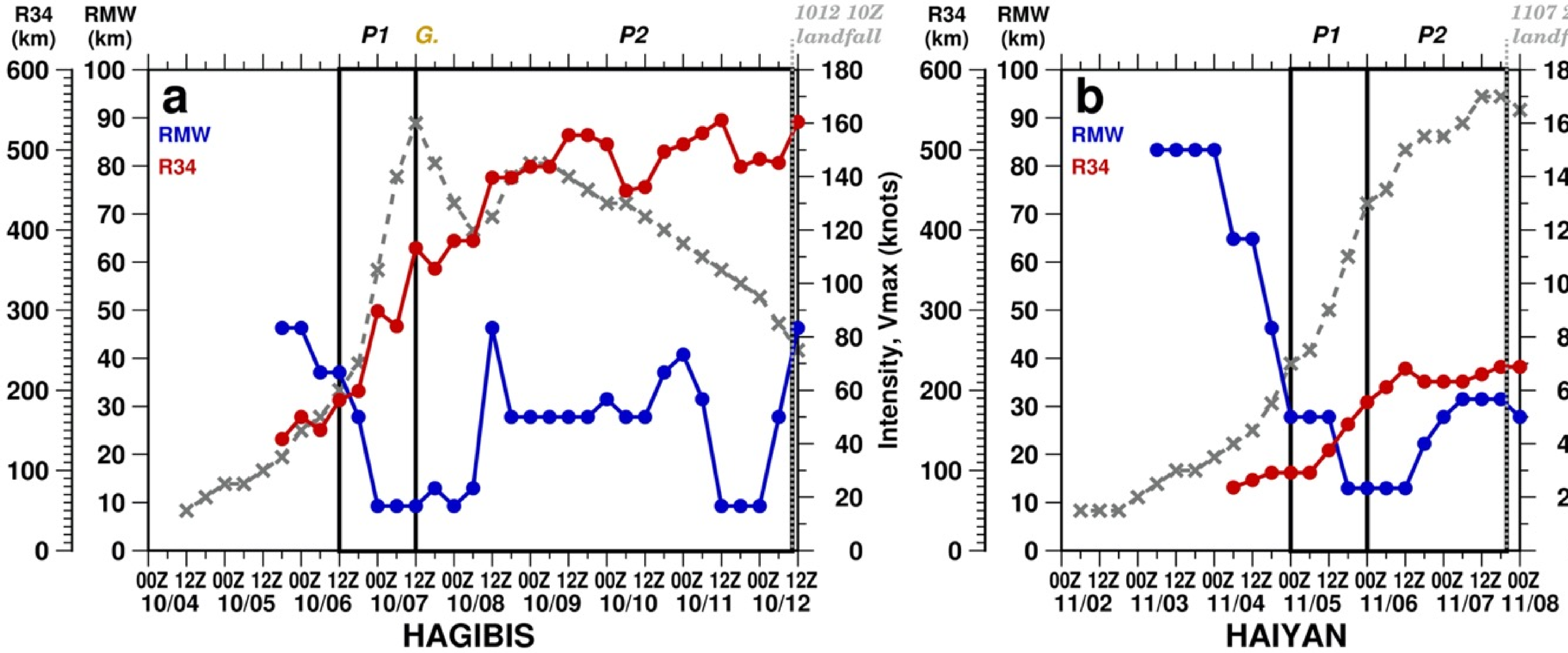
Small RWM, favorable radial location of deep convection and rapid eyewall contraction



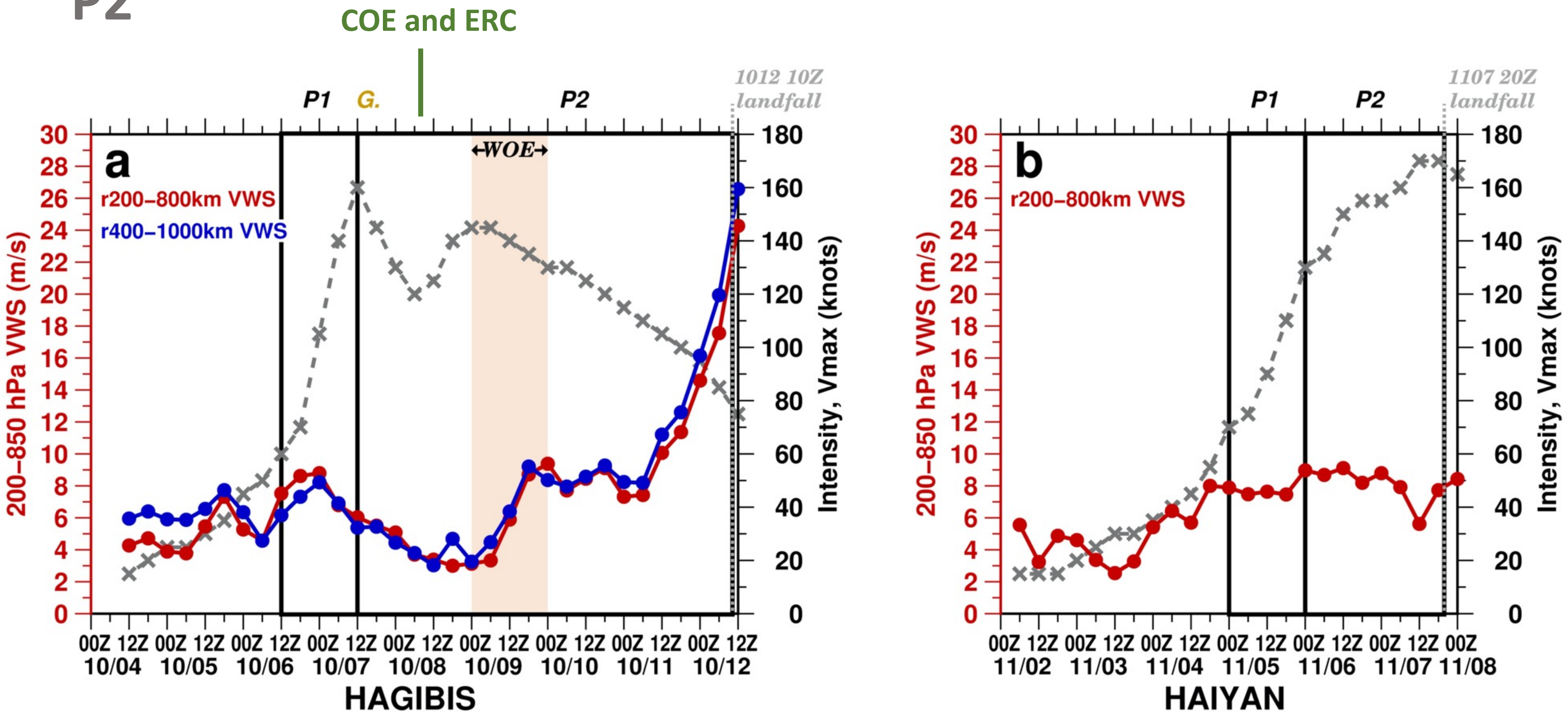
Haiyan:
Ring of convection

Eyewall contraction (30km to 10km in 18h)




R34 (km)
RMW (km)
P1
G.
P2
1012 10Z landfall
a
RMW
R34
Intensity, Vmax (knots)
00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z
10/04 10/05 10/06 10/07 10/08 10/09 10/10 10/11 10/12
HAGIBIS
R34 (km)
RMW (km)
P1
P2
1107 20Z landfall
b
RMW
R34
Intensity, Vmax (knots)
00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z 00Z 12Z 00Z
11/02 11/03 11/04 11/05 11/06 11/07 11/08
HAIYAN

P2

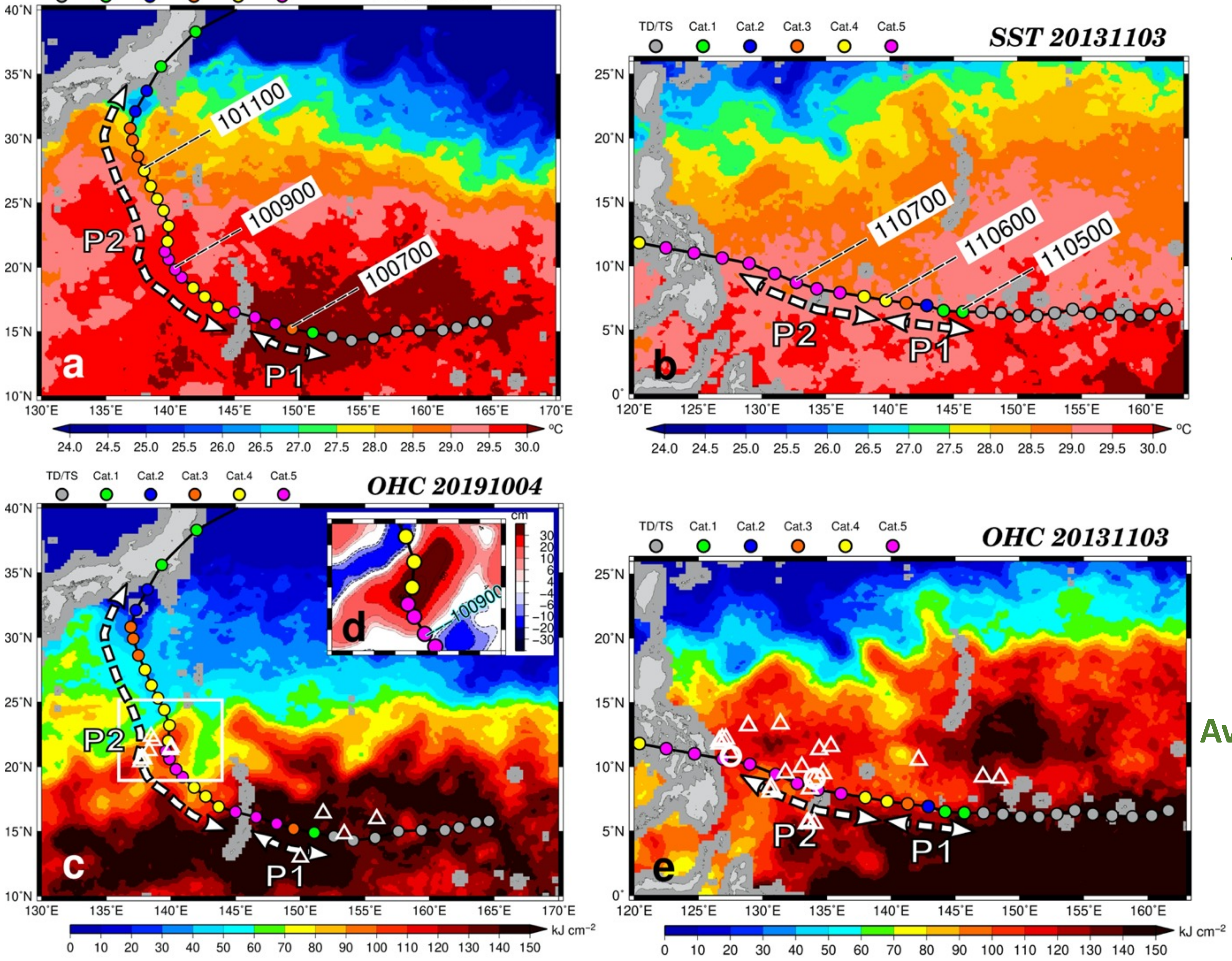


LMI: 160kts

LMI: 170kts

P2

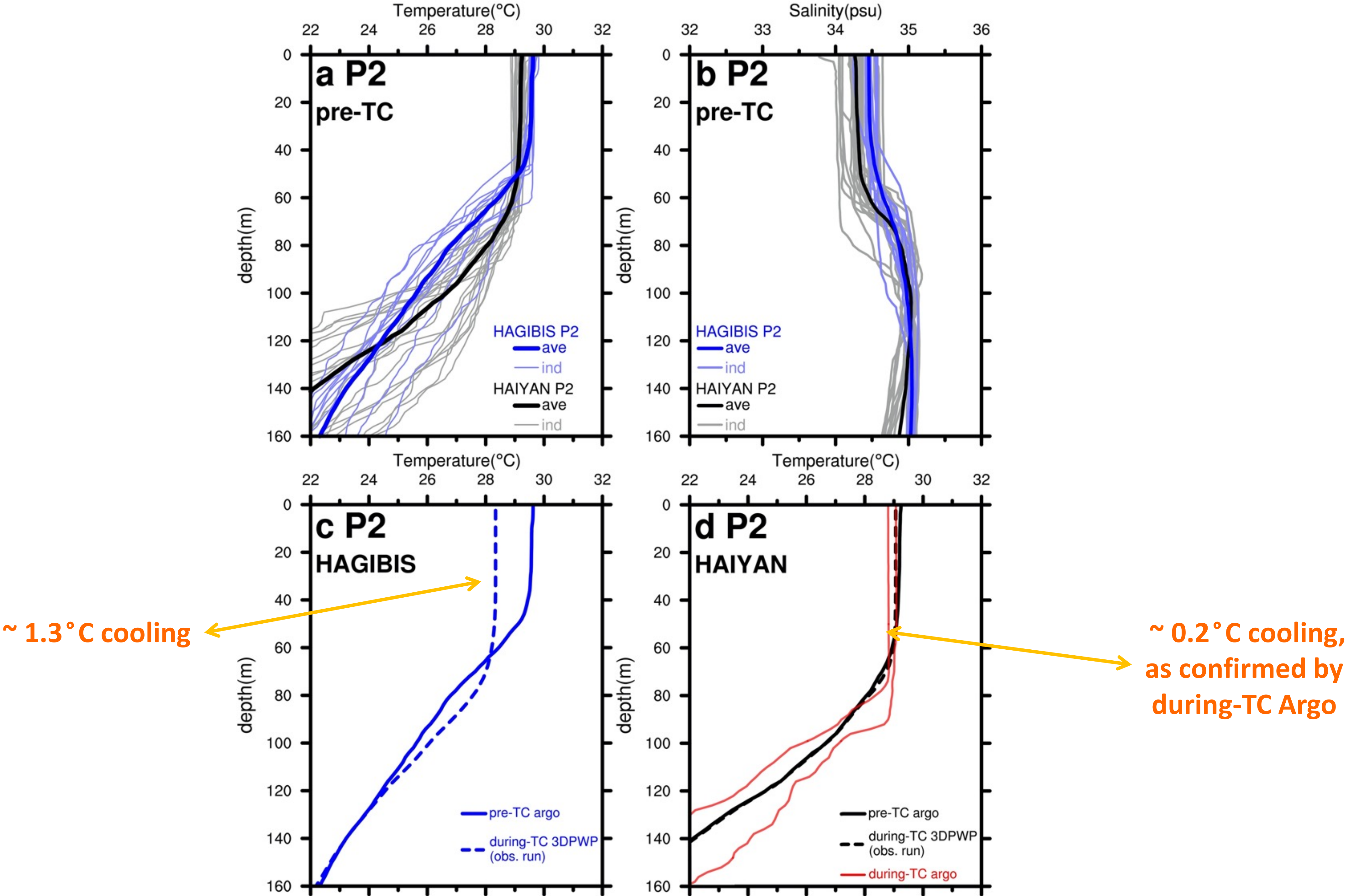
Over WOE
Avg. 29.6° C
Pre-TC SST



Avg. 29.1° C
Pre-TC SST

Over WOE
Avg. 103 kJ/cm2
Pre-TC OHC

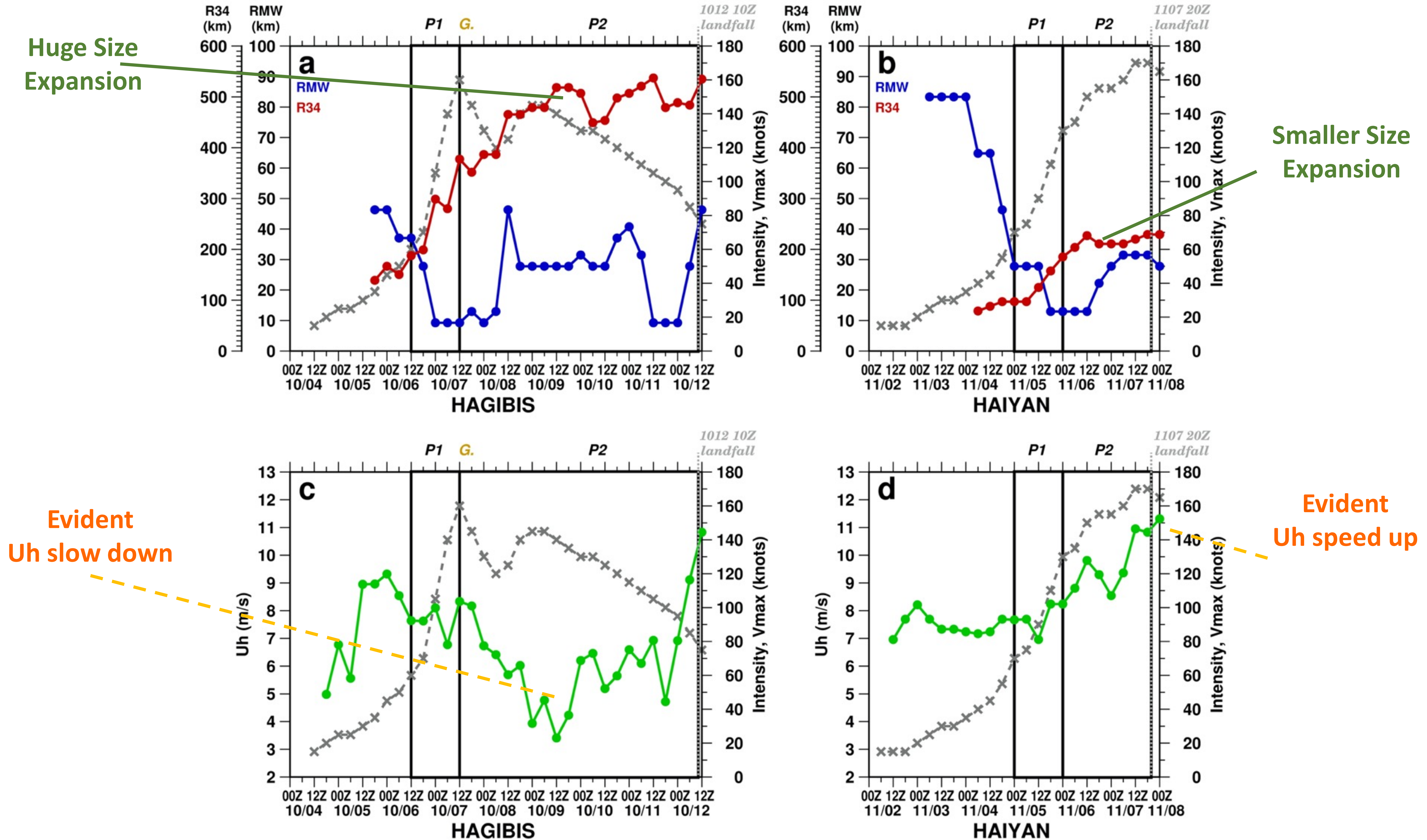
Avg. 109 kJ/cm2
Pre-TC OHC



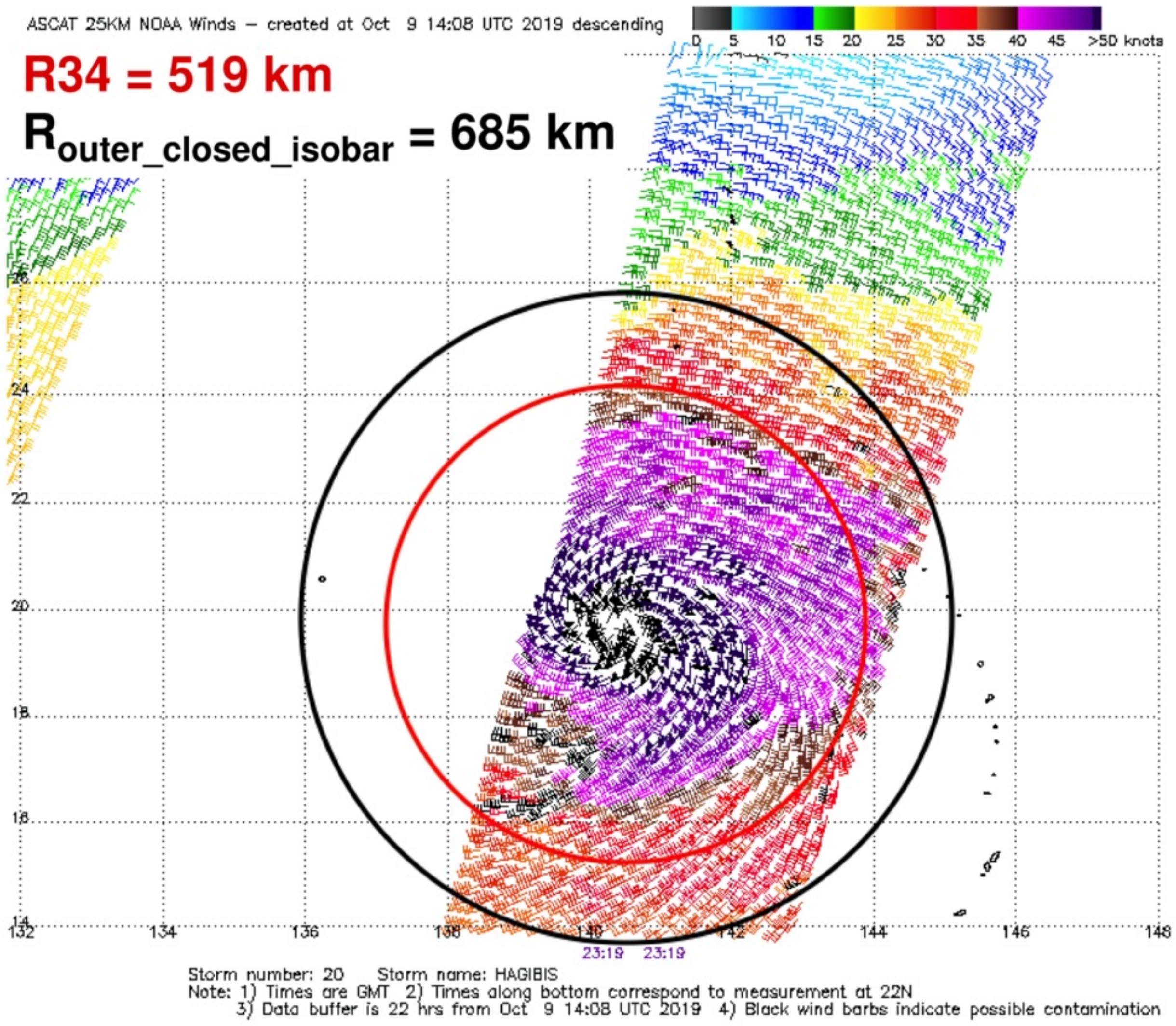
Temperature(°C)
Salinity(psu)
a P2
pre-TC
b P2
pre-TC
c P2
HAGIBIS
d P2
HAIYAN
depth(m)
HAGIBIS P2
ave
ind
HAIYAN P2
ave
ind
pre-TC argo
during-TC 3DPWP
(obs. run)
during-TC argo
~ 1.3 ° C cooling
~ 0.2 ° C cooling,
as confirmed by
during-TC Argo

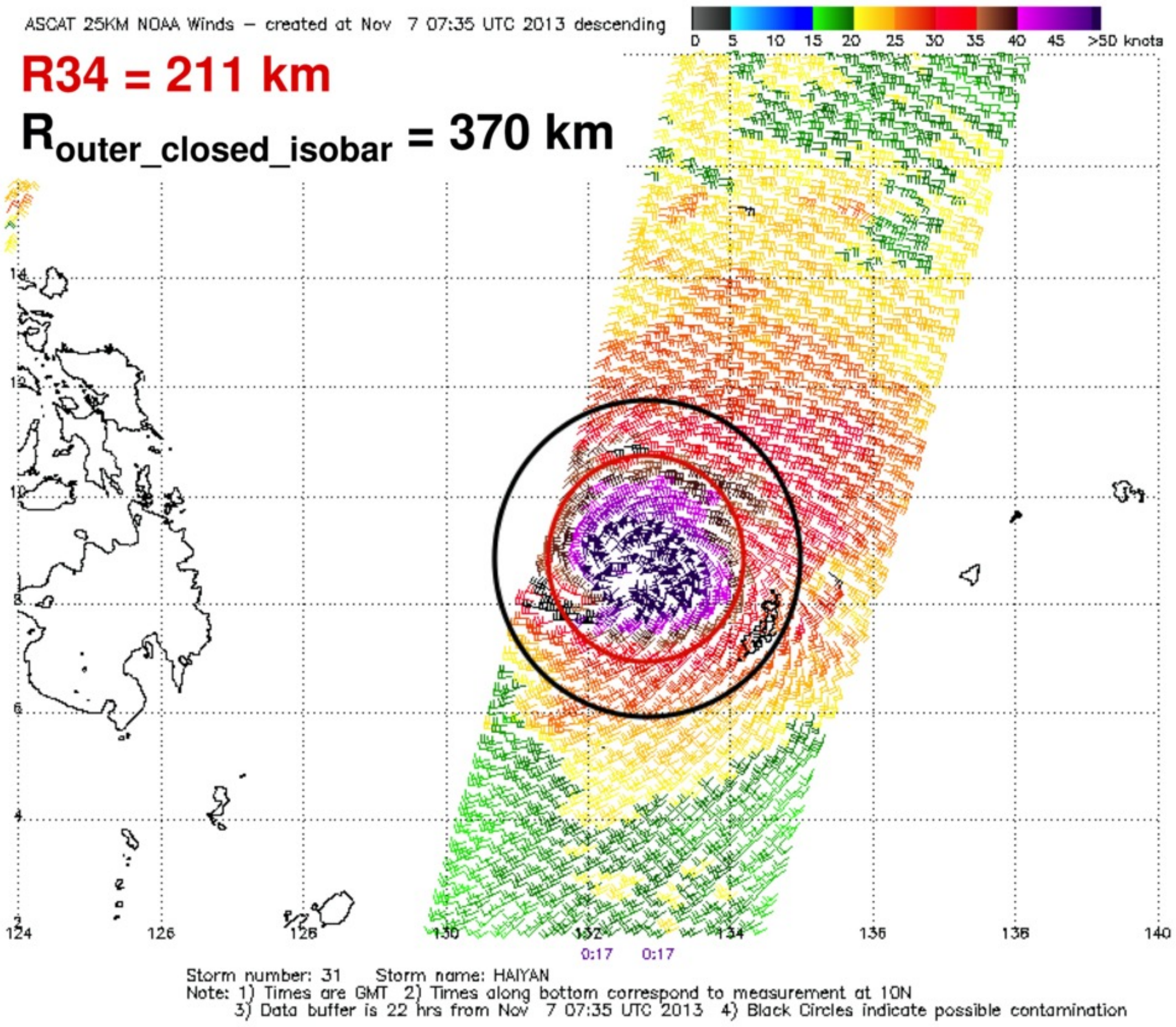
a. P2 (Obs. run)	Input TC Size in D50 (km)	Input TC U_h (m s^{-1})	SST_{preTC} (°C) [from Argo]	$SST_{duringTC}$ (°C) [3DPWP output]	Cooling (°C)
Hagibis obs. run	447.2 ±45.4	4.5 ±1.1	29.62 ±0.10 [10 Argo]	28.34 ±0.26	1.29 ±0.26
Haiyan obs. run	231.6 ±25.6	9.5 ±0.9	29.24 ±0.23 [20 Argo]	29.06 ±0.01	0.18 ±0.01

a. P2 (Obs. run)	$SST_{duringTC}$ (°C) [3DPWP]	T_a (°C) [CFS]	q_s (g kg^{-1}) [$SST_{duringTC}$]	q_a (g kg^{-1}) [CFS]	△T (°C)	△q (g kg^{-1})	SHF (W m^{-2})	LHF (W m^{-2})	Total Flux (W m^{-2})
Hagibis obs. run	28.34 ±0.26	29.29 ±0.33	25.62 ±0.52	21.25 ±0.45	-0.95 ±0.58	4.37 ±0.96	-81 ±51	957 ±163	876 ±213
Haiyan obs. run	29.06 ±0.01	27.65 ±0.77	25.73 ±0.40	19.15 ±0.87	1.41 ±0.78	6.57 ±1.07	138 ±78	1689 ±364	1827 ±416

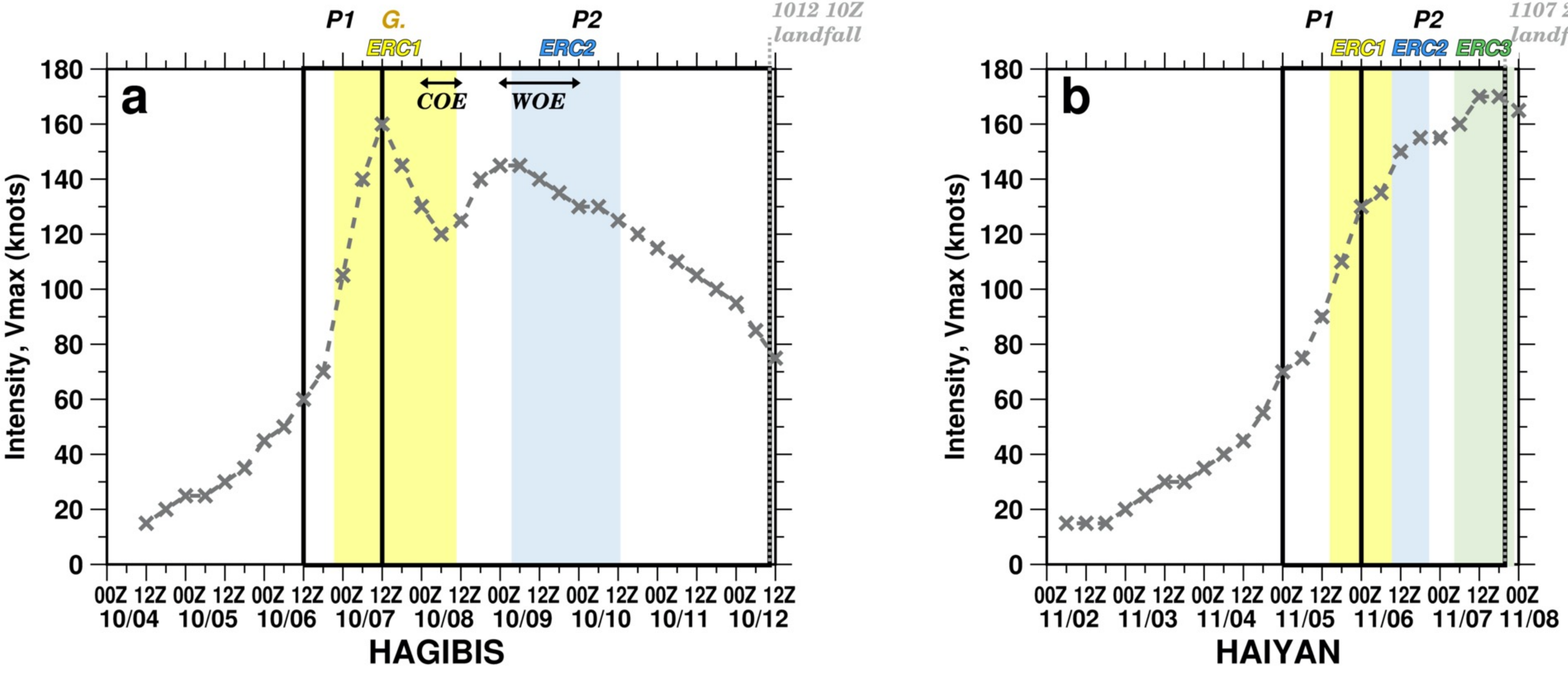


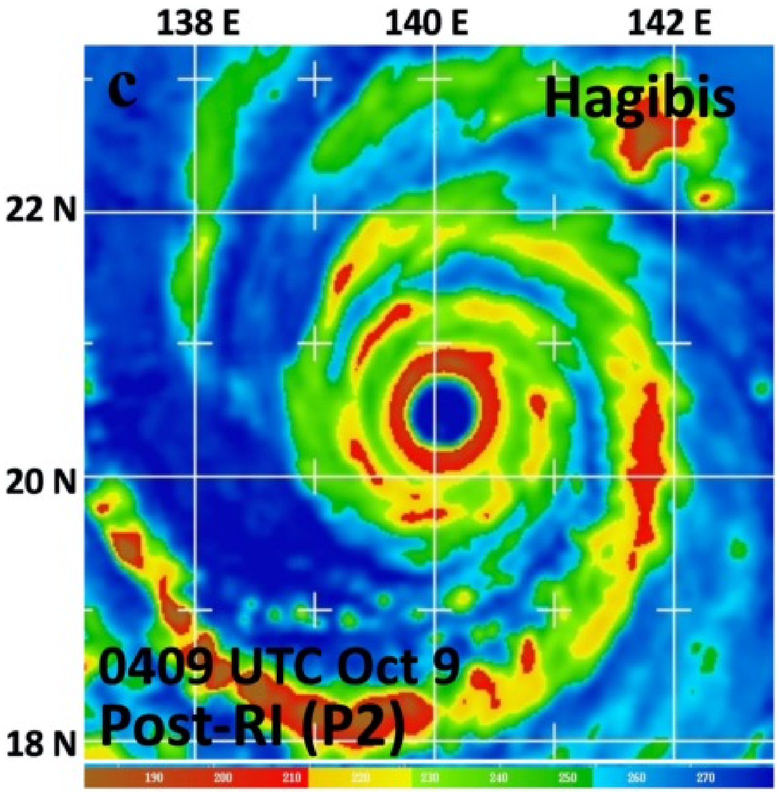
Huge Size Expansion
Smaller Size Expansion
Evident Uh slow down
Evident Uh speed up
a
b
c
d
RMW
R34
R34 (km)
RMW (km)
P1
G.
P2
1012 10Z landfall
1107 20Z landfall
Intensity, Vmax (knots)
Uh (m/s)
HAGIBIS
HAIYAN


ASCAT 25KM NOAA Winds – created at Oct 9 14:08 UTC 2019 descending
0 5 10 15 20 25 30 35 40 45 >50 knots
R34 = 519 km
$R_{outer\_closed\_isobar}$ = 685 km
23:19 23:19
Storm number: 20 Storm name: HAGIBIS
Note: 1) Times are GMT 2) Times along bottom correspond to measurement at 22N
3) Data buffer is 22 hrs from Oct 9 14:08 UTC 2019 4) Black wind barbs indicate possible contamination

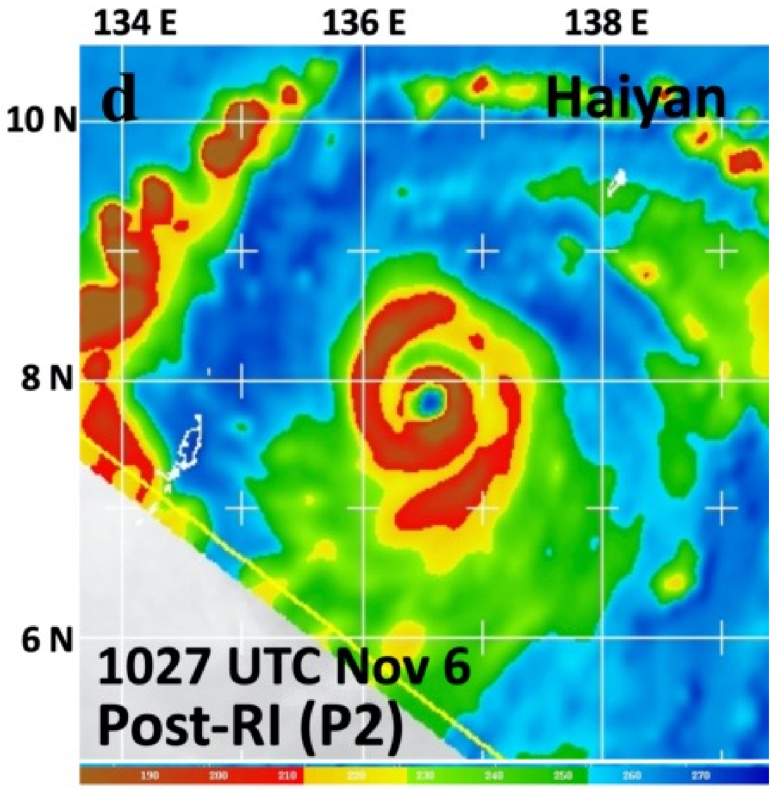

ASCAT 25KM NOAA Winds – created at Nov 7 07:35 UTC 2013 descending
0 5 10 15 20 25 30 35 40 45 >50 knots
R34 = 211 km
$R_{outer\_closed\_isobar}$ = 370 km
0:17 0:17
Storm number: 31 Storm name: HAIYAN
Note: 1) Times are GMT 2) Times along bottom correspond to measurement at 10N
3) Data buffer is 22 hrs from Nov 7 07:35 UTC 2013 4) Black Circles indicate possible contamination

Slower ERCs for larger-sized TCs

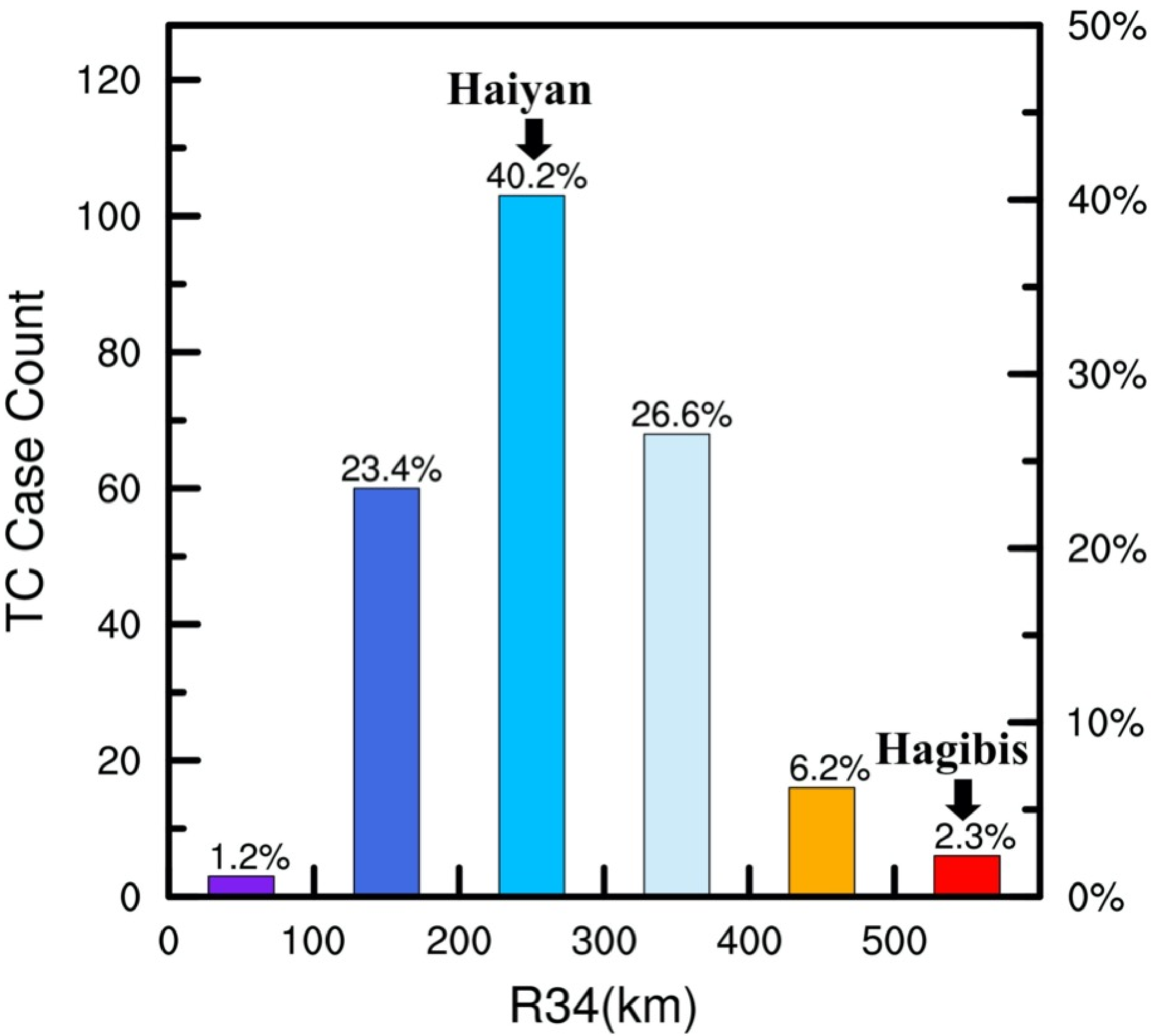




Larger Eye during P2
and broader wind field to
R34 ~ 550km



Haiyan remain compact
R34 ~ 250km



17 Years (2003-2019) of 256 TCs (>= Cat.1)
Of JTWC Records

Proposed Negative Impact of Large-Sized TCs:

1. **Stronger Ocean Cooling/Lower During-TC SST/Smaller delta T & delta q/Less Air-Sea Fluxes**
2. **Slower ERC- possibly prolonging ERC's negative impact**
3. **Possible reduction in radial inflow through enhanced inertial stability in the outer core (Rogers et al. 2013; Martinez et al. 2017)**

Conclusions

1. Ocean plays important roles for both P1 and P2, but the key is not just ocean but its interaction with TC attributes (e.g. Size and Uh). Indeed P1 Hagibis has more flux than Haiyan and vice versa for P2

2. P1: Spectacular RI for Hagibis: During-TC SST ~ 30°C (Pre-TC 30.5° - 0.5° Cooling) 36%/ more flux for Hagibis than Haiyan, strategic convection location and rapid eyewall contraction

3. P2: Size enlargement (nearly double) causes 3 negative factors
   a. Stronger ocean cooling (less flux), Uh reduction also reduces flux, ~ equal contribution
   b. Slower/Longer Eyewall Replacement Cycle (ERC)
   c. Possible reduction in radial inflow via enhanced inertial stability at outer core

4. TC Size: Opens-Up an Interesting New Dimension for Research in TC-Ocean Interaction (from Pun et al. 2018 to this work Lin et al. 2021), Hargibis also is the largest TC in the typhoon record!

5. Salinity and Vertical Wind Shear are not the differentiating factors for these 2 STYs

2.
The Association of Typhoon Intensity Increase with Translation Speed Increase in the South China Sea

Ya-ting Chang, I-I Lin*, Hsiao-Ching Huang, Yi-Chun Liao and Chun-Chi Lien (NTUAS)

Sustainability, 2020

a natureresearch journal

nature

Letter | Published: 06 June 2018

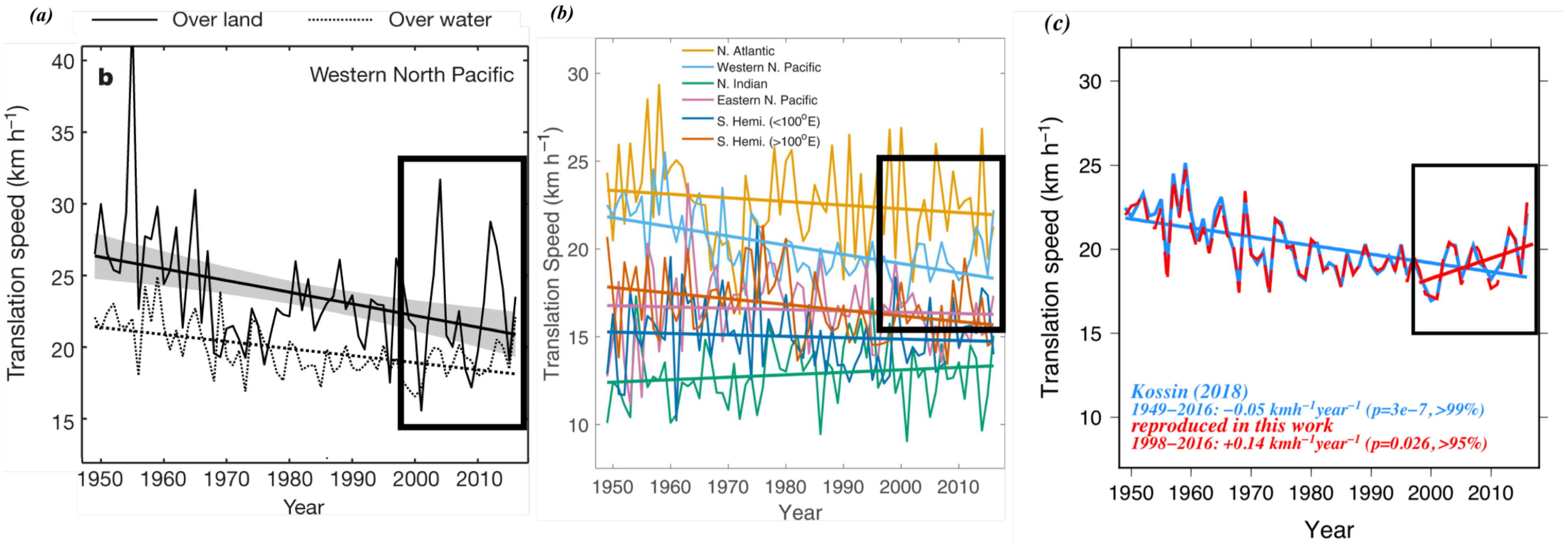
A global slowdown of tropical-cyclone translation speed

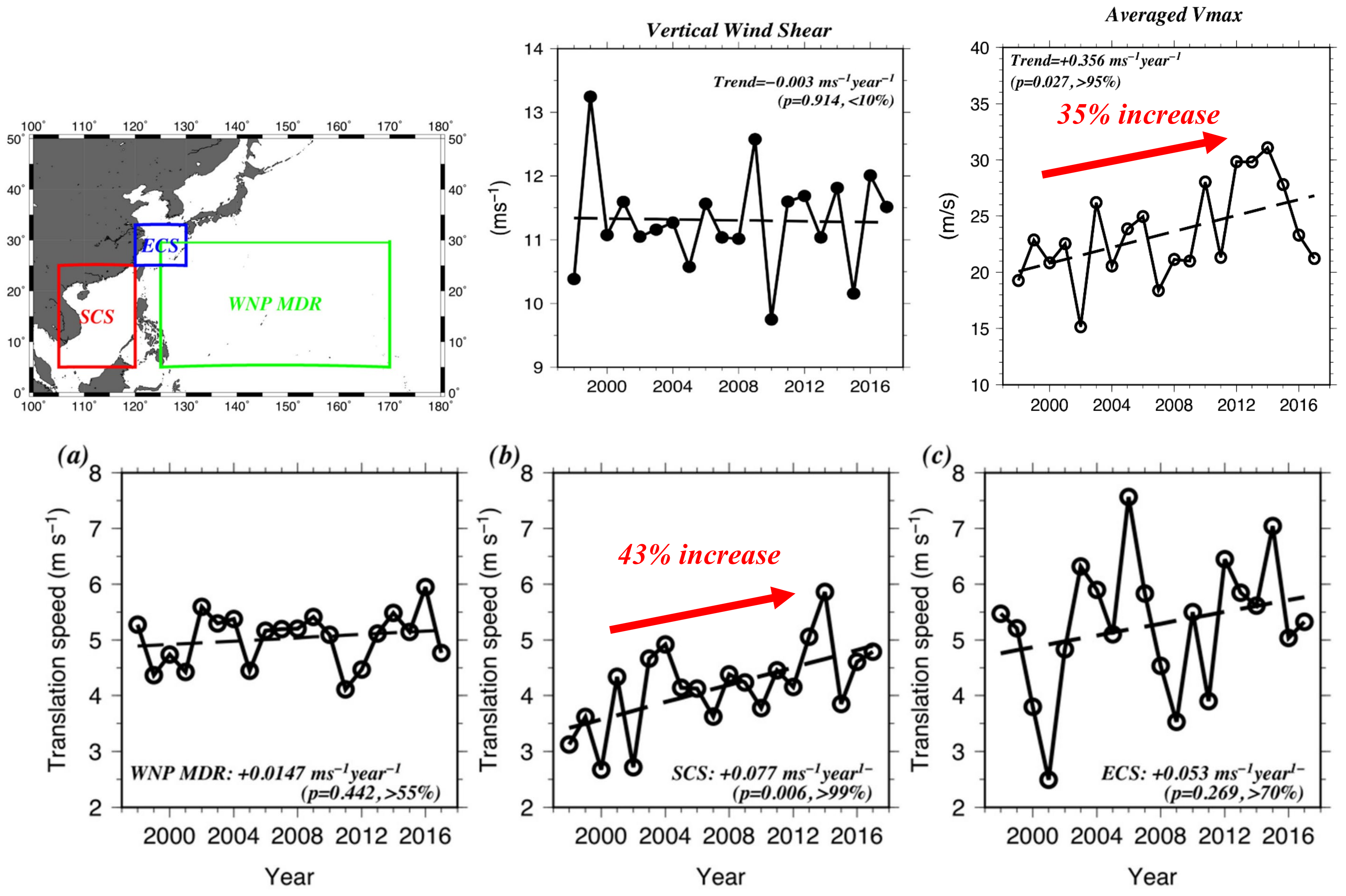
James P. Kossin

Nature **558**, 104–107(2018) | Cite this article

Chang et al. Sustainability 2020

TC Translation Speed & Intensity over the SCS





SCS
ECS
WNP MDR
Vertical Wind Shear
Trend=−0.003 ms⁻¹year⁻¹
(p=0.914, <10%)
(ms⁻¹)
Averaged Vmax
Trend=+0.356 ms⁻¹year⁻¹
(p=0.027, >95%)
35% increase
(m/s)
(a)
WNP MDR: +0.0147 ms⁻¹year⁻¹
(p=0.442, >55%)
(b)
43% increase
SCS: +0.077 ms⁻¹year⁻¹
(p=0.006, >99%)
(c)
ECS: +0.053 ms⁻¹year⁻¹
(p=0.269, >70%)
Translation speed (m s⁻¹)
Year

3.
ENSO, Tropical Cyclone, and Global Warming – A Review

I-I Lin (NTUAS), Suzana J. Camargo (Columbia Uni.), Christina M. Patricola (Lawrence Berkeley Lab/Uni. of Iowa), Johnny C L Chan (City Univ. of Hong Kong), Julien Boucharel (LEGOS, Uni. of Toulouse, France), Savin Chand (Federation University, Australia), Phil Klotzbach (CSU), Bin Wang (Uni. of Hawaii), Ping Chang (Texas A&M Uni.), Tim Li (Uni. of Hawaii), Fei Fei Jin (Uni. of Hawaii)

Chap. 17, AGU 100th Celebration Monograph, 2020

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OCEAN SCIENCES | Editors' Vox

Advancing Knowledge of ENSO in a Changing Climate

A new book highlights research progress on El Niño Southern Oscillation dynamics and impacts and how they may change in a warmer world.

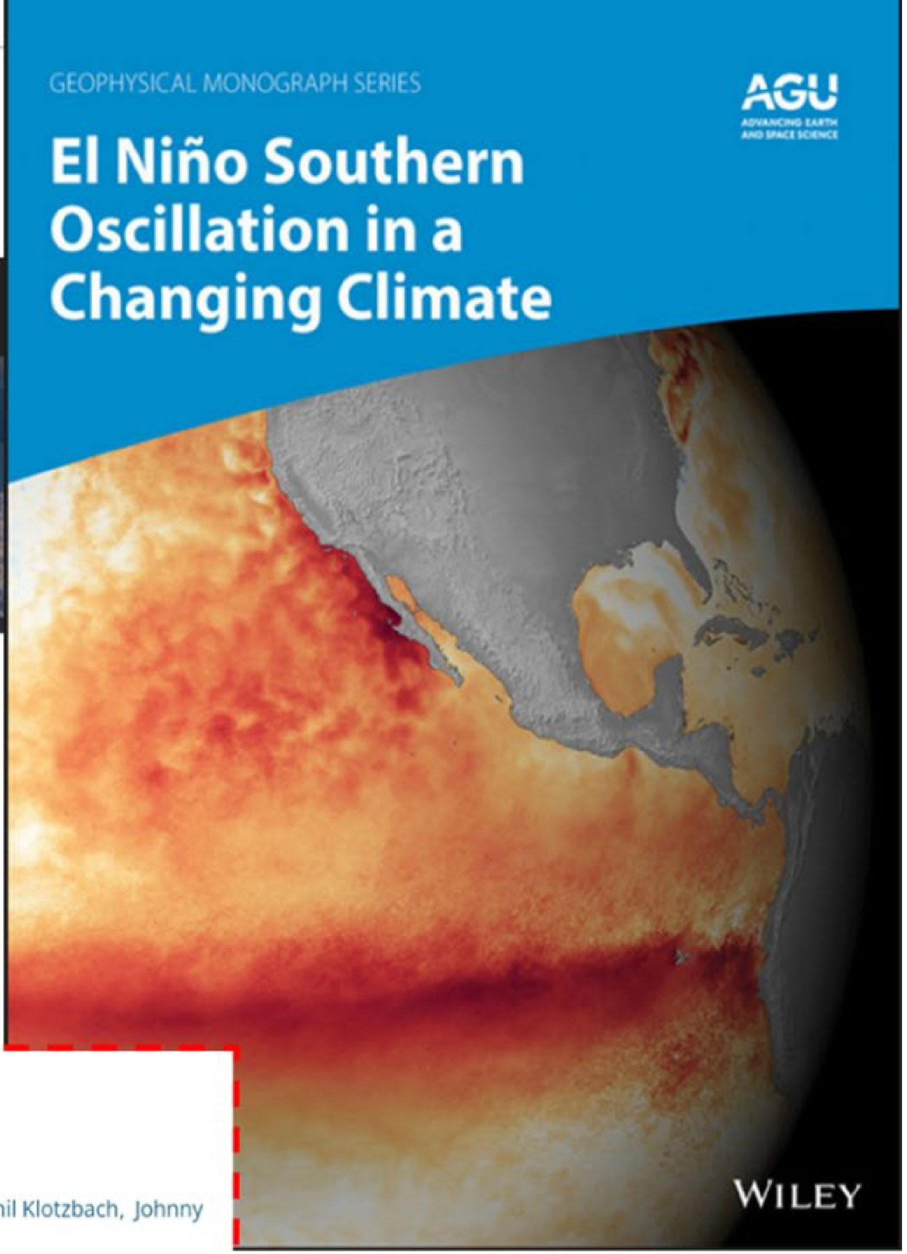
Chapter 17

ENSO and Tropical Cyclones

I-I Lin, Suzana J. Camargo, Christina M. Patricola, Julien Boucharel, Savin Chand, Phil Klotzbach, Johnny C. L. Chan, Bin Wang, Ping Chang, Tim Li, Fei-Fei Jin

Book Editor(s): Michael J. McPhaden, Agus Santoso, Wenju Cai

First published: 23 October 2020 | https://doi.org/10.1002/9781119548164.ch17



Editors

- **Michael J. McPhaden** (PMEL, NOAA, USA)
- **Agus Santoso** (Univ. NSW, Australia)
- **Wenju Cai** (CSHOR/CSIRO,Australia)

Ch 1. Introduction
Editors *(New Issues..)*

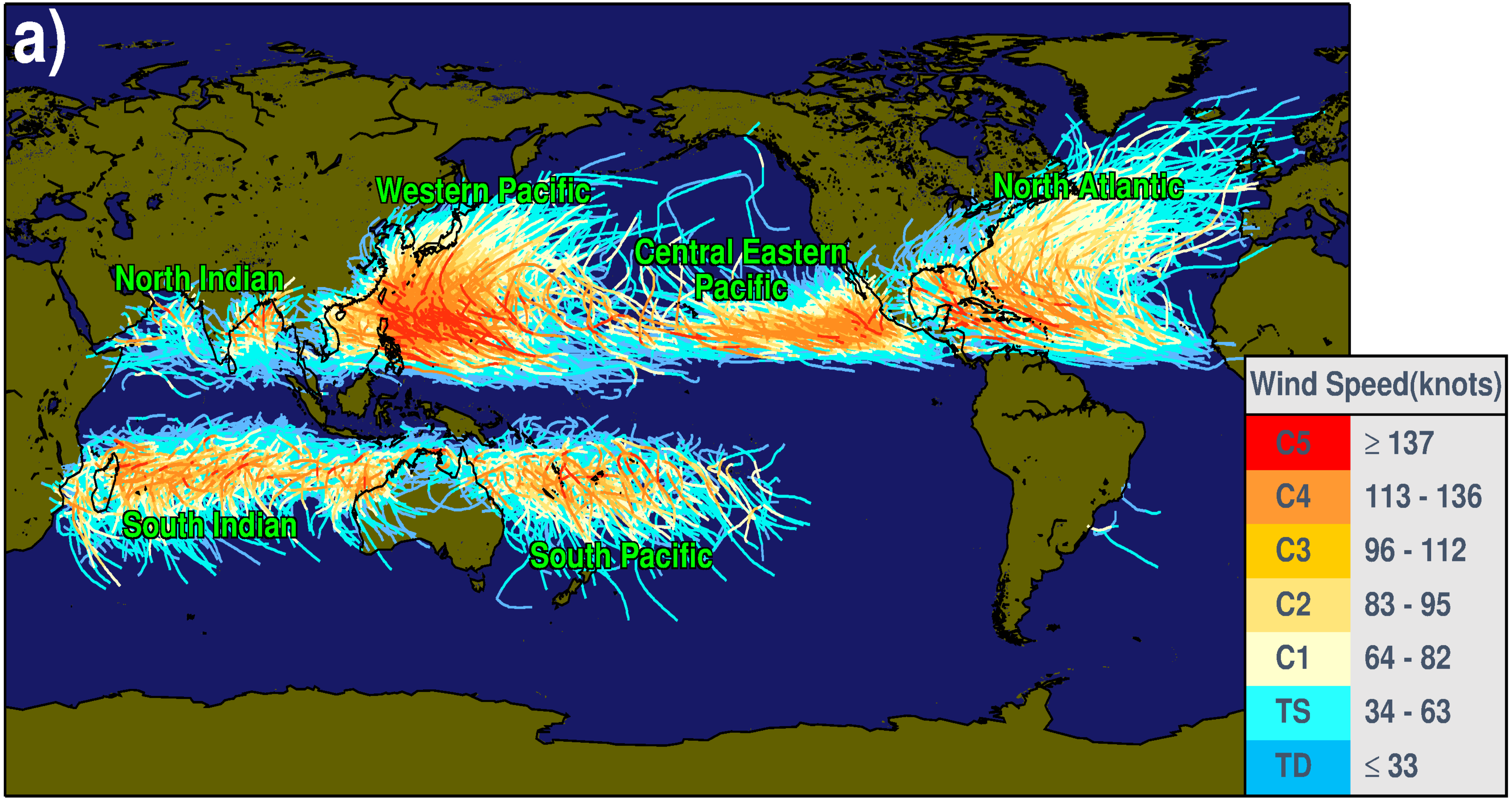
Ch. 2. ENSO in the global climate system
Dr. Kevin Trenberth, UCAR, USA

Ch. 5 ENSO diversity
EP, CP, Mixed type (e.g. 2015)]
Dr. Antonietta Capotondi, NOAA, USA

Ch. 12 Greenhouse forcing
Dr. Wenju Cai, CSIRO, Aus.

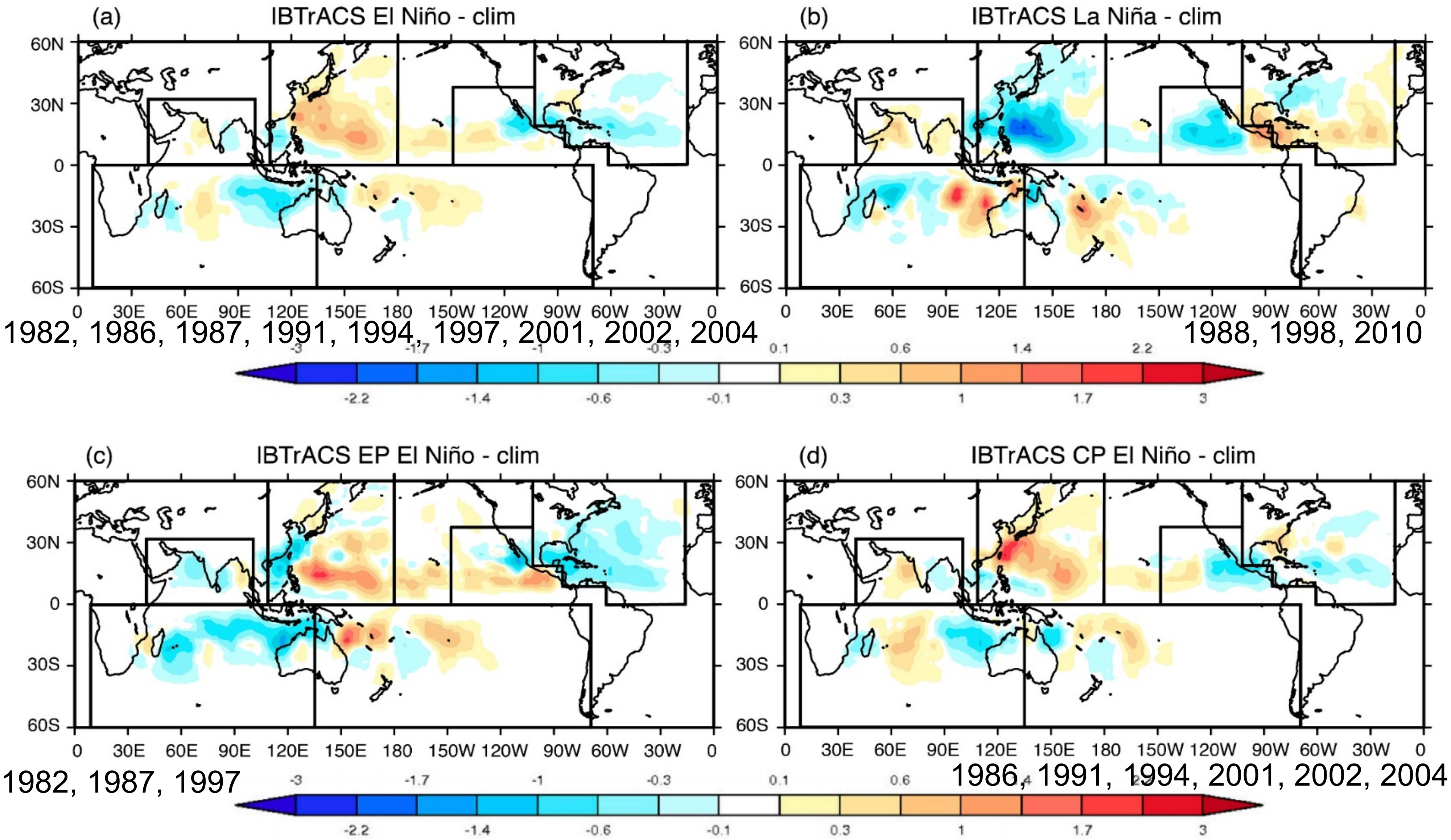
Tropical cyclone intensity distribution

Best track data from NHC and JTWC, 1980~2018 TD TS C1 C2 C3 C4 C5



(courtesy of Dan Fu, after Bell et al. 2014)

TC Track Density Anomaly Maps under El Nino (EP+CP), La Nina, EP, CP



1982, 1986, 1987, 1991, 1994, 1997, 2001, 2002, 2004

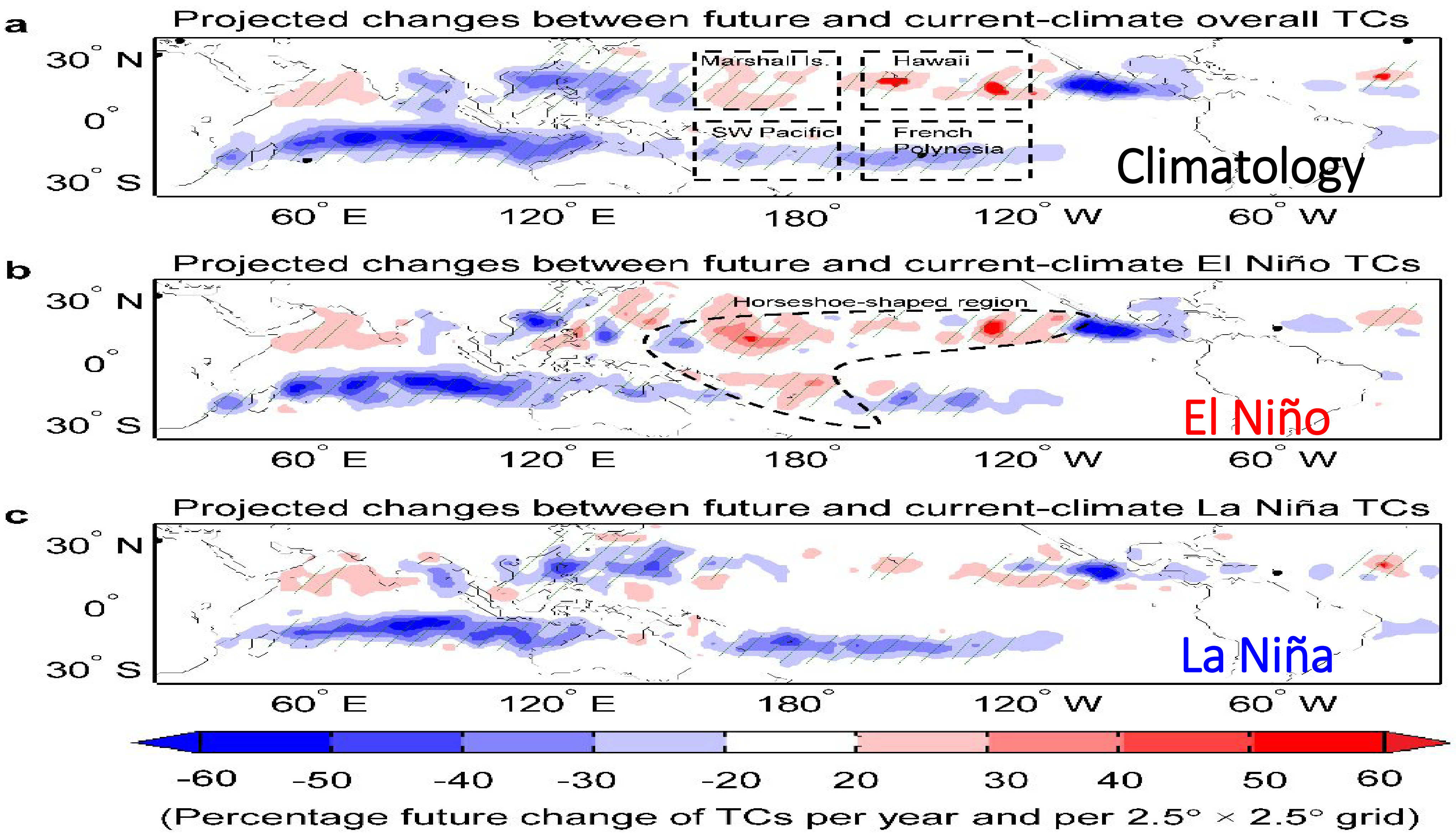
1988, 1998, 2010

1982, 1987, 1997

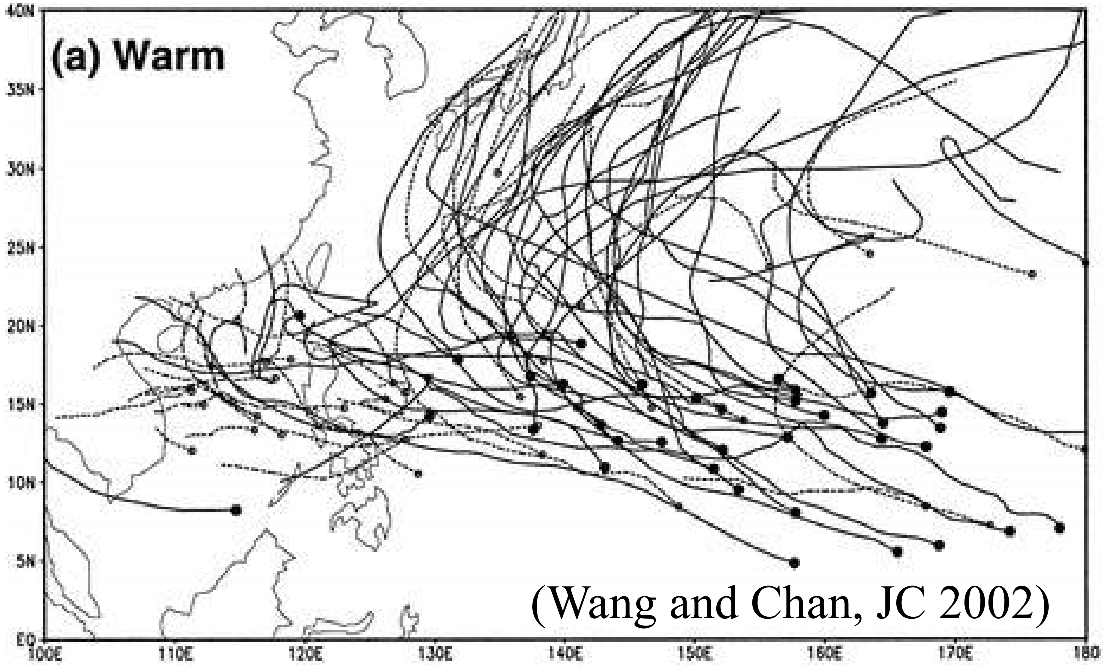
1986, 1991, 1994, 2001, 2002, 2004

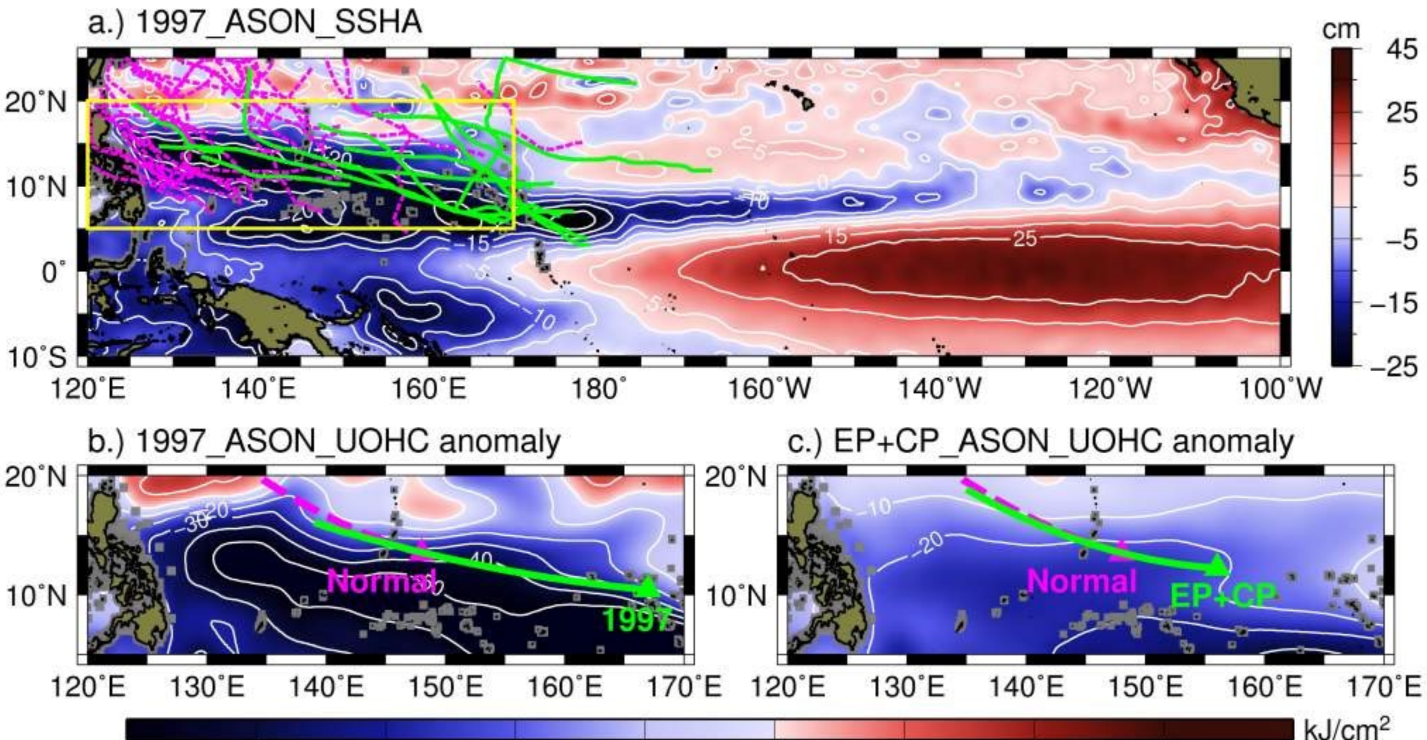
Chand et al. 2017; Bell et al. 2020

Global Warming, TC, and ENSO



El Niño & Typhoons





OHC drop 30%!

Zheng, Lin, Wang..

et al. Sci. Rep. 2015

ENSO and 6 TC Basins

Ocean Heat Content Drops 30% During El Niño Over Western North Pacific (Zheng et al. Sci. Rep. 2015)

Ocean Heat Content Increases During La Nina/La Nina Like Multi-Decadal Condition to Fuel Record-Breaking Super typhoons (Lin et al. GRL 2014)

supplementary

a. P1 (Obs. run)	**Input TC Size in D50 (km)**	**Input TC U_h (m s^{-1})**	**SST_{preTC} (°C) [from Argo]**	**$SST_{duringTC}$ (°C) [3DPWP output]**	**Cooling (°C)**
Hagibis obs. run	266.8 ±91.2	7.7 ±0.6	30.33 ±0.20 [4 Argo]	29.76 ±0.30	0.57 ±0.30
Haiyan obs. run	157.4 ±53.2	7.8 ±0.5	29.05 ±0.59 [3 Argo]	28.94 ±0.05	0.11 ±0.05

b. P1 (Sens. run)	**Input TC Size in D50 (km)**	**Input TC U_h (m s^{-1})**	**SST_{preTC} (°C) [from Argo]**	**$SST_{duringTC}$ (°C) [3DPWP output]**	**Cooling (°C)**
Size sens. run	157.4 ±53.2	7.7 ±0.6	30.33 ±0.20 [4 Argo]	30.03 ±0.06	0.29 ±0.06
U_h sens. run	266.8 ±91.2	7.8 ±0.5	30.33 ±0.20 [4 Argo]	29.77 ±0.30	0.56 ±0.30
Size + U_h sens. run	157.4 ±53.2	7.8 ±0.5	30.33 ±0.20 [4 Argo]	30.04 ±0.06	0.29 ±0.06
Salinity sens. run	266.8 ±91.2	7.7 ±0.6	30.33 ±0.20 [4 Argo]	29.78 ±0.28	0.54 ±0.28

a. P1 (Obs. run)	$SST_{duringTC}$ (°C) [3DPWP]	T_a (°C) [CFS]	q_s (g kg^{-1}) [$SST_{duringTC}$]	q_a (g kg^{-1}) [CFS]	△ T (°C)	△ q (g kg^{-1})	SHF (W m^{-2})	LHF (W m^{-2})	Total Flux (W m^{-2})
Hagibis obs. run	29.76 ±0.30	28.42 ±0.35	25.74 ±0.31	19.33 ±0.28	1.34 ±0.60	6.42 ±0.25	82 ±23	1169 ±433	1250 ±433
Haiyan obs. run	28.94 ±0.05	27.78 ±1.11	24.61 ±0.16	19.37 ±0.23	1.15 ±1.10	5.24 ±0.09	69 ±65	853 ±212	923 ±240

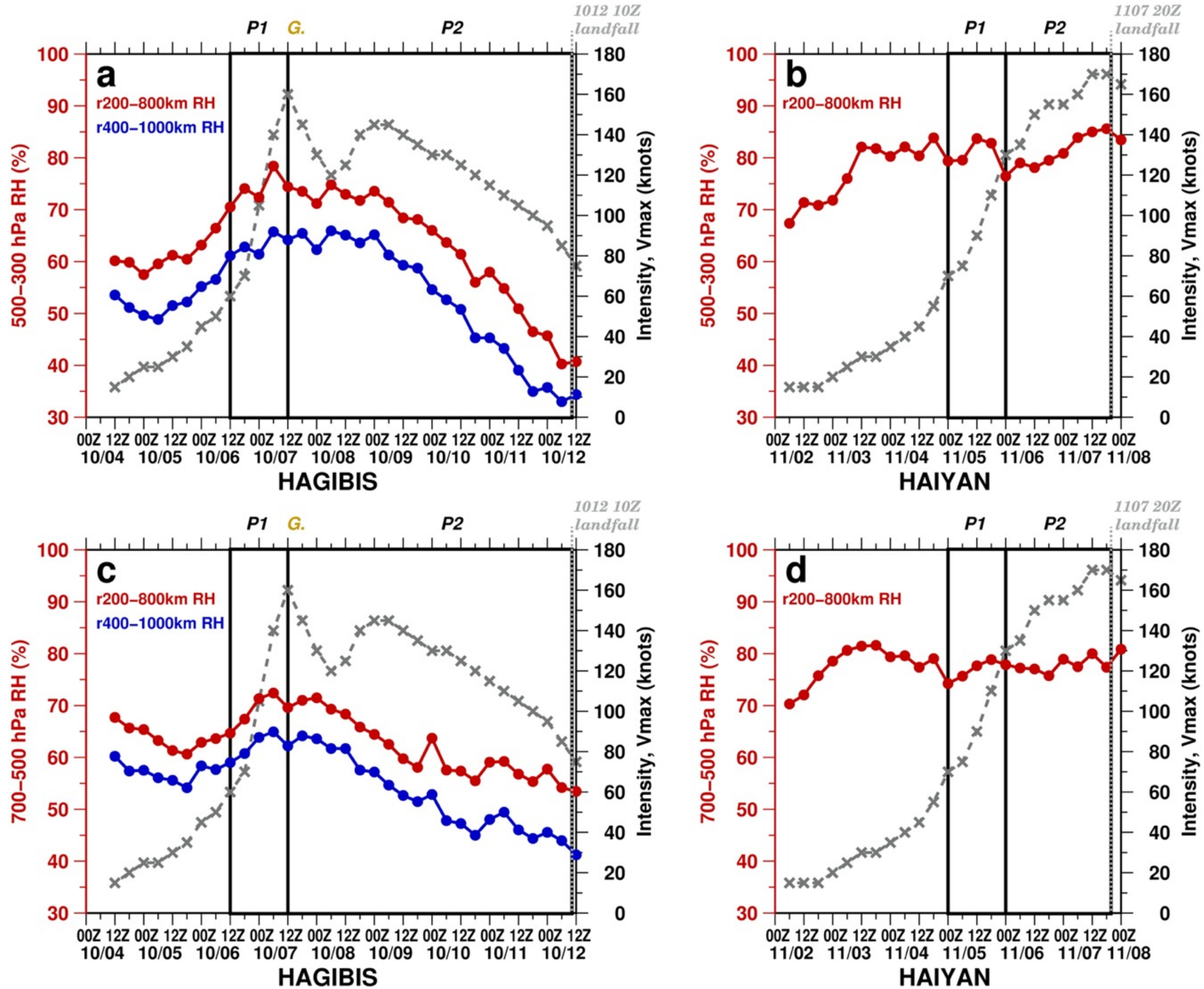
b. P1 (Sens. run)	$SST_{duringTC}$ (°C)[3DPWP]	T_a (°C) [CFS]	q_s (g kg^{-1}) [$SST_{duringTC}$]	q_a (g kg^{-1}) [CFS]	△ T (°C)	△ q (g kg^{-1})	SHF (W m^{-2})	LHF (W m^{-2})	Total Flux (W m^{-2})
Size sens. run	30.03 ±0.06	28.42 ±0.35	26.15 ±0.08	19.33 ±0.28	1.62 ±0.40	6.82 ±0.30	106 ±33	1264 ±529	1370 ±554
U_h sens. run	29.77 ±0.30	28.42 ±0.35	25.75 ±0.30	19.33 ±0.28	1.35 ±0.57	6.43 ±0.28	82 ±19	1171 ±435	1253 ±435
Size + U_h sens. run	30.04 ±0.06	28.42 ±0.35	26.16 ±0.08	19.33 ±0.28	1.62 ±0.39	6.83 ±0.30	106 ±32	1266 ±530	1372 ±554
Salinity sens. run	29.78 ±0.28	28.42 ±0.35	25.78 ±0.28	19.33 ±0.28	1.36 ±0.58	6.45 ±0.24	83 ±23	1176 ±440	1260 ±442

a. P2 (Obs. run)	Input TC Size in D50 (km)	Input TC U_h (m s^{-1})	SST_{preTC} (°C) [from Argo]	$SST_{duringTC}$ (°C) [3DPWP output]	Cooling (°C)
Hagibis obs. run	447.2 ±45.4	4.5 ±1.1	29.62 ±0.10 [10 Argo]	28.34 ±0.26	1.29 ±0.26
Haiyan obs. run	231.6 ±25.6	9.5 ±0.9	29.24 ±0.23 [20 Argo]	29.06 ±0.01	0.18 ±0.01

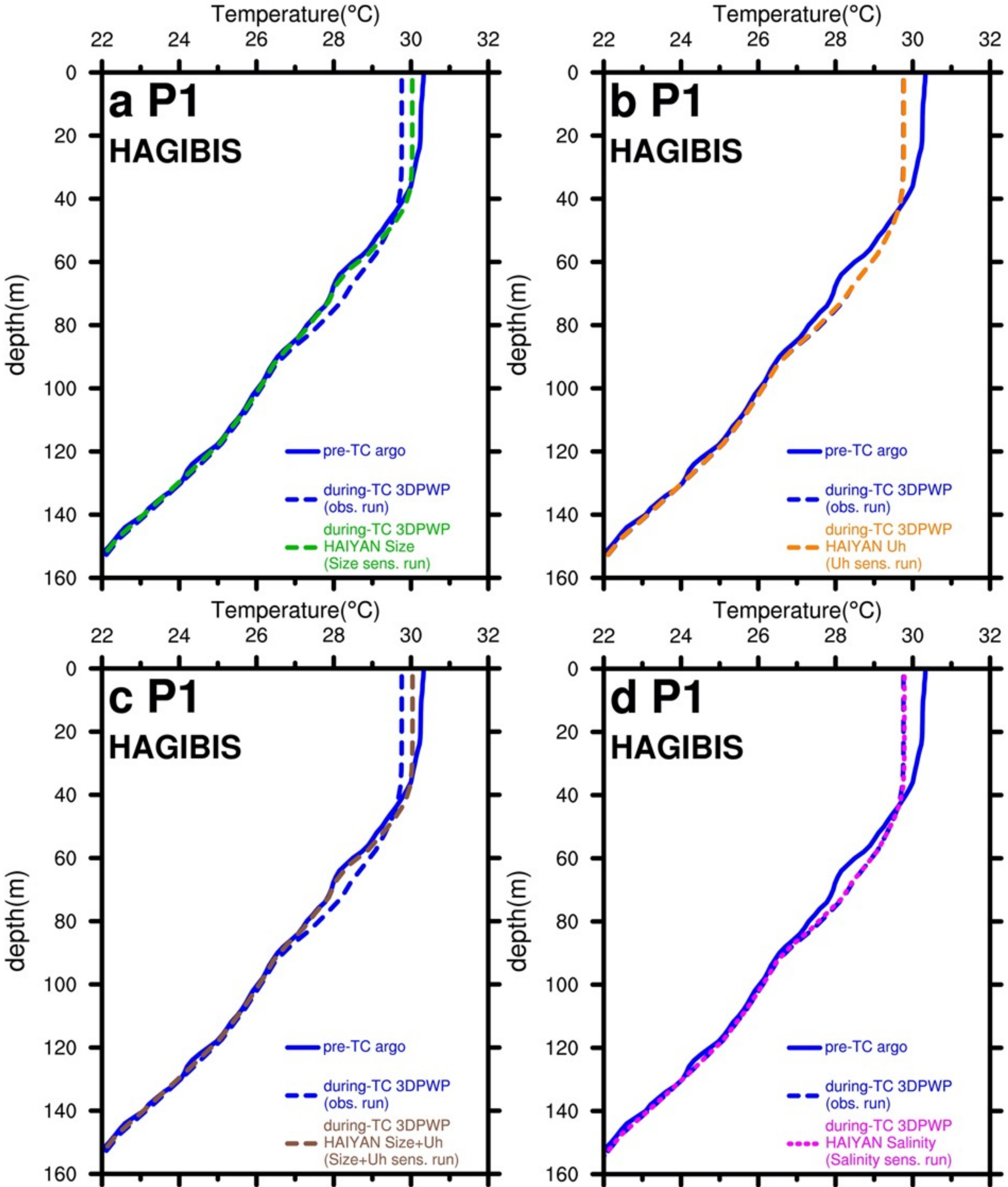
b. P2 (Sens. run)	Input TC Size in D50 (km)	Input TC U_h (m s^{-1})	SST_{preTC} (°C) [from Argo]	$SST_{duringTC}$ (°C) [3DPWP output]	Cooling (°C)
Size sens. run	231.6 ±25.6	4.5 ±1.1	29.62 ±0.10 [10 Argo]	28.96 ±0.17	0.66 ±0.17
U_h sens. run	447.2 ±45.4	9.5 ±0.9	29.62 ±0.10 [10 Argo]	29.00 ±0.02	0.62 ±0.02
Size + U_h sens. run	231.6 ±25.6	9.5 ±0.9	29.62 ±0.10 [10 Argo]	29.34 ±0.01	0.28 ±0.01
Salinity sens. run	447.2 ±45.4	4.5 ±1.1	29.62 ±0.10 [10 Argo]	28.39 ±0.25	1.24 ±0.25

a. P2 (Obs. run)	$SST_{duringTC}$ (°C) [3DPWP]	T_a (°C) [CFS]	q_s (g kg^{-1}) [$SST_{duringTC}$]	q_a (g kg^{-1}) [CFS]	△ T (°C)	△ q (g kg^{-1})	SHF (W m^{-2})	LHF (W m^{-2})	Total Flux (W m^{-2})
Hagibis obs. run	28.34 ±0.26	29.29 ±0.33	25.62 ±0.52	21.25 ±0.45	-0.95 ±0.58	4.37 ±0.96	-81 ±51	957 ±163	876 ±213
Haiyan obs. run	29.06 ±0.01	27.65 ±0.77	25.73 ±0.40	19.15 ±0.87	1.41 ±0.78	6.57 ±1.07	138 ±78	1689 ±364	1827 ±416

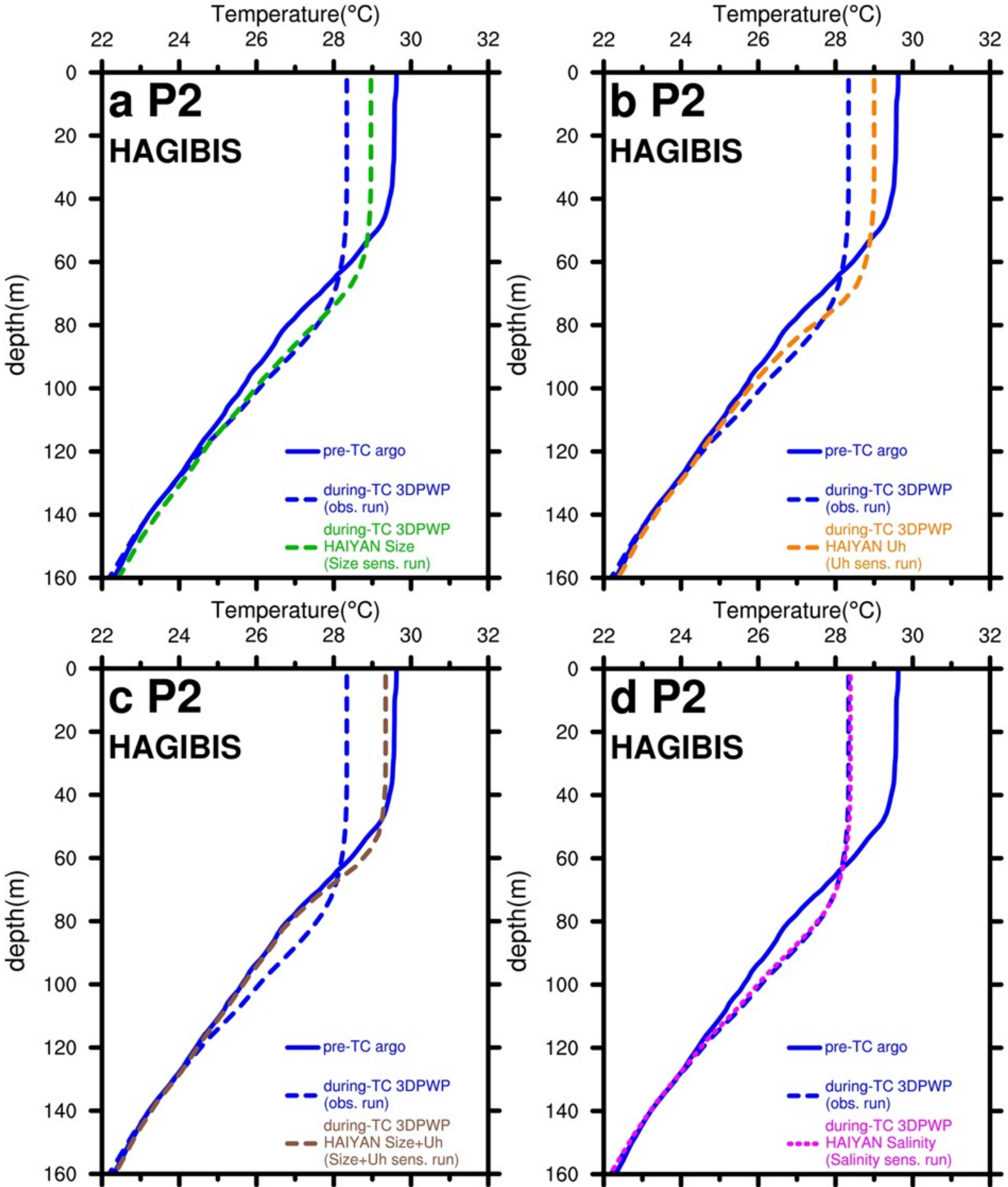
b. P2 (Sens. run)	$SST_{duringTC}$ (°C) [3DPWP]	T_a (°C) [CFS]	q_s (g kg^{-1}) [$SST_{duringTC}$]	q_a (g kg^{-1}) [CFS]	△ T (°C)	△ q (g kg^{-1})	SHF (W m^{-2})	LHF (W m^{-2})	Total Flux (W m^{-2})
Size sens. run	28.96 ±0.17	29.29 ±0.33	26.56 ±0.40	21.25 ±0.45	-0.32 ± 0.49	5.31 ±0.81	-28 ±41	1166 ±124	1138 ±164
U_h sens. run	29.00 ±0.02	29.29 ±0.33	26.62 ±0.21	21.25 ±0.45	-0.29 ± 0.34	5.37 ±0.62	-25 ±29	1180 ±81	1155 ±107
Size + U_h sens. run	29.34 ±0.01	29.29 ±0.33	27.15 ±0.19	21.25 ±0.45	0.06 ± 0.34	5.90 ±0.62	4 ±28	1297 ±75	1301 ±100
Salinity sens. run	28.39 ±0.25	29.29 ±0.33	25.69 ±0.52	21.25 ±0.45	-0.90 ± 0.58	4.44 ±0.95	-77 ±51	973 ±162	896 ±211



P1
G.
P2
1012 10Z landfall
a
r200–800km RH
r400–1000km RH
500–300 hPa RH (%)
Intensity, Vmax (knots)
HAGIBIS
b
r200–800km RH
1107 20Z landfall
HAIYAN
c
700–500 hPa RH (%)
d



Temperature(°C)
22
24
26
28
30
32
0
20
40
60
80
100
120
140
160
depth(m)
a P1
HAGIBIS
pre-TC argo
during-TC 3DPWP
(obs. run)
during-TC 3DPWP
HAIYAN Size
(Size sens. run)
b P1
HAGIBIS
during-TC 3DPWP
HAIYAN Uh
(Uh sens. run)
c P1
HAGIBIS
during-TC 3DPWP
HAIYAN Size+Uh
(Size+Uh sens. run)
d P1
HAGIBIS
during-TC 3DPWP
HAIYAN Salinity
(Salinity sens. run)



a P2
HAGIBIS
b P2
HAGIBIS
c P2
HAGIBIS
d P2
HAGIBIS
Temperature(°C)
depth(m)
pre-TC argo
during-TC 3DPWP (obs. run)
during-TC 3DPWP HAIYAN Size (Size sens. run)
during-TC 3DPWP HAIYAN Uh (Uh sens. run)
during-TC 3DPWP HAIYAN Size+Uh (Size+Uh sens. run)
during-TC 3DPWP HAIYAN Salinity (Salinity sens. run)

Summary

1. **Weather: Rapid Intensification (RI), Ocean Eddy, TC Translation Speed (Uh), TC Size, Shallow Water RI**

2. **ITOP & Ocean Coupling Potential Intensity**

3. **Climate: Cat. 6, Haiyan/Hiatus, Patricia/2015 El Niño, ElNiño's stealth heat supply, South China Sea Uh/intensity trend**

4. **Global Warming**
   PDI reduction, Increase in subsurface stratification,
   Sea level rise and surge, Global Warming-Future ENSO-TC

5. **Offset, Competition (Atm./Ocean), & Gaia**
   Inter-annual, Multi-decadal, Centennial/Global Warming Scales

Negative process exist to offset positive processs to prevent TCs from developing towards only 1 direction

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July 2017

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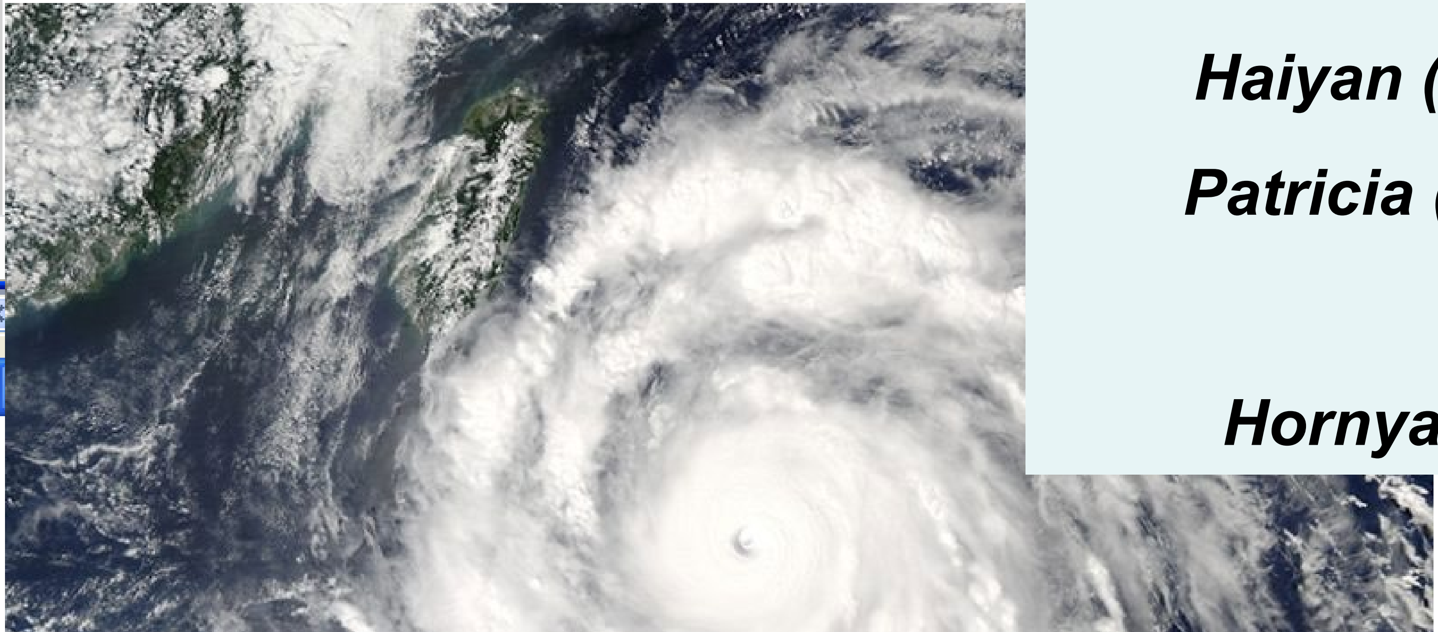
Probing the Power of Pacific Supertyphoons



Importance of Category '6'

Haiyan (170kts, 2013)

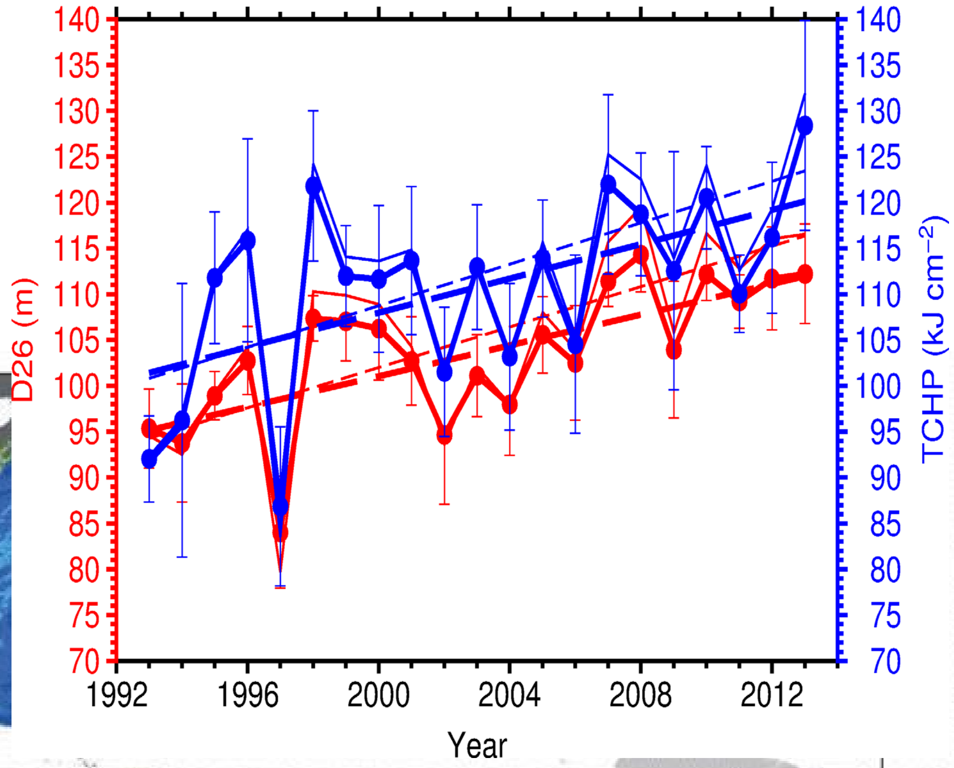
Patricia (185kts, 2015)

Hornyak EOS 2017;

頁 15 節 1

開始

Pun et al. GRL, Sep. 2013



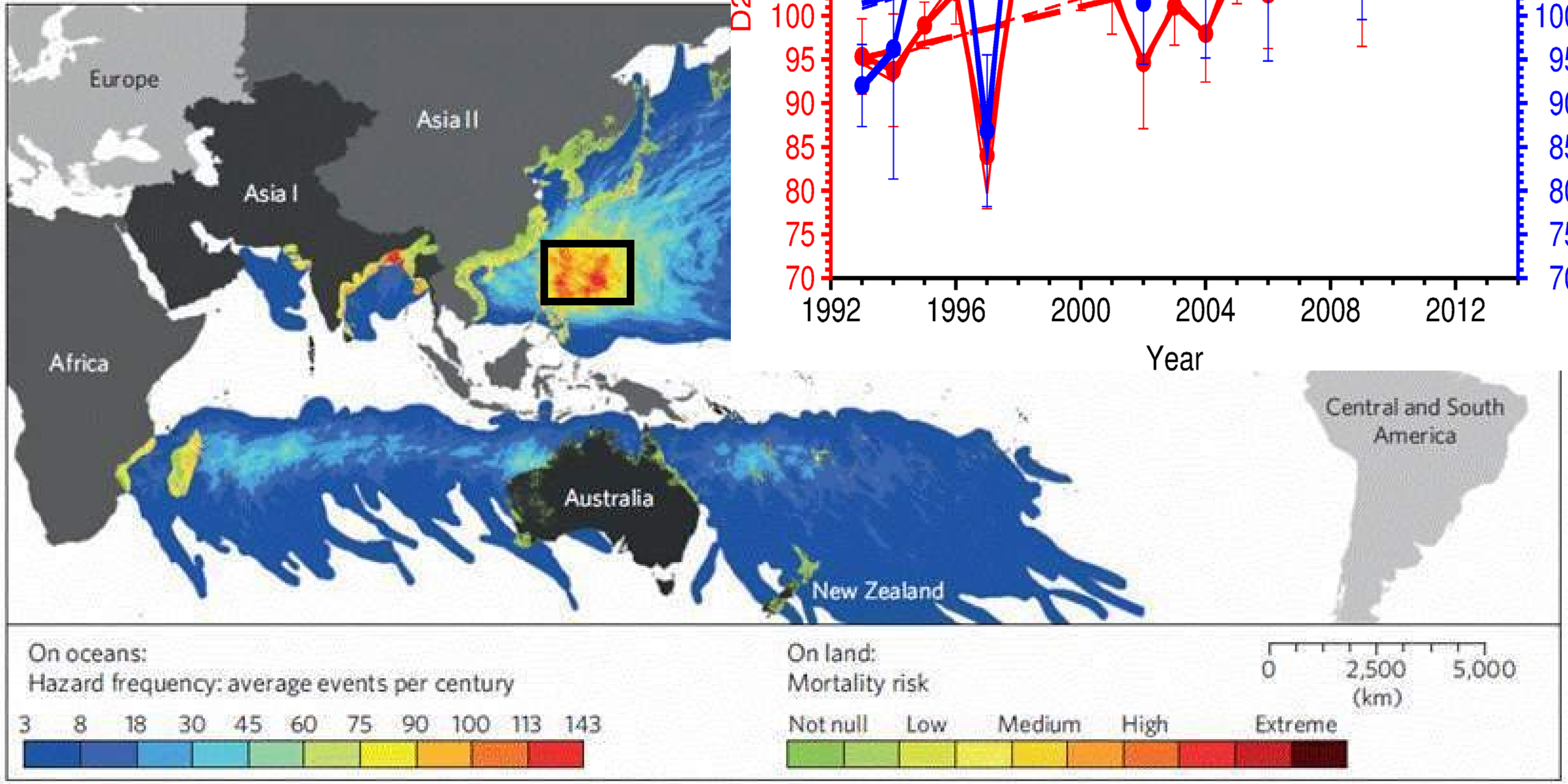
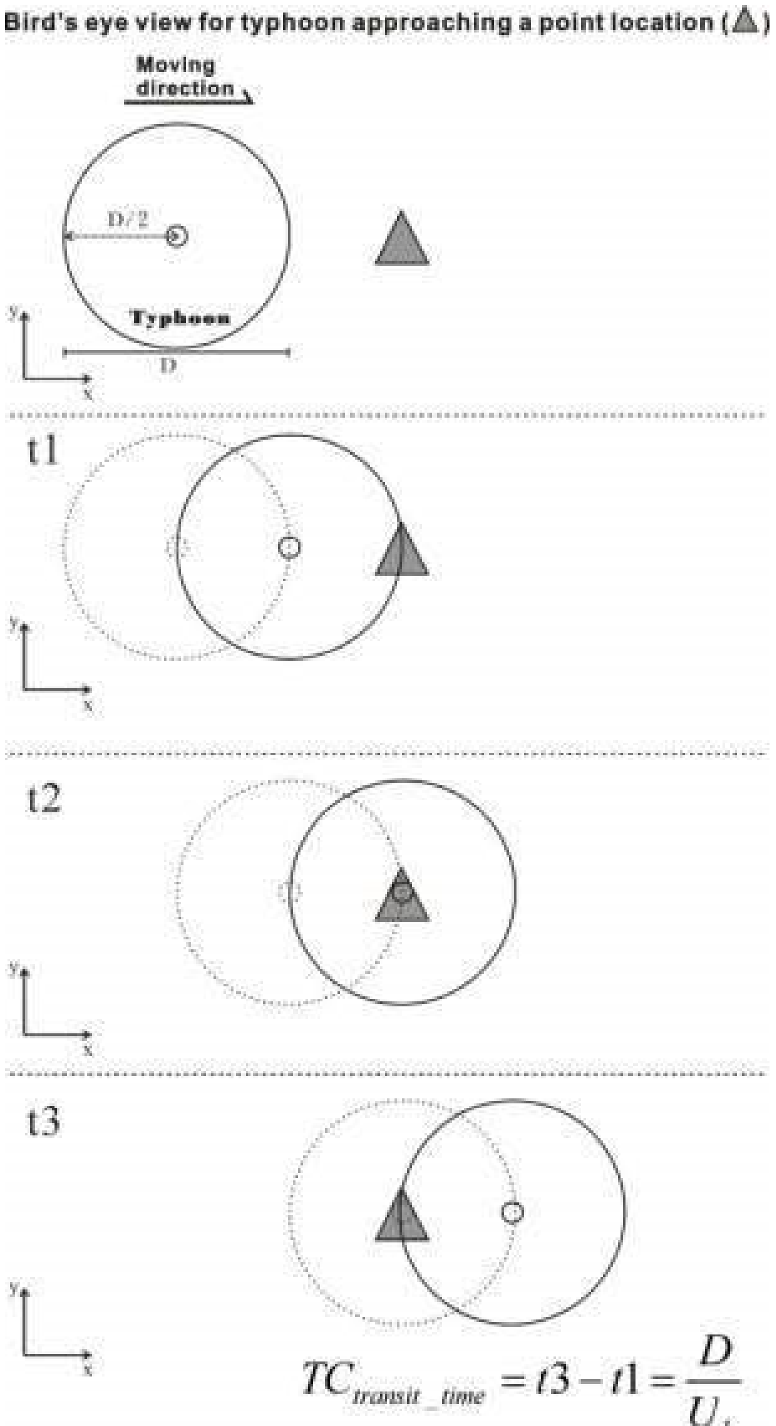


Figure 1 | Map showing distribution of hazard frequency and mortality risk from TCs for the year 2010. Estimates are applied to all pixels on a geographic grid. Mortality risk is categorized from low to extreme.

Peduzzi et al. *Nat. C.C.* 2012



$$TC_{transit\_time} = t3 - t1 = \frac{D}{U_t}$$

4 factors affect the cooling effect

- ***Pre-existing ocean T-S profile***
- ***TC wind speed***
- ***TC translation speed***
- ***TC size***

**** TC_transit time***

= D/Uh

Lin et al. MWR 2009; Lin JGR 2012, Lin et al. GRL 2013

The bulk formulae for SHF and LHF calculations are, SHF: $Q_S = C_H W(T_s - T_a)\rho_a C_{pa}$, LHF: $Q_L = C_E W(q_s - q_a)\rho_a L_{va}$, where C_H and C_E are the sensible and latent heat exchange coefficients under high wind condition (Zhang et al. 2008). As in Zhang et al. 2008, C_H (C_E) is 1.1 (1.2) x 10^{-3}. W is ocean surface wind speed (in 1-min average, from JTWC), T_S and T_a are during-TC SST and near surface air temperature, q_s and q_a are surface and air specific humidity. ρ_a, C_{pa}, and L_{va} are air density, heat capacity of the air, and latent heat of vaporization. q_s is calculated from the during-TC SST.

REWRITING THE TROPICAL RECORD BOOKS

The Extraordinary Intensification of Hurricane Patricia (2015)

Robert F. Rogers, Sim Aberson, Michael M. Bell, Daniel J. Cecil, James D. Doyle, Todd B. Kimberlain, Josh Morgerman, Lynn K. Shay, and Christopher Velden

East Pacific Hurricane Patricia (2015) broke several records, including intensification rate and peak intensity. An impressive array of observations was collected in this storm for much of its life cycle.

In late October 2015, a remarkable meteorological event unfolded off the west coast of Mexico. At first, the event seemed like a typical east Pacific

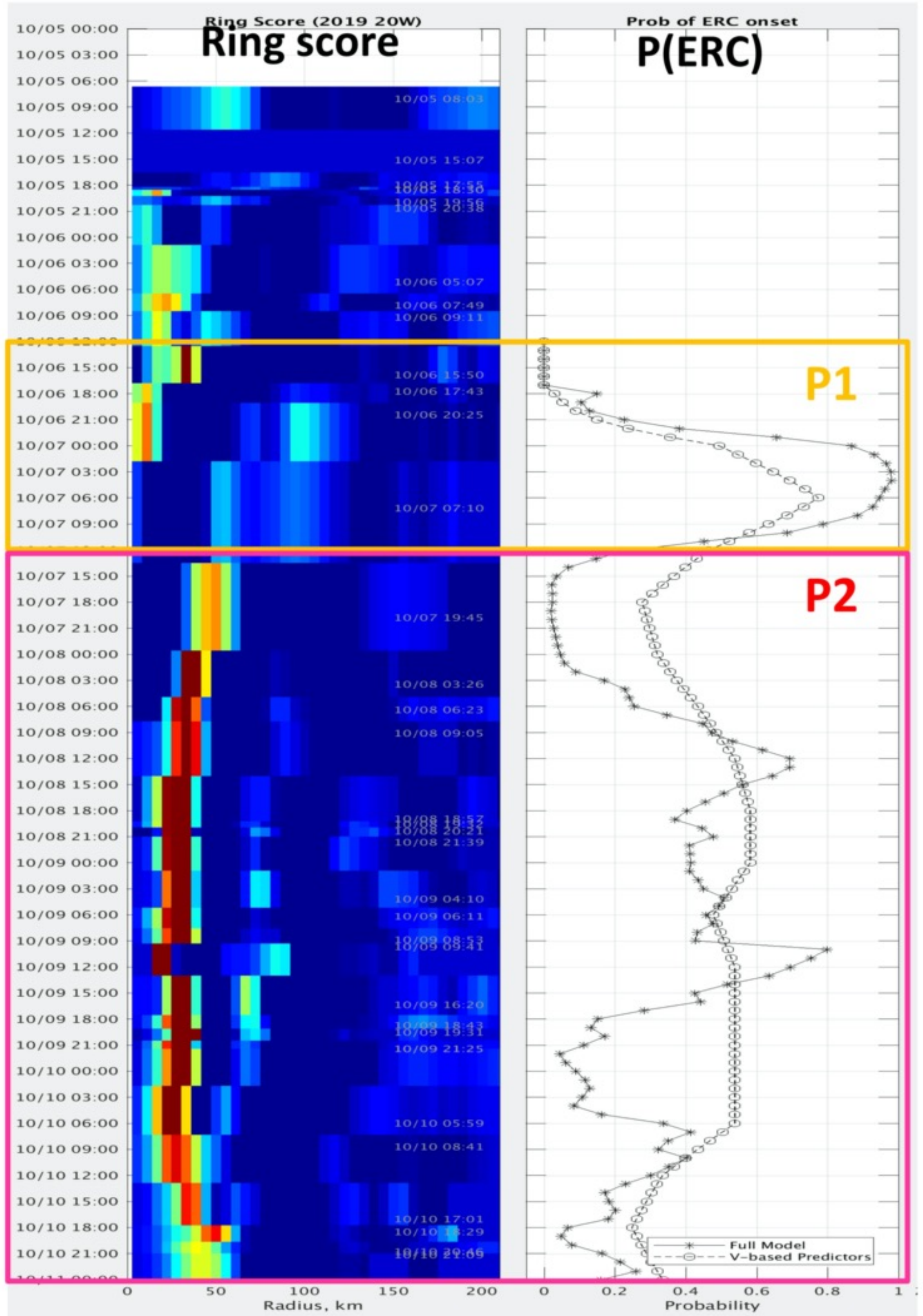
Hurricane Center (NHC), the WMO's Archive of Weather and Climate Extremes, a compendium of internationally accepted extremes (https://wmo.asu

MIMIC Animations

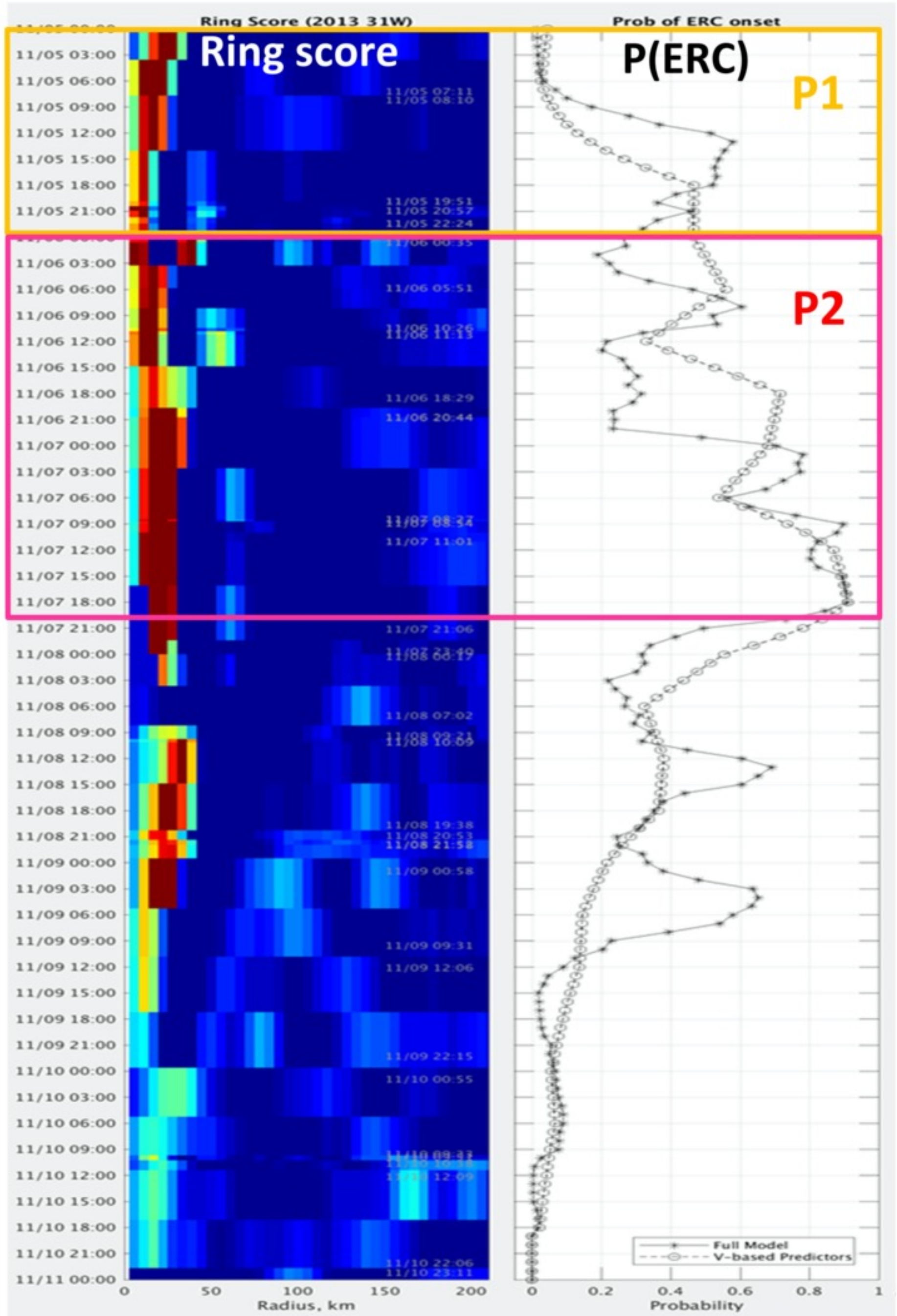
Hagibis
http://tropic.ssec.wisc.edu/real-time/mimtc/2019_20W/web/displayGifsBy12hr_07.html

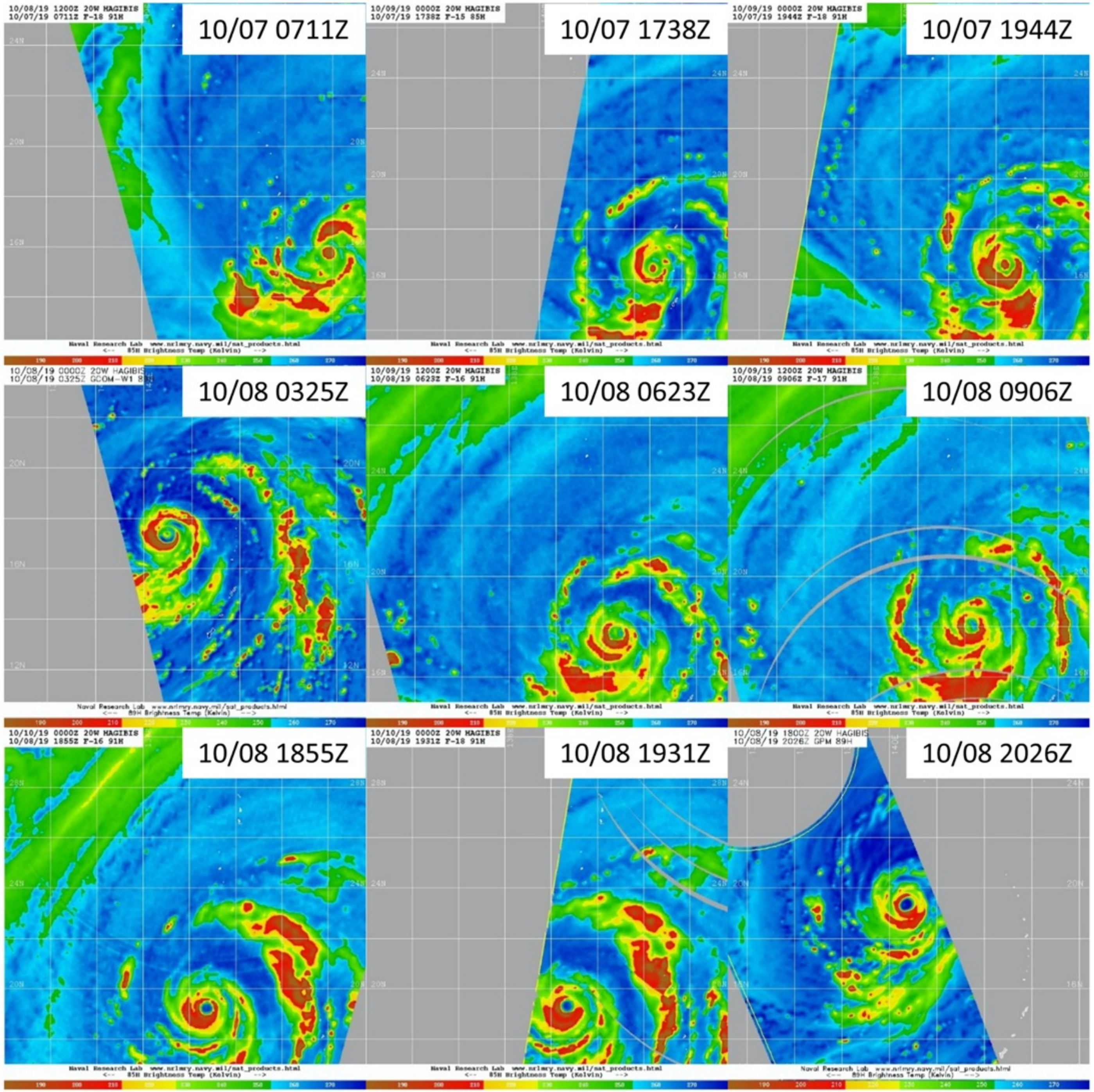
Haiyan
http://tropic.ssec.wisc.edu/real-time/mimic-tc/2013_31W/webManager/mainpage.html

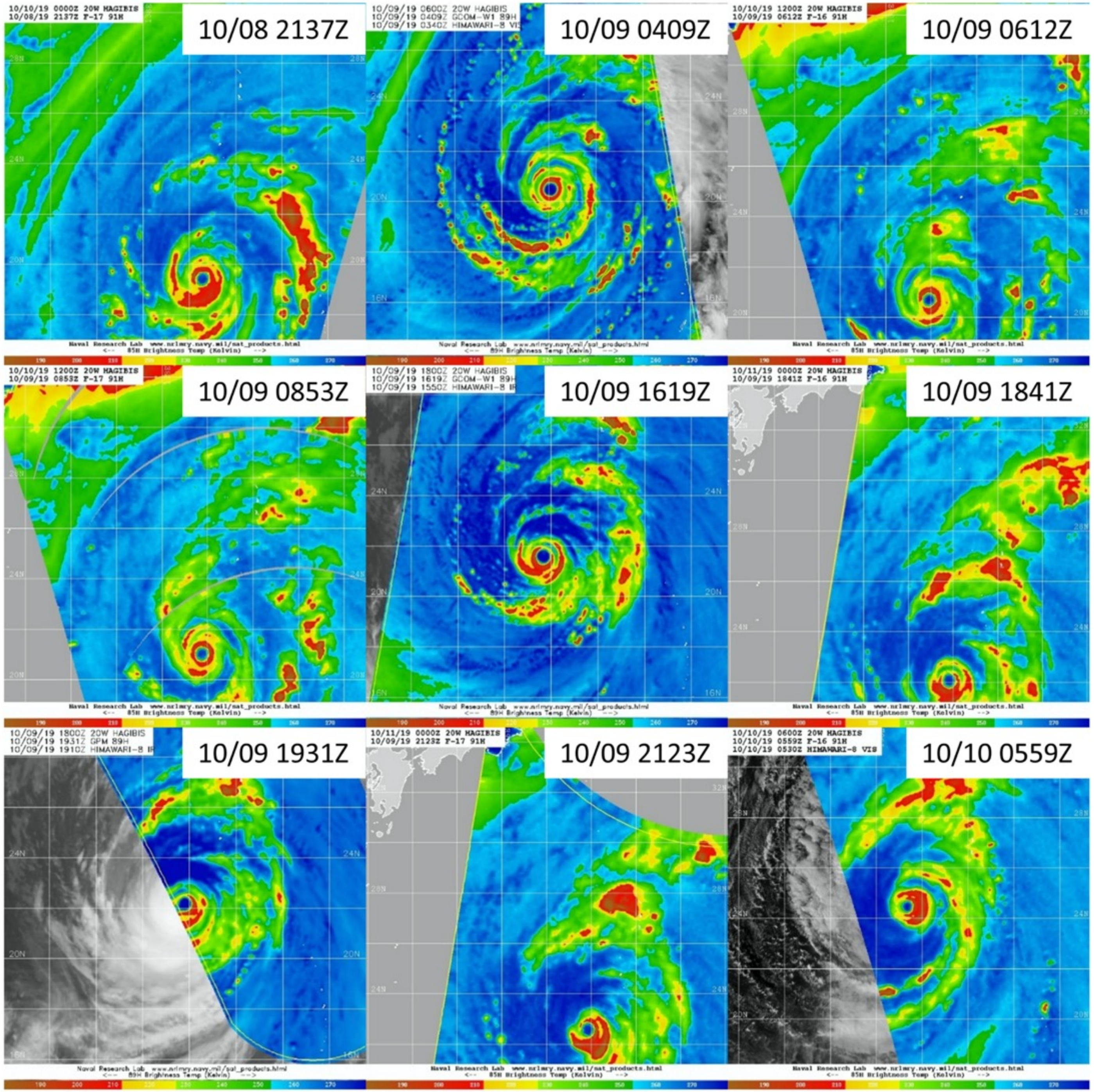
Hagibis

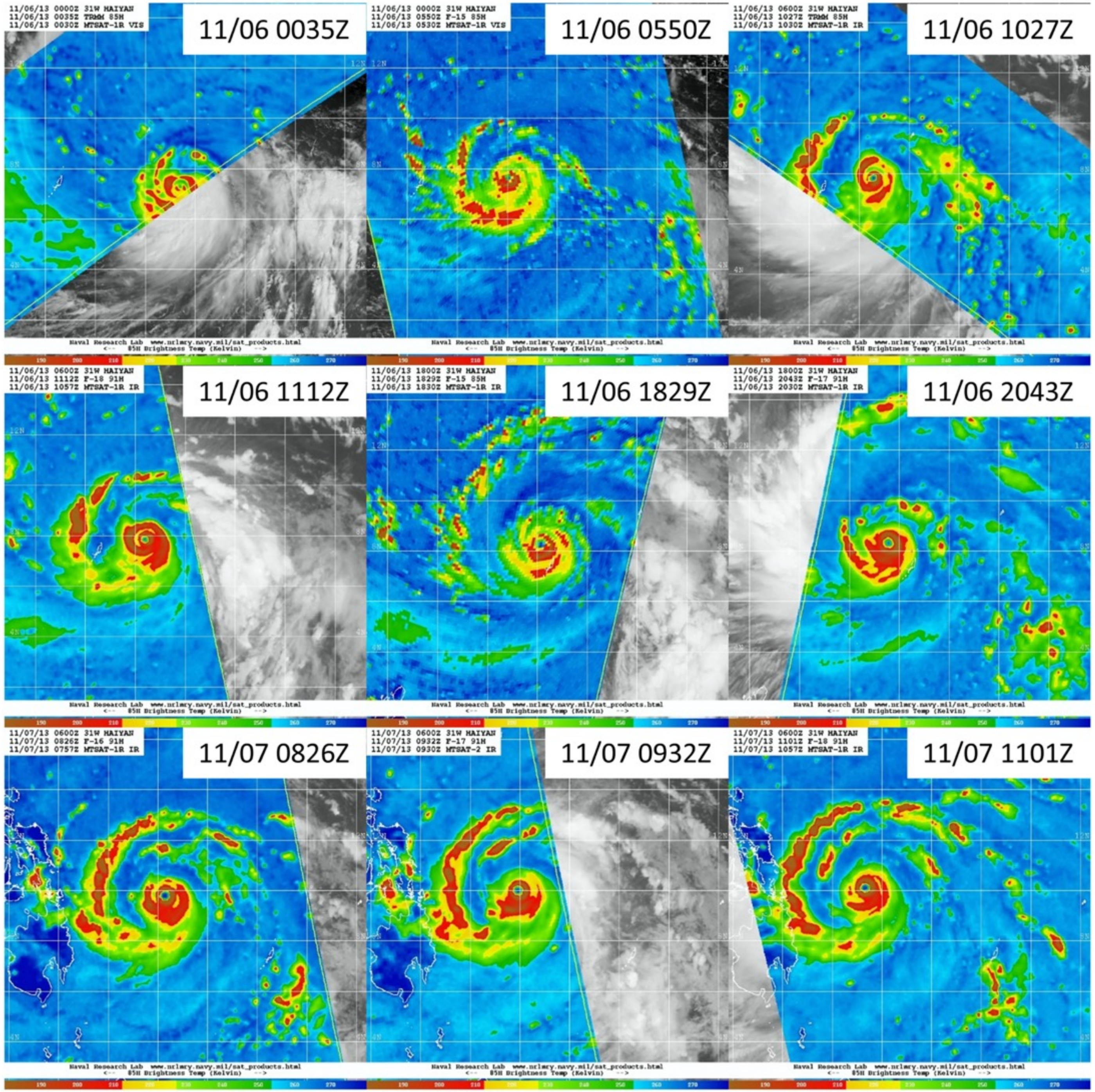


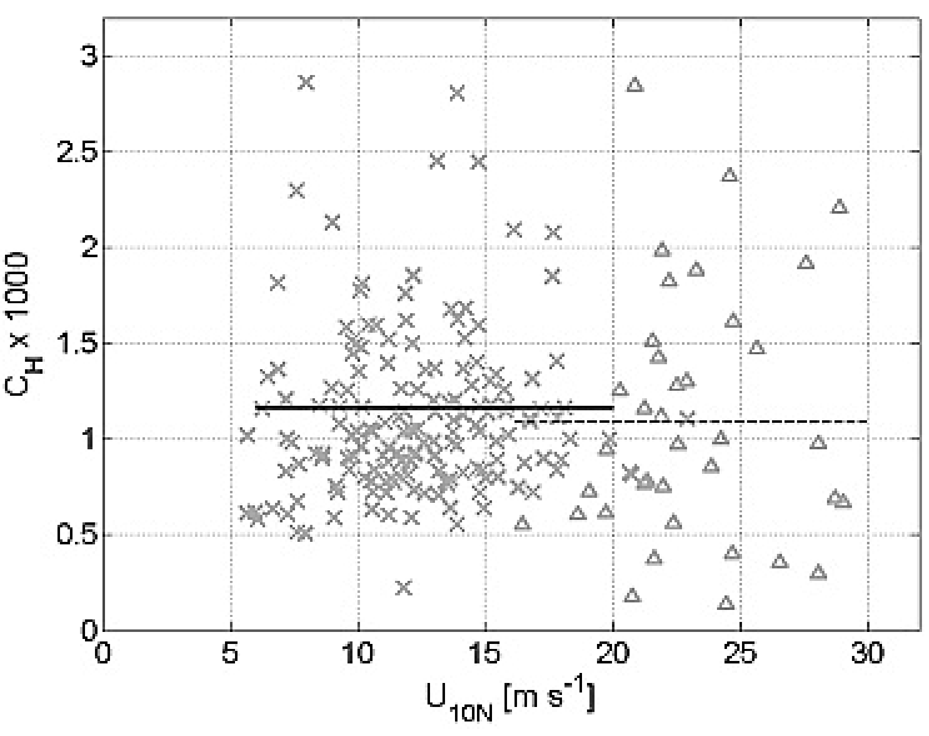
Haiyan

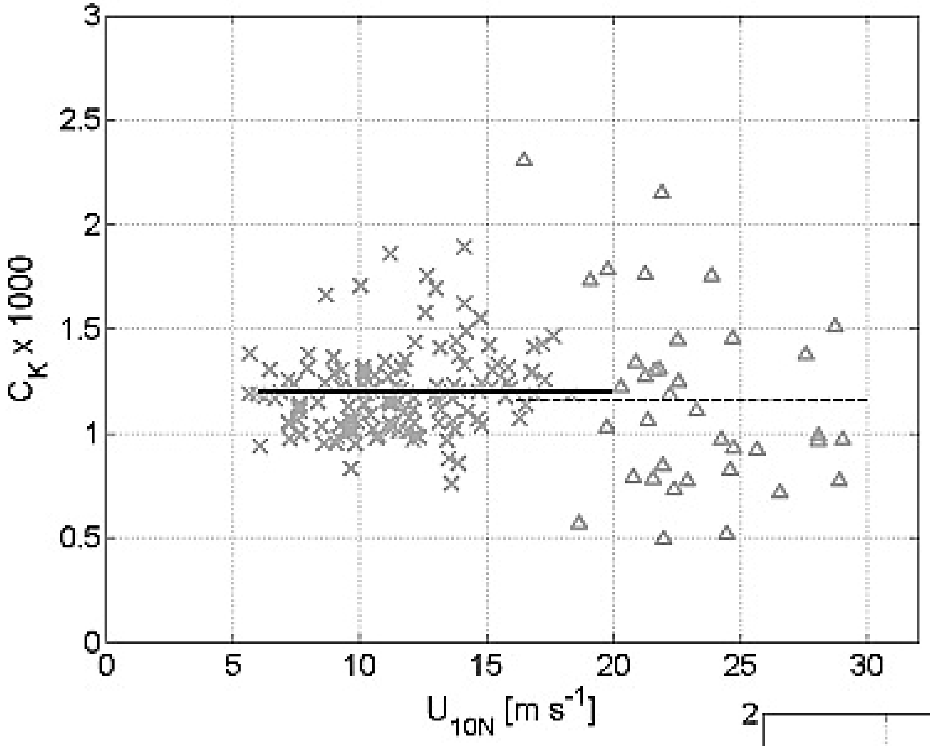


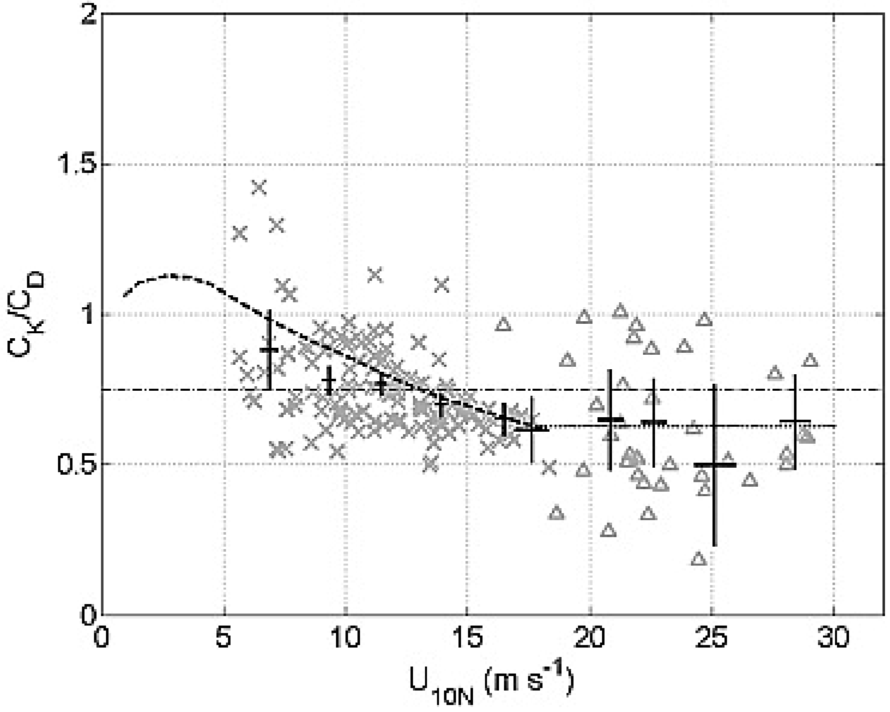

10/07 0711Z
10/07 1738Z
10/07 1944Z
10/08 0325Z
10/08 0623Z
10/08 0906Z
10/08 1855Z
10/08 1931Z
10/08 2026Z


10/08 2137Z
10/09 0409Z
10/09 0612Z
10/09 0853Z
10/09 1619Z
10/09 1841Z
10/09 1931Z
10/09 2123Z
10/10 0559Z


11/06/13 0000Z 31W HAIYAN
11/06/13 0035Z TRMM 85H
11/06/13 0030Z MTSAT-1R VIS
11/06 0035Z
11/06/13 0000Z 31W HAIYAN
11/06/13 0550Z F-15 85H
11/06/13 0530Z MTSAT-1R VIS
11/06 0550Z
11/06/13 0600Z 31W HAIYAN
11/06/13 1027Z TRMM 85H
11/06/13 1030Z MTSAT-1R IR
11/06 1027Z
11/06/13 0600Z 31W HAIYAN
11/06/13 1112Z F-18 91H
11/06/13 1057Z MTSAT-1R IR
11/06 1112Z
11/06/13 1800Z 31W HAIYAN
11/06/13 1829Z F-15 85H
11/06/13 1830Z MTSAT-1R IR
11/06 1829Z
11/06/13 1800Z 31W HAIYAN
11/06/13 2043Z F-17 91H
11/06/13 2030Z MTSAT-1R IR
11/06 2043Z
11/07/13 0600Z 31W HAIYAN
11/07/13 0826Z F-16 91H
11/07/13 0757Z MTSAT-1R IR
11/07 0826Z
11/07/13 0600Z 31W HAIYAN
11/07/13 0932Z F-17 91H
11/07/13 0930Z MTSAT-2 IR
11/07 0932Z
11/07/13 0600Z 31W HAIYAN
11/07/13 1101Z F-18 91H
11/07/13 1057Z MTSAT-1R IR
11/07 1101Z
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
85H Brightness Temp (Kelvin)







From CBLAST Exp. Zhang, Black et al. GRL 2008

M-PERC (Microwave-based Probability of Eyewall Replacement Cycle)

CIMSS Tropical Cyclones Page

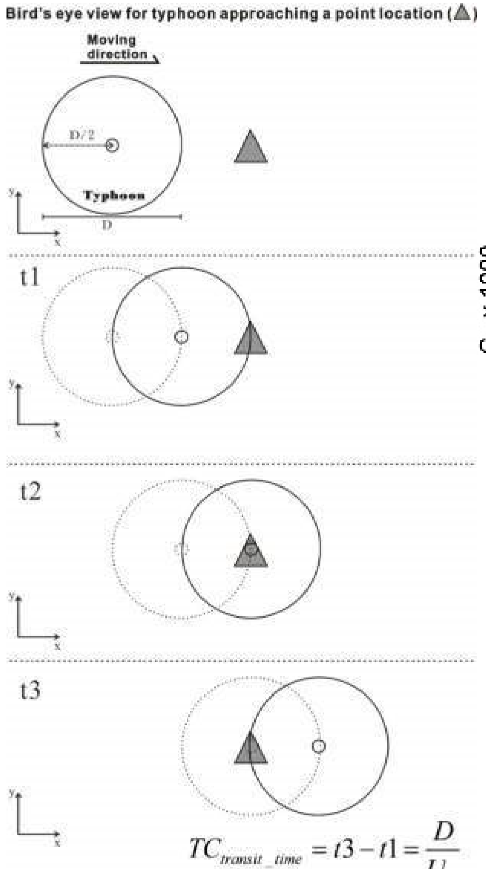
ERC archive dataset (1999-2011, 2016)

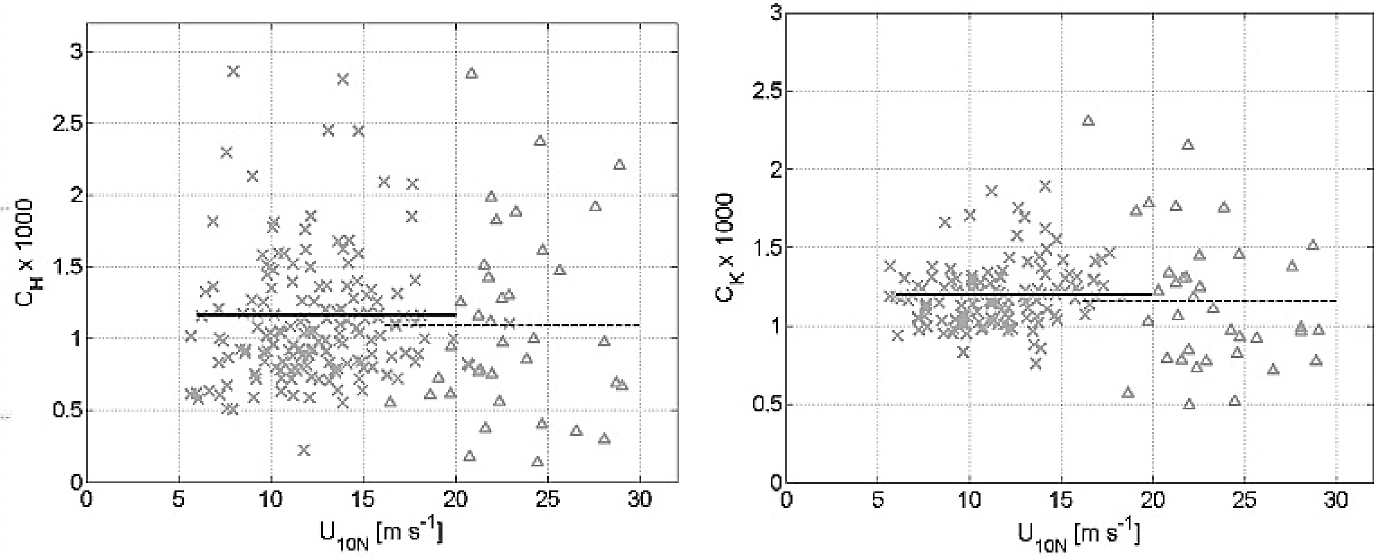
Cindy	1999_04L	Hovmoller	ARCHER Track
Dennis	1999_05L	Hovmoller	ARCHER Track
Floyd	1999_08L	Hovmoller	ARCHER Track
Gert	1999_09L	Hovmoller	ARCHER Track
Lenny	1999_16L	Hovmoller	ARCHER Track
Alberto	2000_03L	Hovmoller	ARCHER Track
Isaac	2000_13L	Hovmoller	ARCHER Track
Keith	2000_15L	Hovmoller	ARCHER Track
Erin	2001_06L	Hovmoller	ARCHER Track
Felix	2001_07L	Hovmoller	ARCHER Track
Michelle	2001_15L	Hovmoller	ARCHER Track

Data & Method-2 : Numerical Simulations & Air-Sea Flux Estimation

3-D PWP (Price-Weller-Pinkel, Price et al. 1986; 1994) Ocean Model
Drag Coefficient: high wind Cd, Powell et al. 2013
TC's Transit Time (Size in D50/Uh) at each 6hrly point.
Input: pre-TC Argo T/S profiles and JTWC max. intensity and wind profile shape

6 Experiments: 2 Observational + 4 Sensitivity Experiments (for Uh, Size, Uh+Size, Salinity)





From CBLAST Exp. Zhang, Black et al. GRL 2008

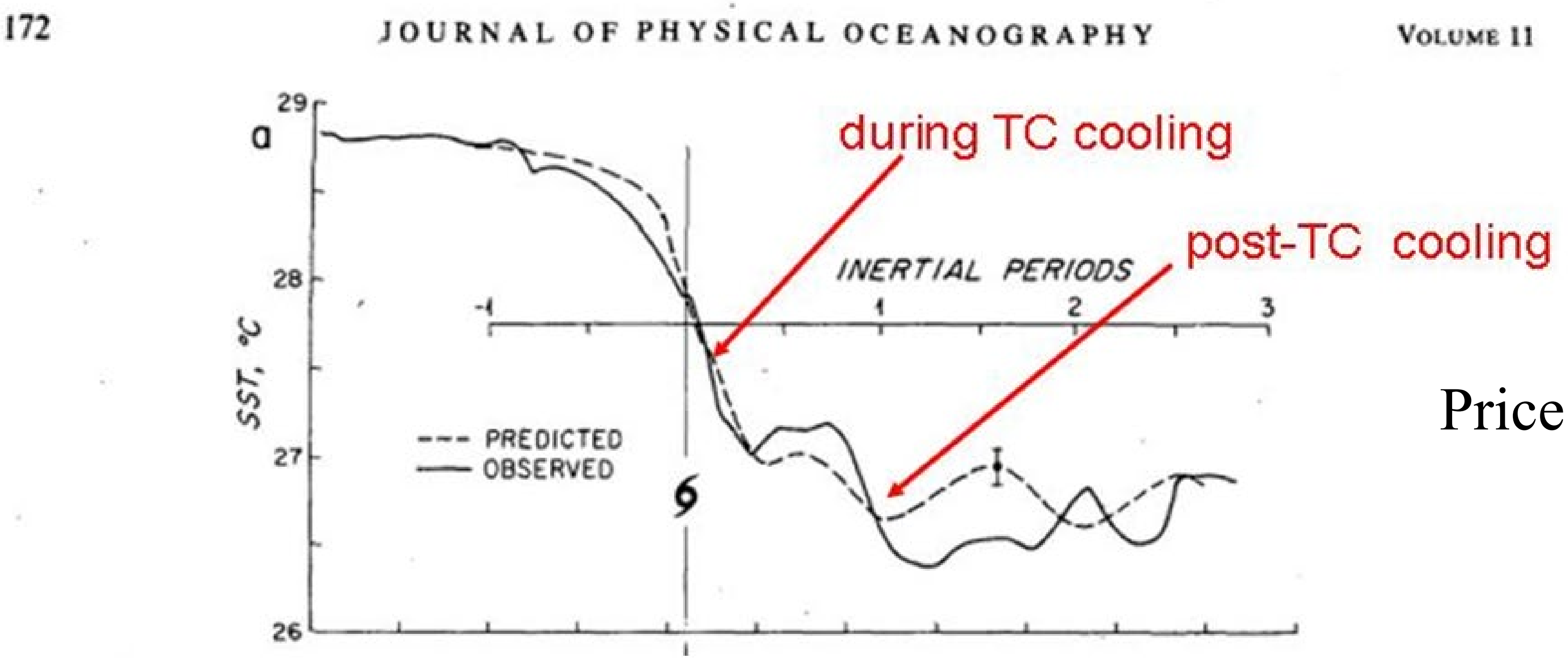
During-TC SST (Pre-TC minus cooling)

$$Q_S = C_H W (T_s - T_a) \rho_a C_{pa}$$

$$Q_L = C_E W (q_s - q_a) \rho_a L_{va}$$

Fcn. of during-TC SST

Lin et al. MWR 2008; JGR 2012, GRL 2013; Huang, Lin et al. Nature Comm. 2015



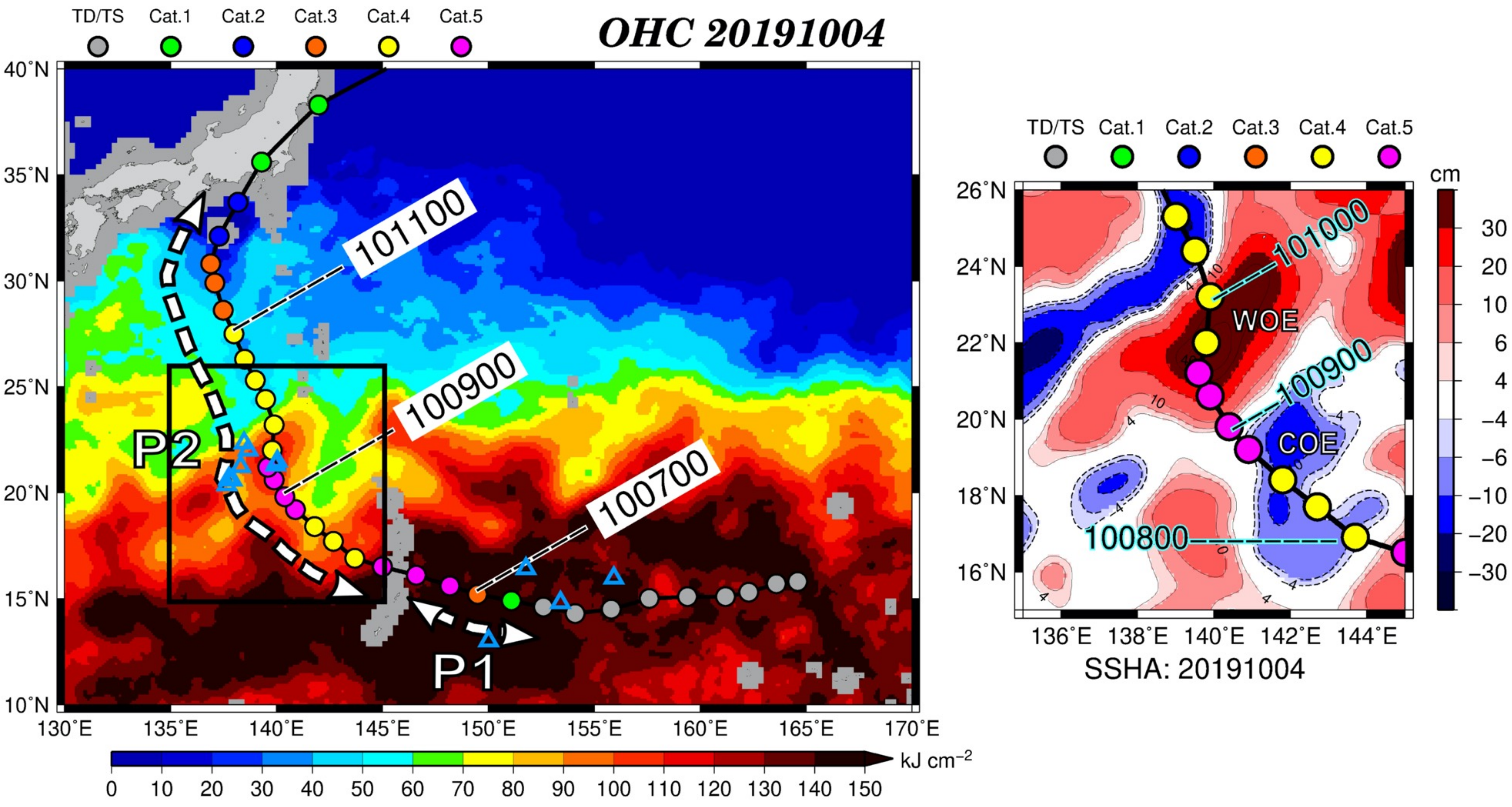
Price 1981

4 factors affect the cooling effect

- ***Pre-existing ocean T-S profile***
- ***TC wind speed***
- ***TC translation speed***
- ***TC size***

**** TC_transit time = D/Uh***

Lin et al. MWR 2009; Lin JGR 2012



TD/TS
Cat.1
Cat.2
Cat.3
Cat.4
Cat.5
OHC 20191004
101100
100900
100700
P2
P1
40°N
35°N
30°N
25°N
20°N
15°N
10°N
130°E
135°E
140°E
145°E
150°E
155°E
160°E
165°E
170°E
kJ cm^{-2}
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
TD/TS
Cat.1
Cat.2
Cat.3
Cat.4
Cat.5
cm
26°N
24°N
22°N
20°N
18°N
16°N
136°E
138°E
140°E
142°E
144°E
101000
100900
100800
WOE
COE
30
20
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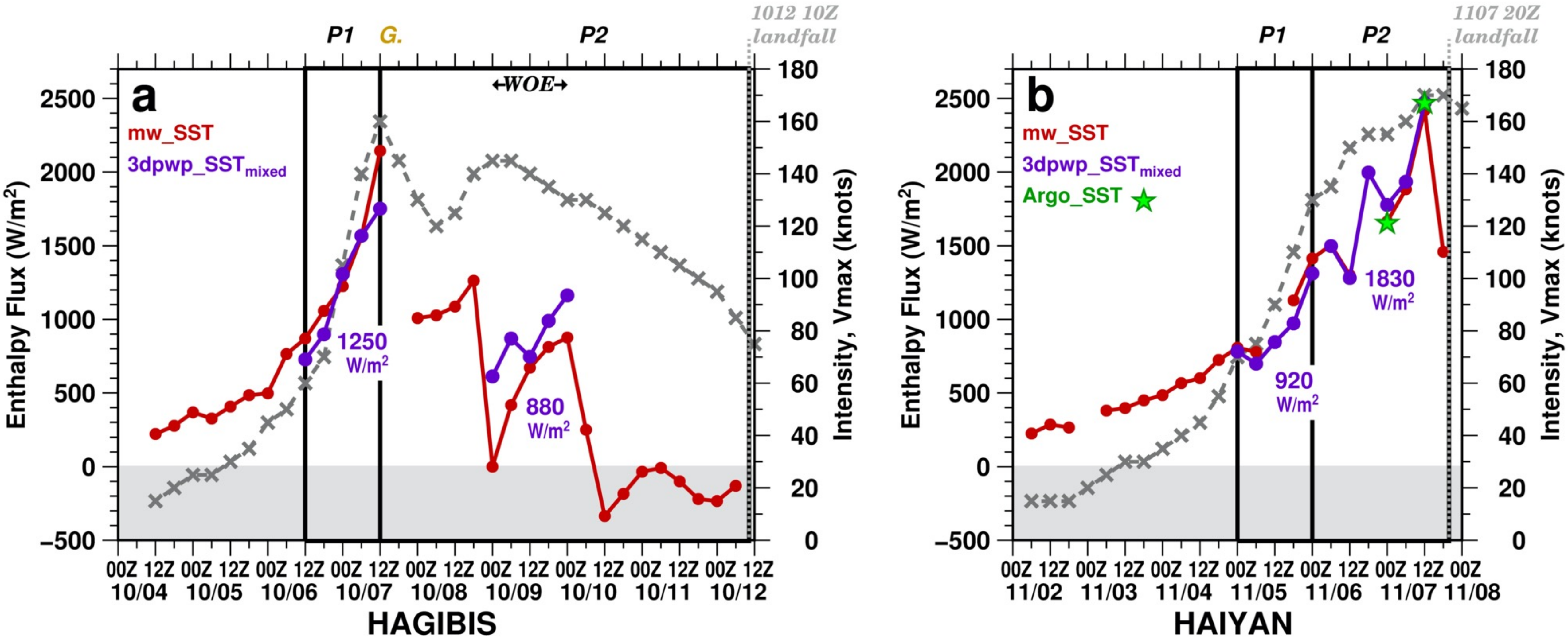
−20
−30
SSHA: 20191004



RI: 1250-920/920= 36%

Conclusions –ALL MULTIPLES FACOTRS MU;TIP

Conclusions

1. P1: Ocean cooling small for both STYs (fast Uh & TS profile), but Hagibis had really high pre-TC SST, so during-TC SST still maintain ~ 30° C .vs. ~ 29° C for Haiyan. 36% more flux for Hagibis. Strategic location of deep convection nearly coincident at center, rapid eyewall contraction (30km to 10km in 6h) -favouring Hagibis's Explosive RI

2. P2: Major size expansion for Hagibis (>200%, R34 ~520km), Haiyan remained compact. Proposed negative impacts on Hagibis's intensity: larger cooling (also slower Uh), slower ERCs, & possible reduction in radial inflow via enhanced inertial stability at outer core

3. Multi-scale interactions:
   - Change in vortex-scale properties (e.g., size) to impact TC intensity via interacting with large-scale ocean environment & ocean sub-surface pathway
   - Size change may impact TC intensity via ERC pathway
   - Configuration of convective-scale feature, e.g., ice scattering at TC center may associate with vortex-scale rapid eyewall contraction to favour RI

Nature's fascinating and co-existing cross-scale interaction pathways:
Delicate Control on TC Intensity