# 1. Climate-Scale Study:

## Change in Tropical Cyclone (TC) Translation Speed in the South China Sea and Implication on TC Intensity

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

*Chang et al. Sustainability, 2020 (Kossin Nature 2018)*

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# 2. Weather-Scale Study:

## The Explosive Intensification of Super Typhoon Hagibis (2019)

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

*Lin et al. BAMS, Sep. 2021*

a natureresearch journal

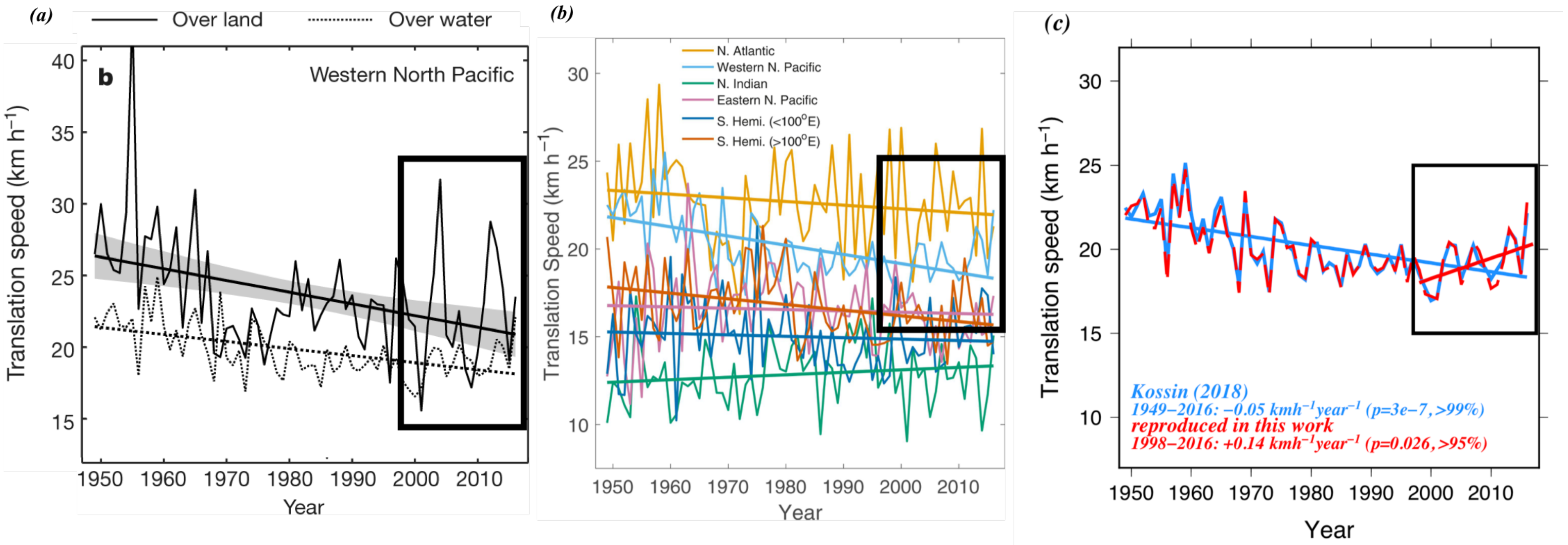
nature

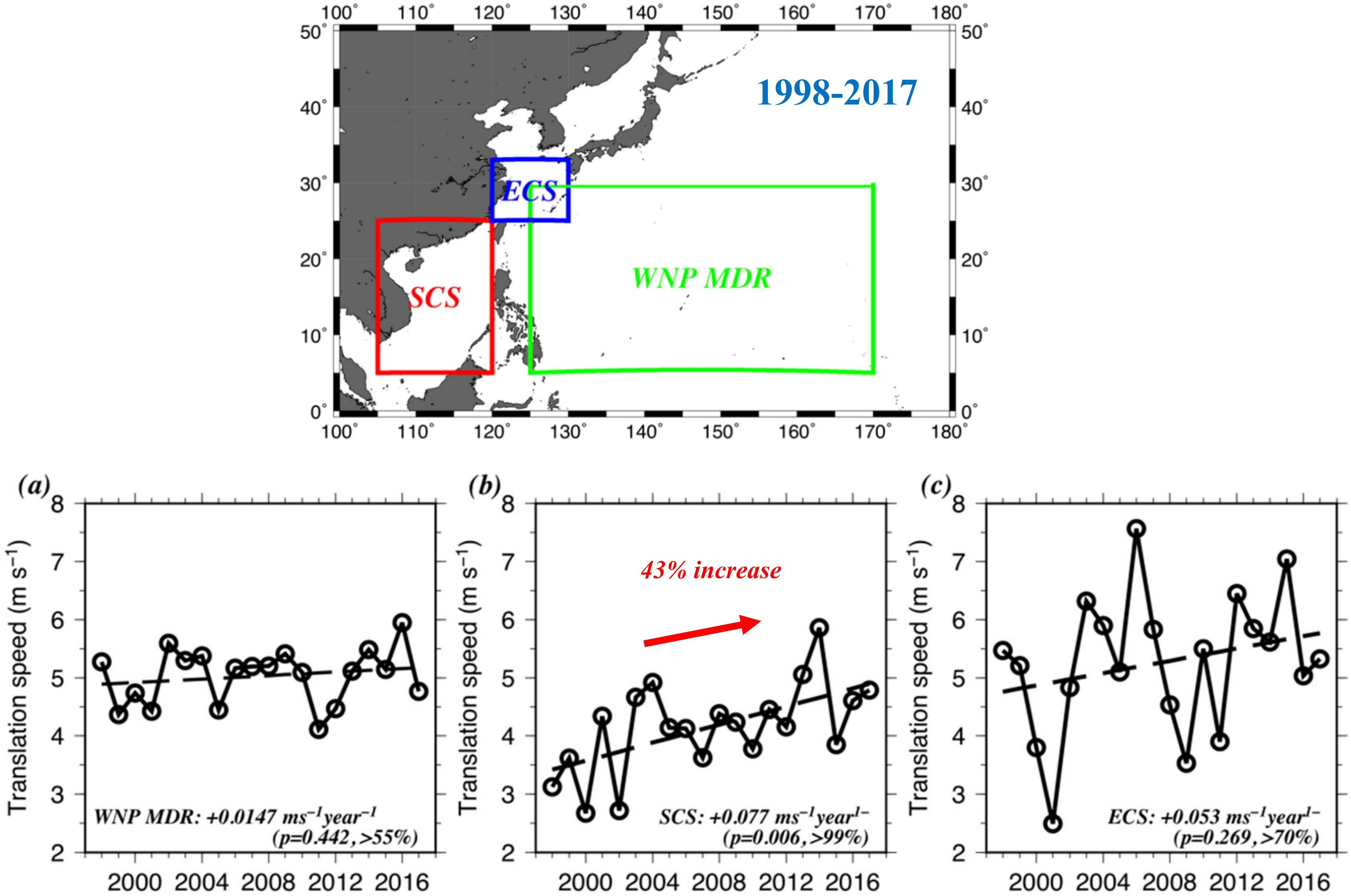
Letter | Published: 06 June 2018

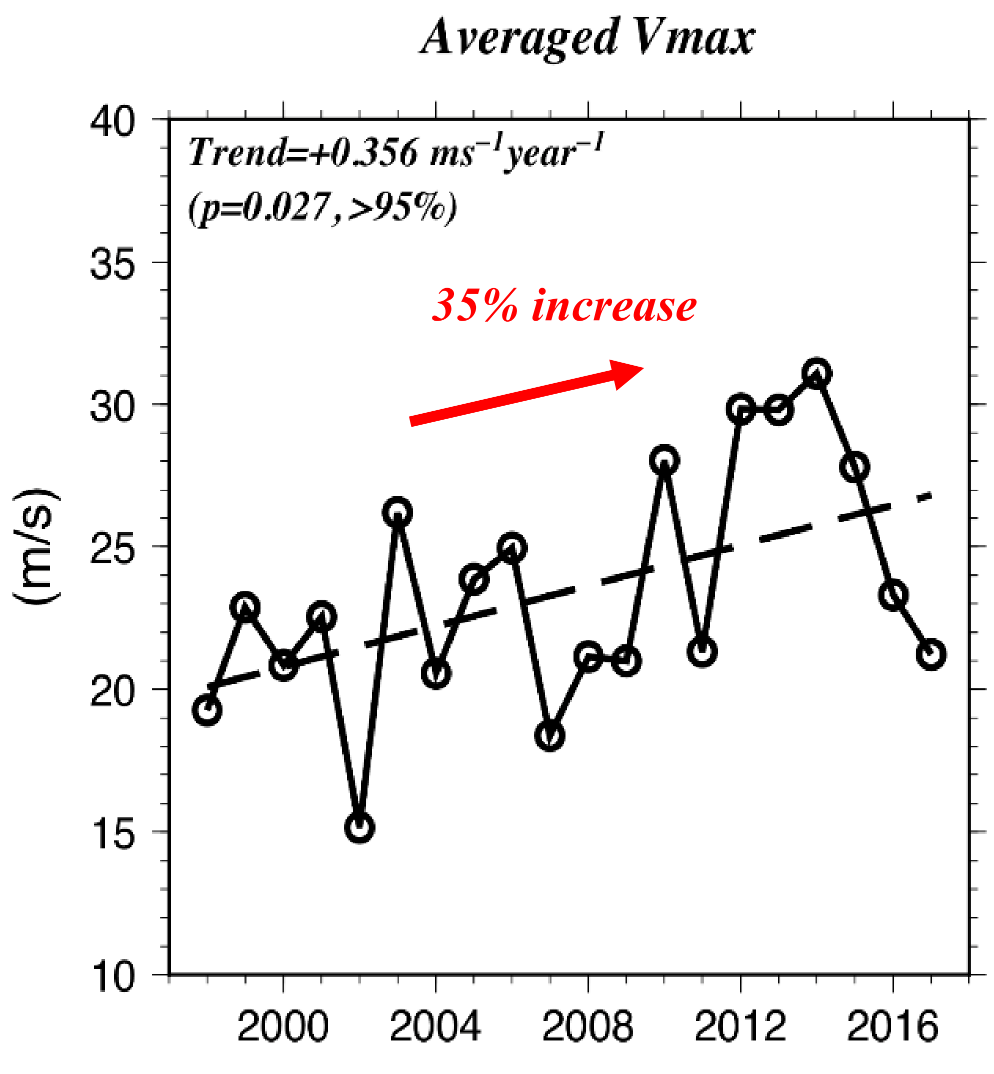
# A global slowdown of tropical-cyclone translation speed

James P. Kossin

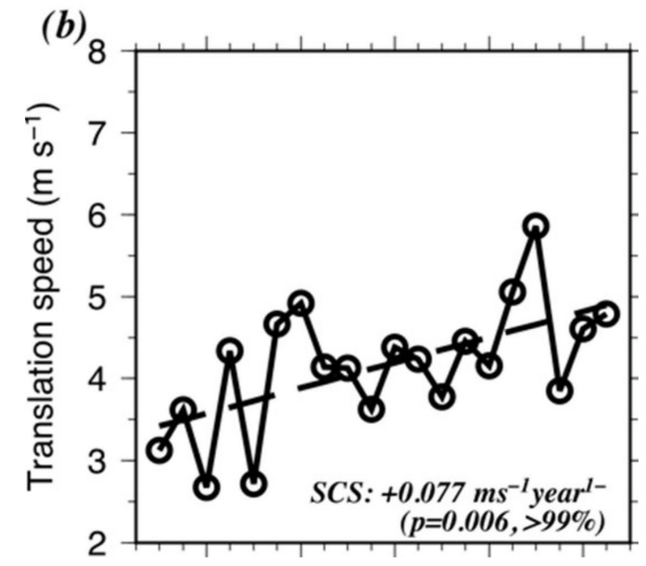
*Nature* **558**, 104–107(2018) | Cite this article

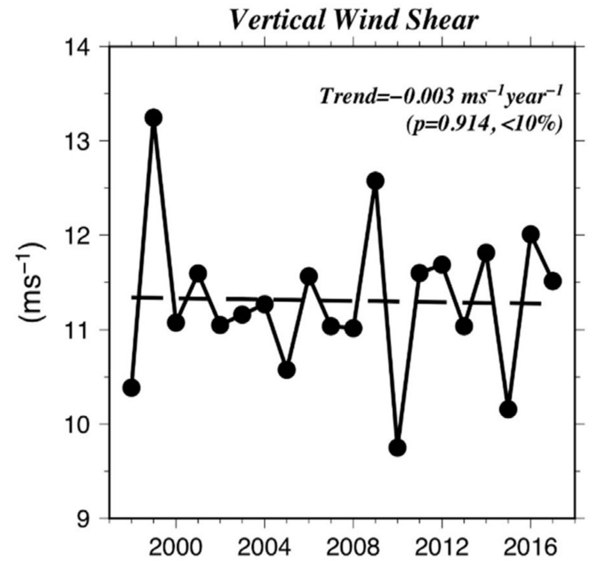


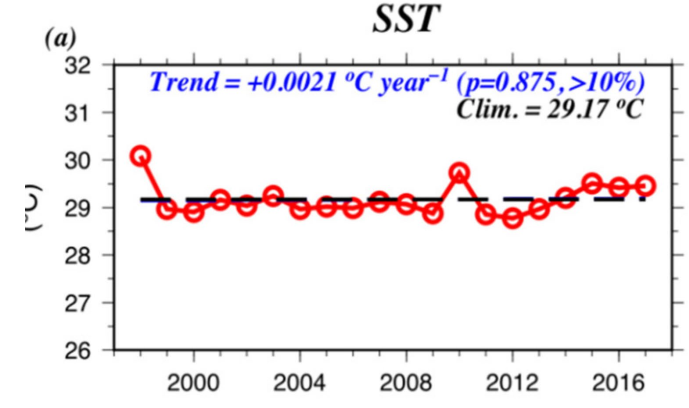

1998-2017
ECS
SCS
WNP MDR
(a)
WNP MDR: +0.0147 ms⁻¹year⁻¹
(p=0.442, >55%)
Translation speed (m s⁻¹)
(b)
43% increase
SCS: +0.077 ms⁻¹year¹⁻
(p=0.006, >99%)
(c)
ECS: +0.053 ms⁻¹year¹⁻
(p=0.269, >70%)

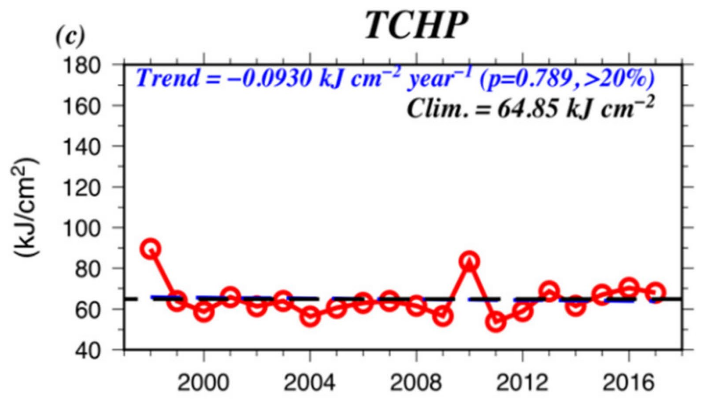


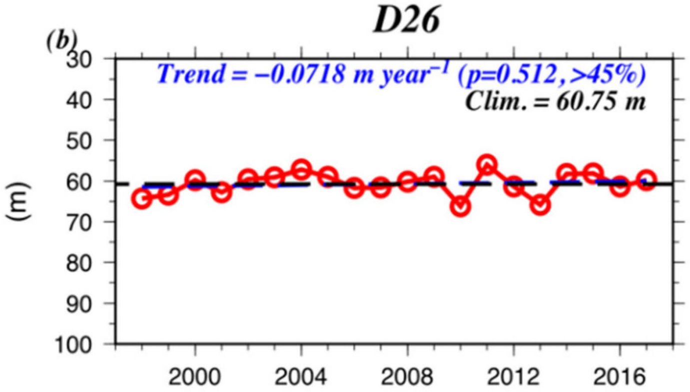

Chang et al. 2020

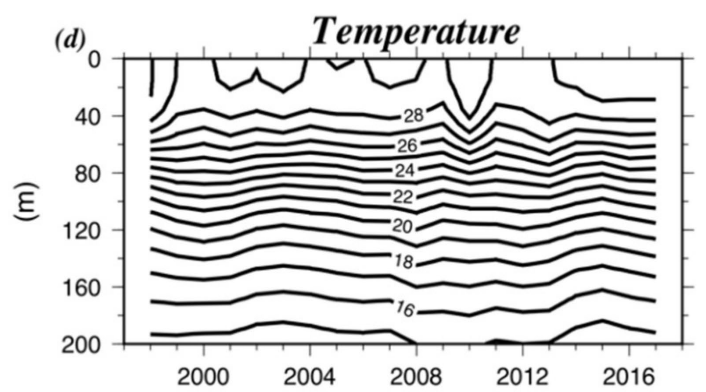


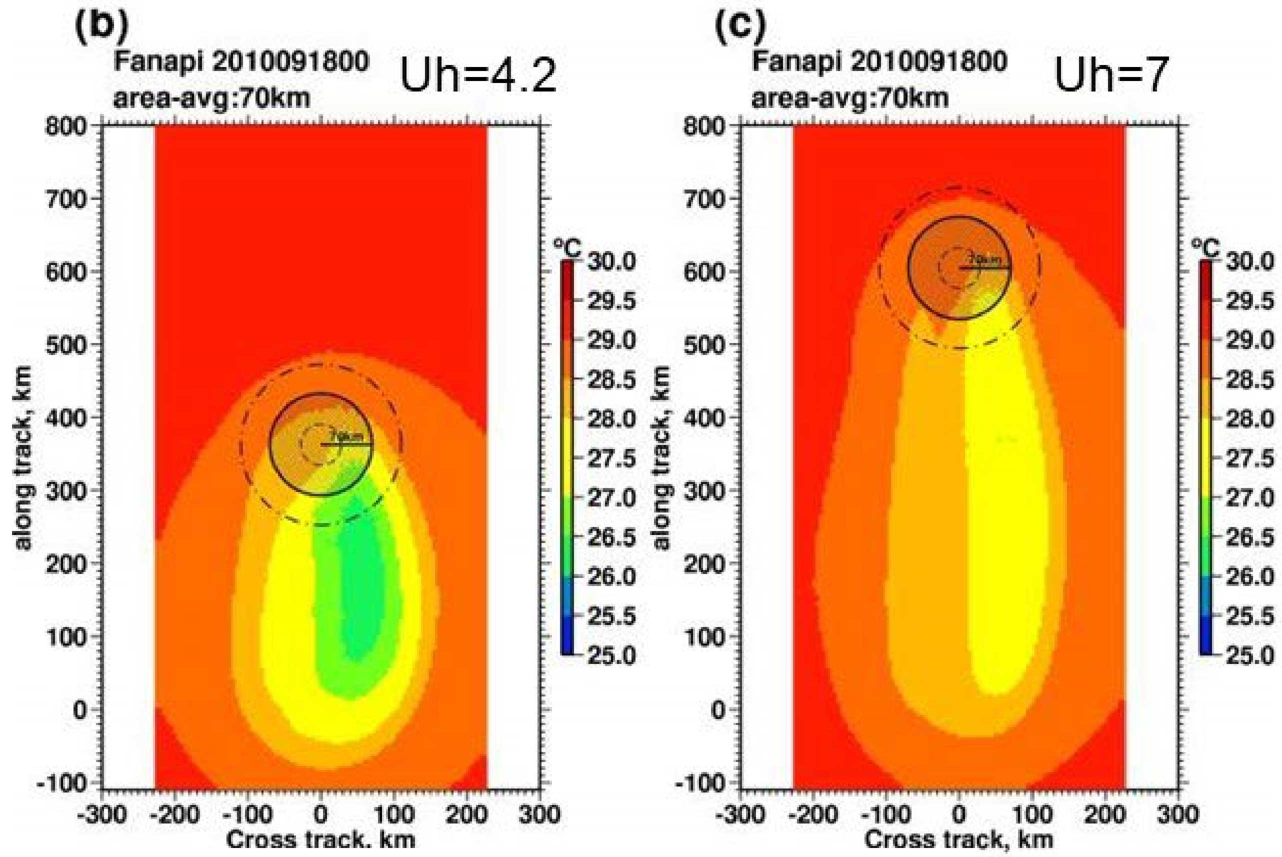



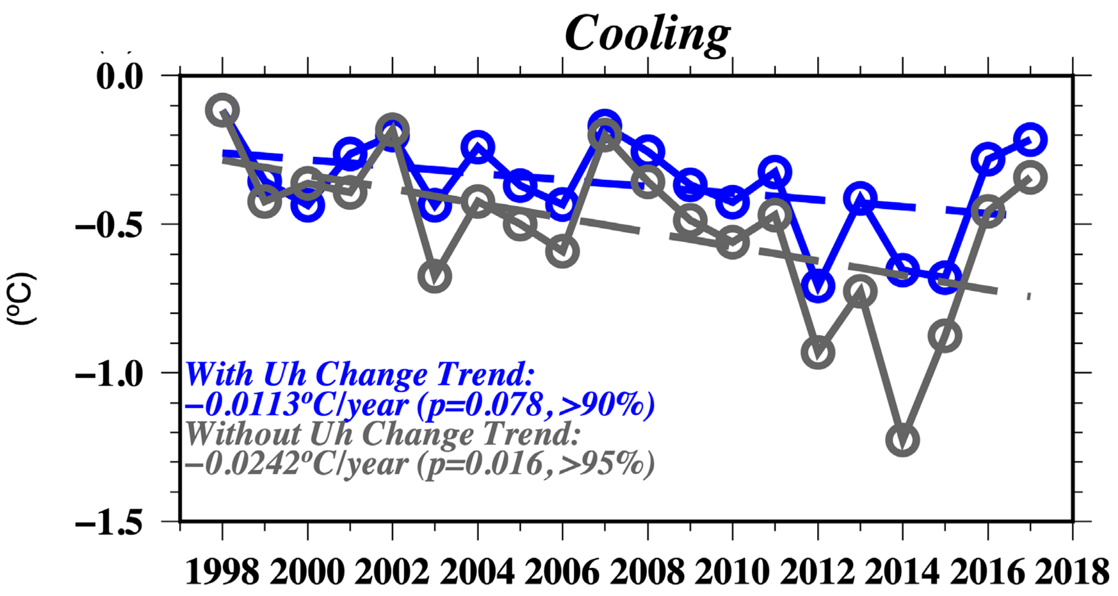



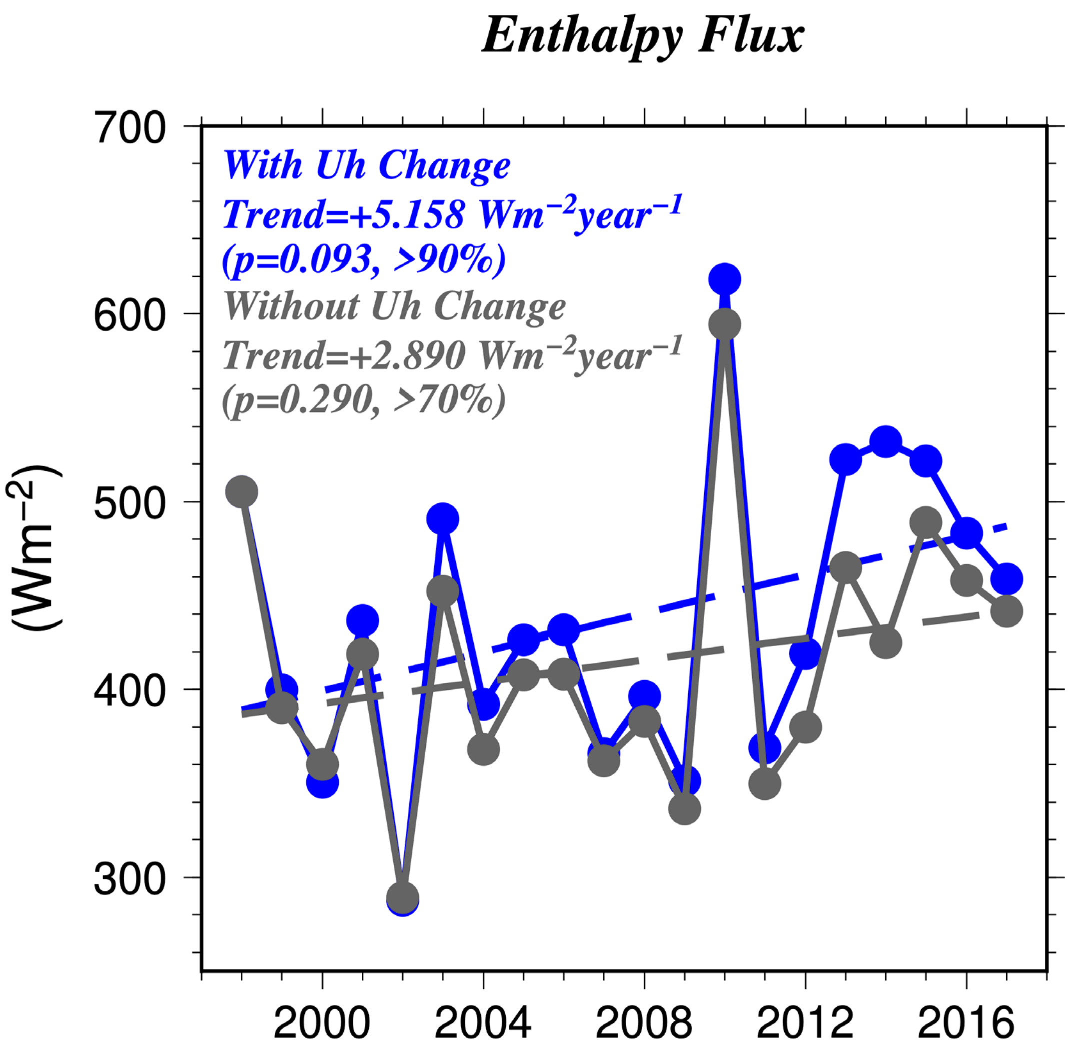






**Lin et al. GRL 2013**




| Vmax V. S. | corr. Coeff. | p-Value |
|---|---|---|
| Uh | 0.553 | 0.011, >95% |
| SST | 0.010 | 0.965, < 5% |
| D26 | 0.212 | 0.370, >60% |
| TCHP | 0.131 | 0.583, >40% |
| VWS | -0.0956 | 0.6886, >30% |
| cooling with Uh change | 0.615 | 0.004, >99% |
| cooling without Uh change | 0.236 | 0.317, >65% |




Chang et al. 2020

# Conclusion for Part 1

*TC Translation Speed (Uh) in the SCS increase by 43% from 1998 to 2017 with statistical significance.*

*TC intensity also increase by 35% in the same time, with significance.*

*Among all parameters tested, Uh and TC intensity has the highest correlation (~ 0.6). It appears that fast Uh likely to be a positive contributor to TC intensity* increase in the SCS.

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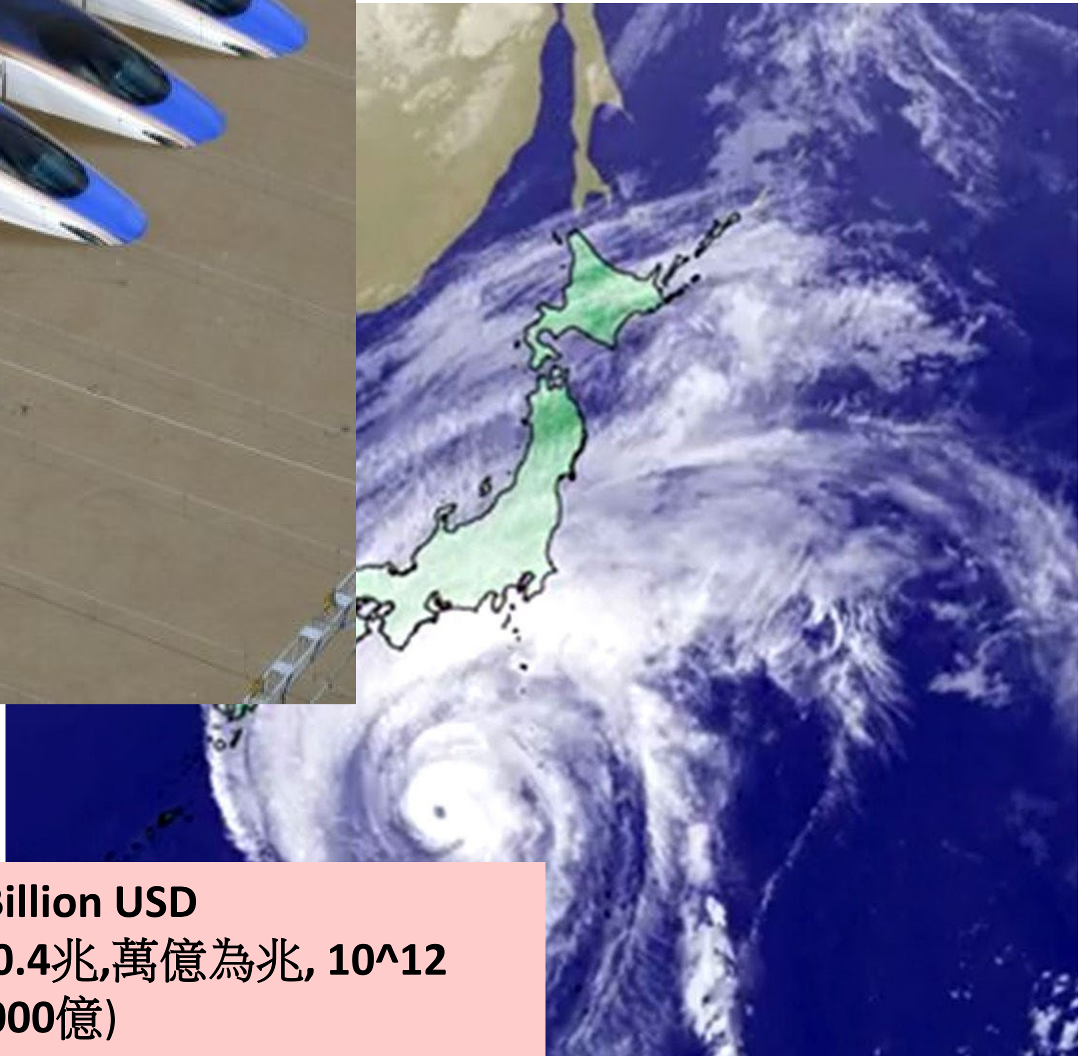
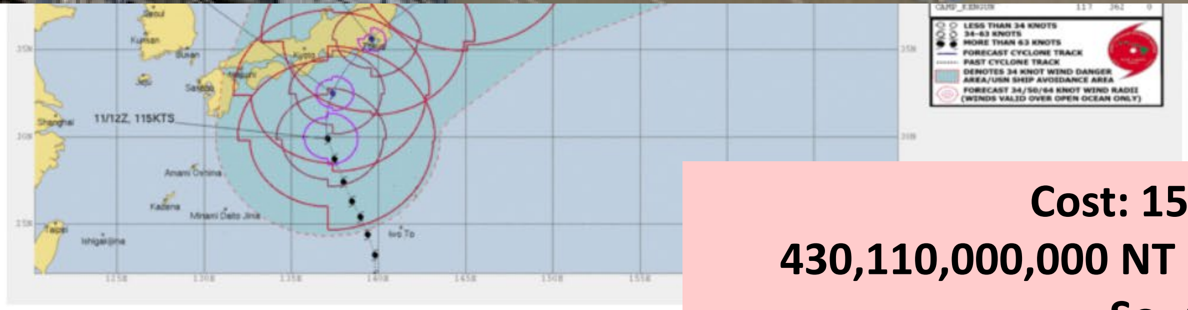
**Question:**

**Why SCS Uh increases so much in 1998-2017? PDO?**

# Supertyphoon Hagibis (Oct. 2019)






The forecast track from the Joint Typhoon Warning Center predict

**Cost: 15 Billion USD**
**430,110,000,000 NT (0.4兆,萬億為兆, 10^12**
**So, 4000億)**

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

Typhoon Haiyan

Print edition

# Worse than hell

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

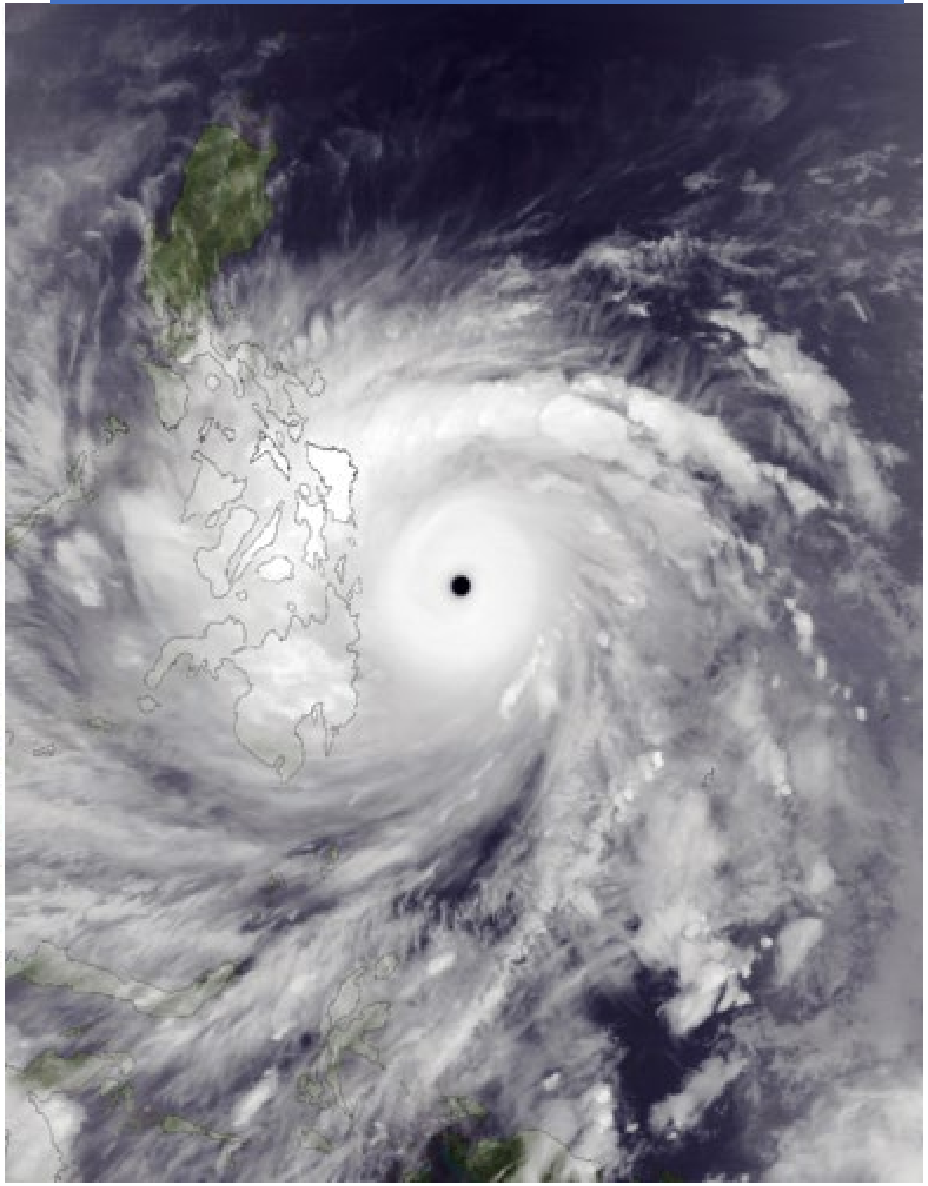
Nov 16th 2013 | CEBU, HANOI AND MANILA | From the print edition

Timekeeper | Like 33 | Tweet 37


**Record holder**

Lin et al. 2014
Mori et al. 2014
Lagmay et al. 2015

**Cat. '6', Haiyan (海燕颱風): 170kts!**



**Death: 6300; Injured: 28689;**

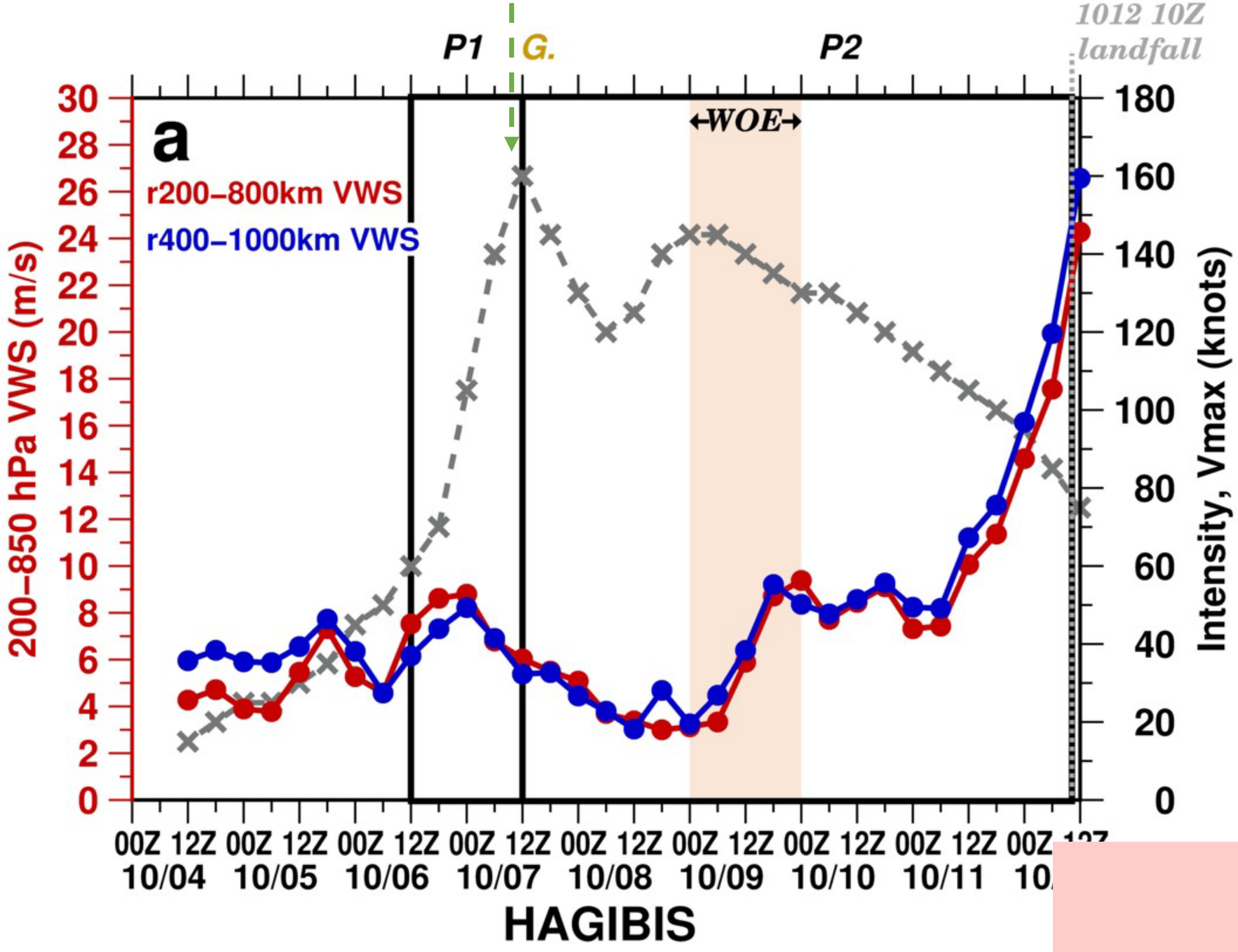
**Damage : US $ 2,051,710,653 (2 billion)**

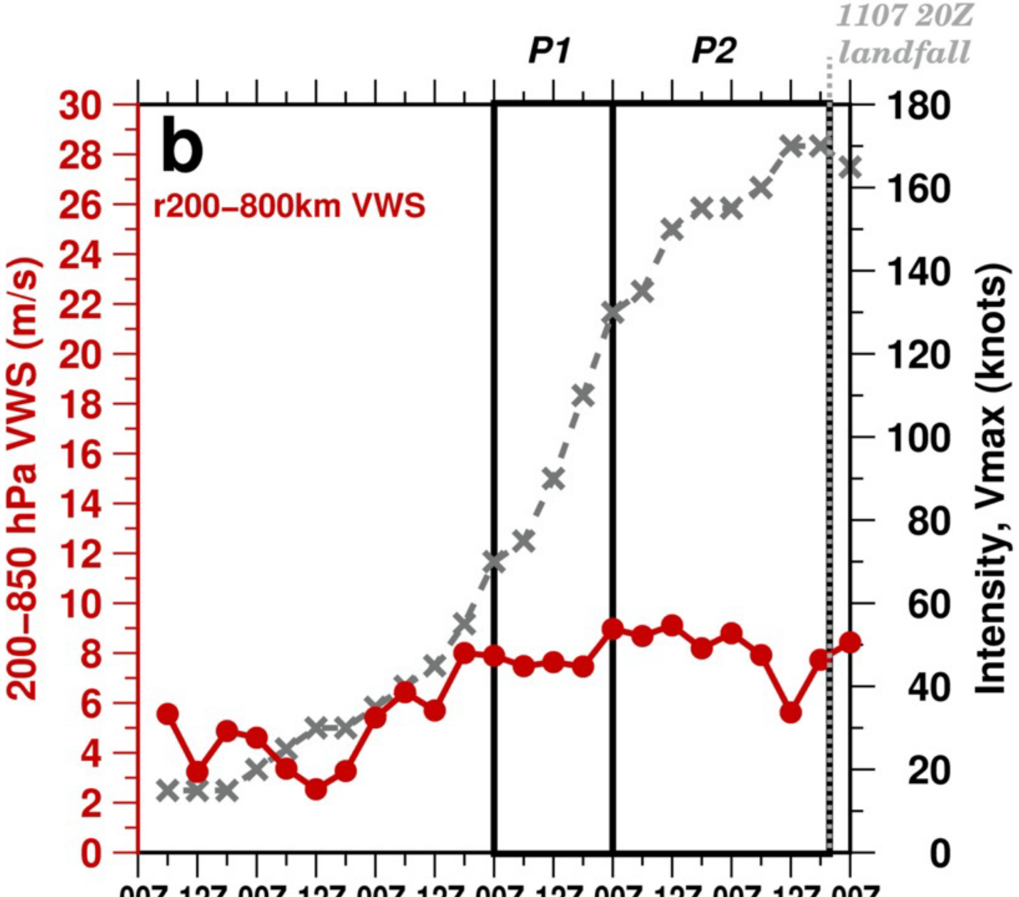
**http://en.wikipedia.org/wiki/Typhoon_Haiyan**

100 kt RI in 24h (Explosive RI,
333% of the RI Threshold (30kt)!, Kaplan & DeMaria 2003)
.vs. Patricia’s 105 kt RI in 24h (Rogers et al. 2017)

LMI: 170kts

60 kt RI in 24h for Haiyan




# 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 | 83-95 | 6,889 | 571,787 |
| 3 | 96-113 | 9,216 | 884,736 |
| 4 | 114-135 | | |
| 5 (Katrina) | >135 - 159 | | |
| **'Cat 6'?** | **>=160 (170)** | **28,900** | **4,913,000** |

Annotations between rows (winds): *19*, *13*, *18*, *22*, *25*

Annotations between rows (V^2): *x1.7*, *x1.3*

Annotations between rows (V^3): *x2.2*, *x1.5*

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

**.vs.**

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

# TC Intensification

1. **Large-Scale Atmospheric Environment: Vertical Wind Shear (VWS) & RH (Relative Humidity); 200-800km Ring/400-1000km Ring**

2. **Large-Scale, Pre-TC Ocean (SST, Ocean Heat Content (OHC)) & During-TC, Local-Scale Air-Sea Interaction (During-TC Cooling and Air-Sea Sensible and Latent Heat Fluxes**

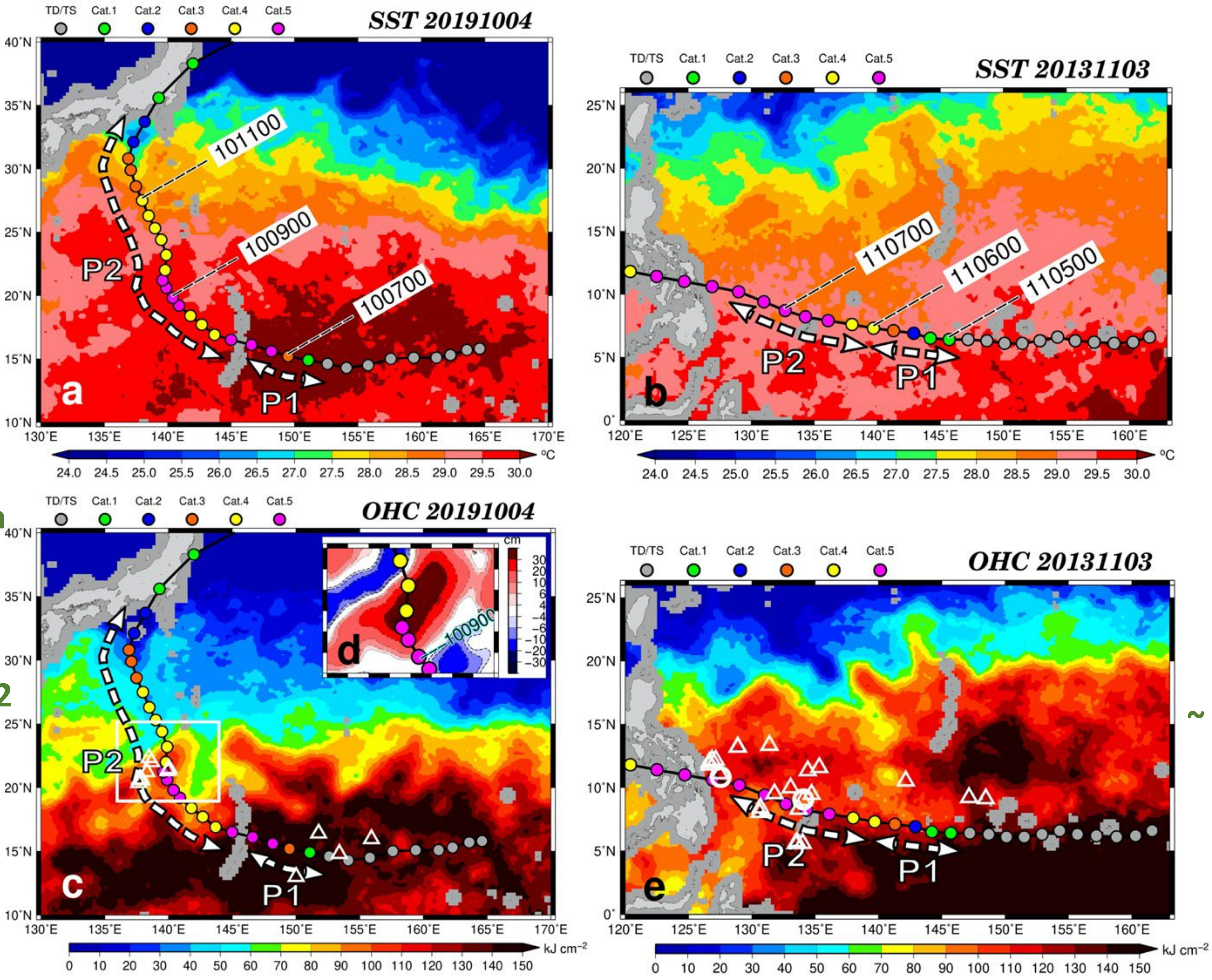
3. **Vortex-Scale TC Properties & Convective-Scale Features: Uh (Translation Speed), Size (RMW, R64, R50, R34], Eyewall Replacement Cycle (ERC), Convective-Scale Features (Radial Location of Deep Convection)**

# P1

~ 30-30.5° C
Pre-TC SST

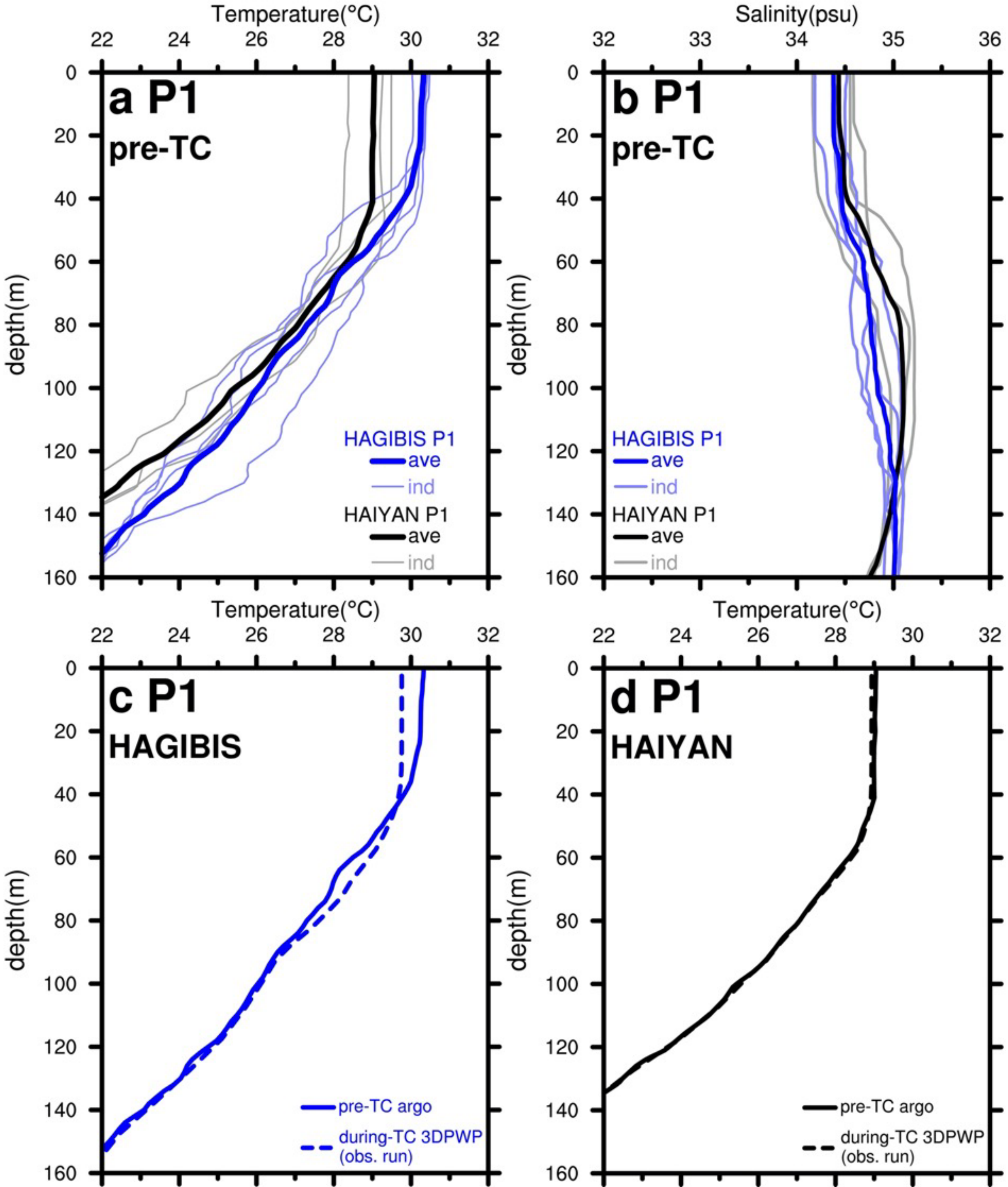
One of the best ever observed. Even better than Haiyan

~ 140-160 kJ/cm2
Pre-TC OHC




~ 29-29.5° C
Pre-TC SST

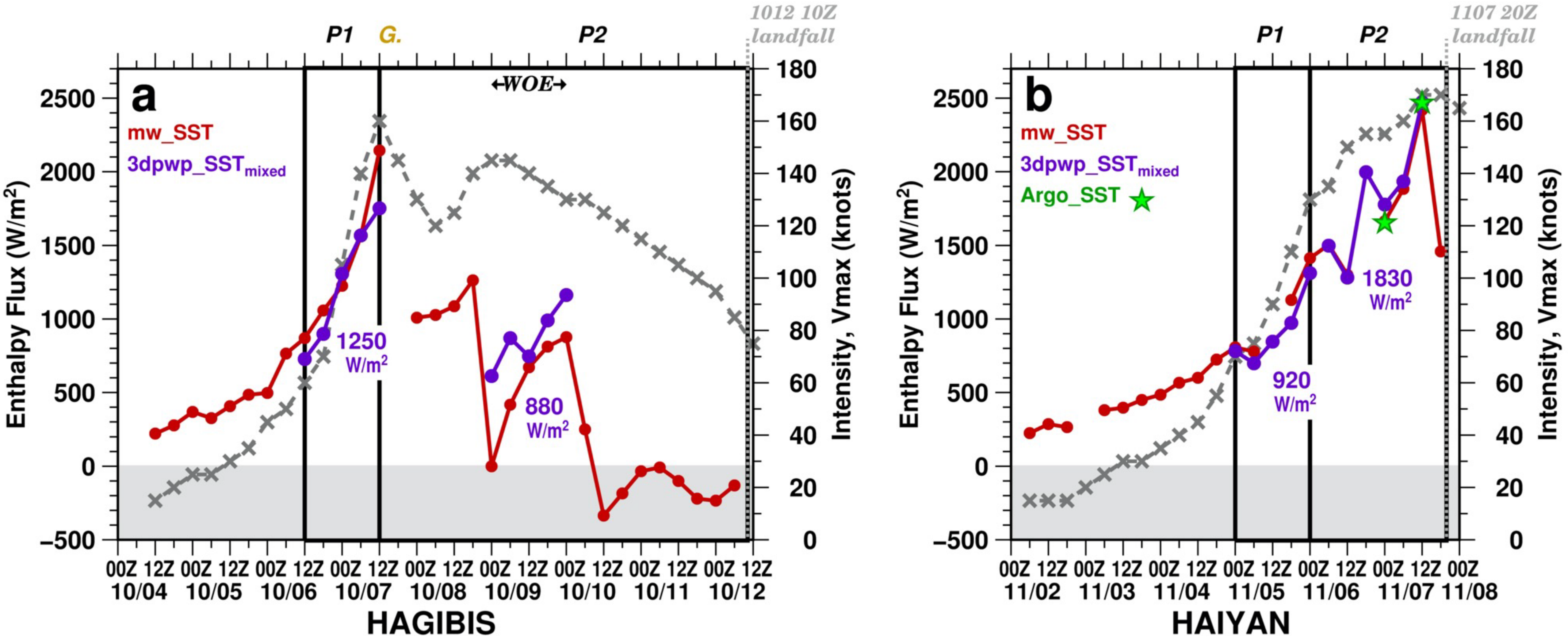
~ 115-135 kJ/cm2
Pre-TC OHC



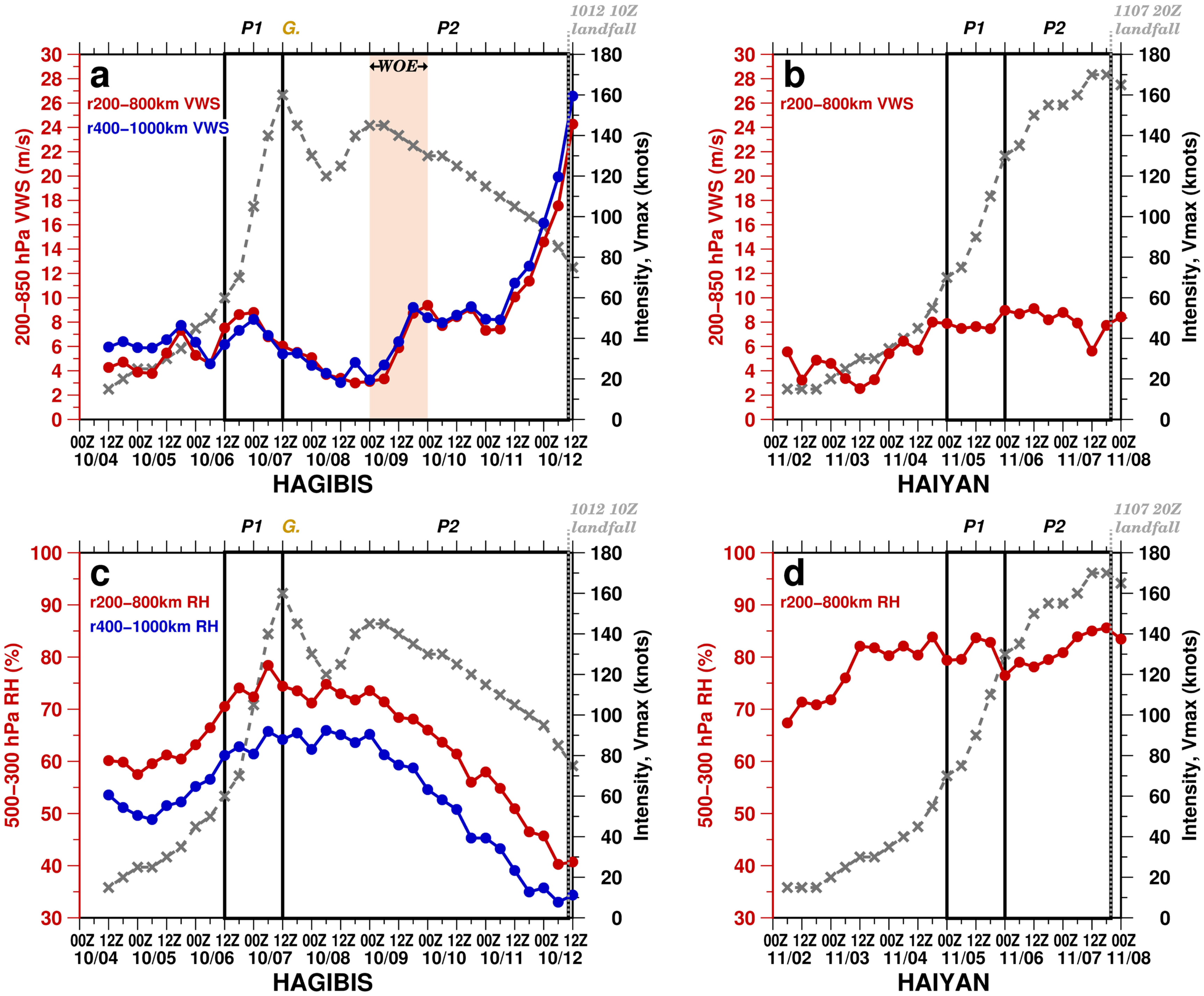
Temperature(°C)
a P1
pre-TC
depth(m)
HAGIBIS P1
ave
ind
HAIYAN P1
ave
ind
Salinity(psu)
b P1
pre-TC
HAGIBIS P1
ave
ind
HAIYAN P1
ave
ind
Temperature(°C)
c P1
HAGIBIS
pre-TC argo
during-TC 3DPWP
(obs. run)
Temperature(°C)
d P1
HAIYAN
pre-TC argo
during-TC 3DPWP
(obs. run)

| 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 |




**RI: 1250-920/920= 36%**


a
b
c
d
P1
G.
P2
WOE
1012 10Z landfall
1107 20Z landfall
r200–800km VWS
r400–1000km VWS
r200–800km RH
r400–1000km RH
200–850 hPa VWS (m/s)
500–300 hPa RH (%)
Intensity, Vmax (knots)
HAGIBIS
HAIYAN
00Z 12Z
10/04 10/05 10/06 10/07 10/08 10/09 10/10 10/11 10/12
11/02 11/03 11/04 11/05 11/06 11/07 11/08

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

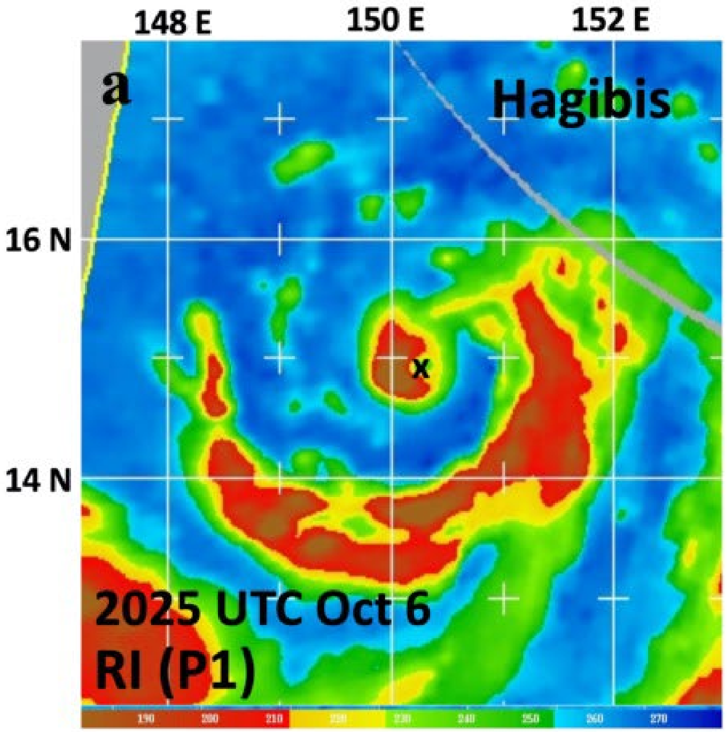
Rapid eyewall contraction
30km to 10km in 6h

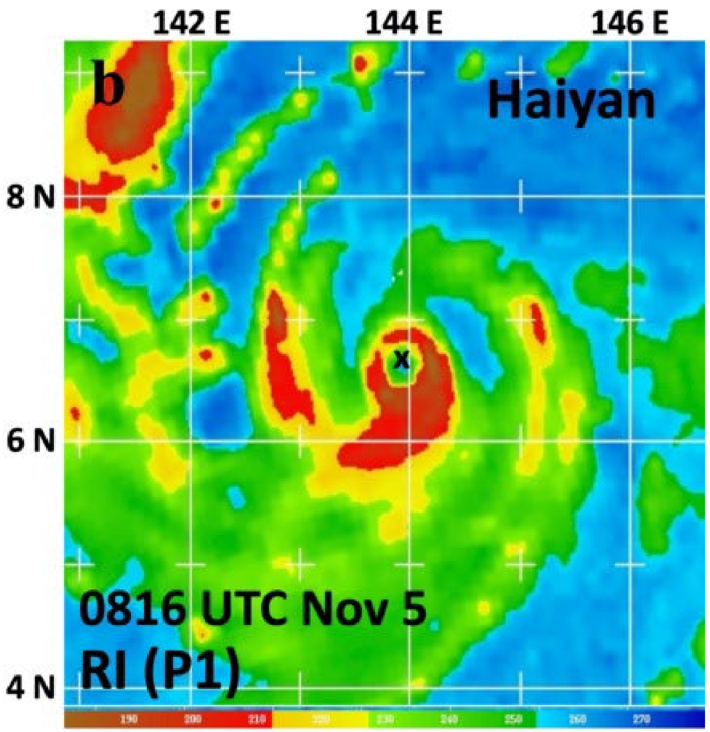
Deep convection at TC center: linking with intensification due to peak diabatic heating being preferentially located within a region of high inertial stability (Pendergrass and Willoughby 2009; Vigh and Schubert 2009; Rogers et al. 2013)
&
More likely to cause inward transport of angular momentum and rapid eyewall contraction (Smith and Montgomery 2016; Chen et al. 2018)

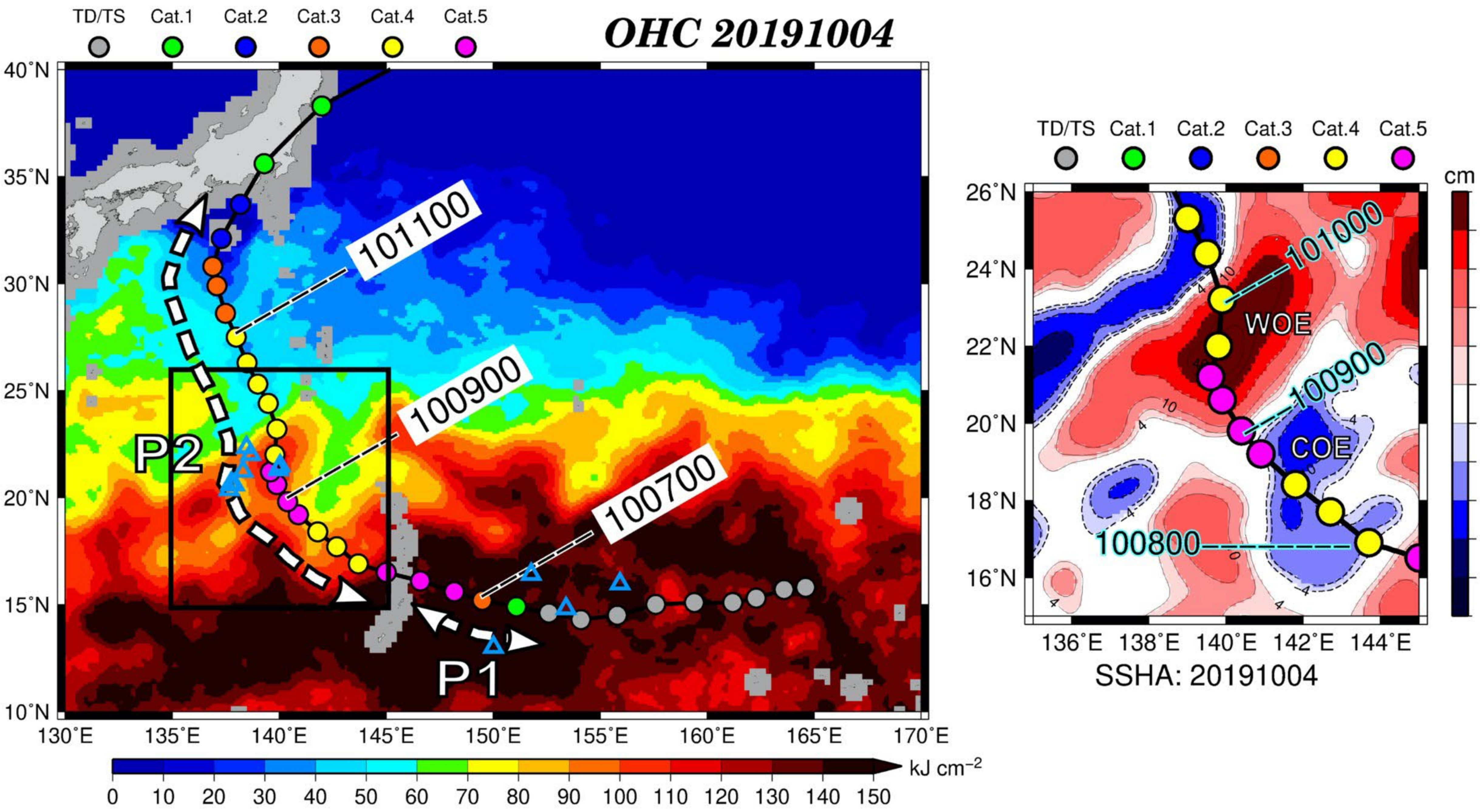
*Small RWM, favorable radial location of deep convection and rapid eyewall contraction favor Hagibis's extraordinary RI*

Haiyan:
Ring of convection

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

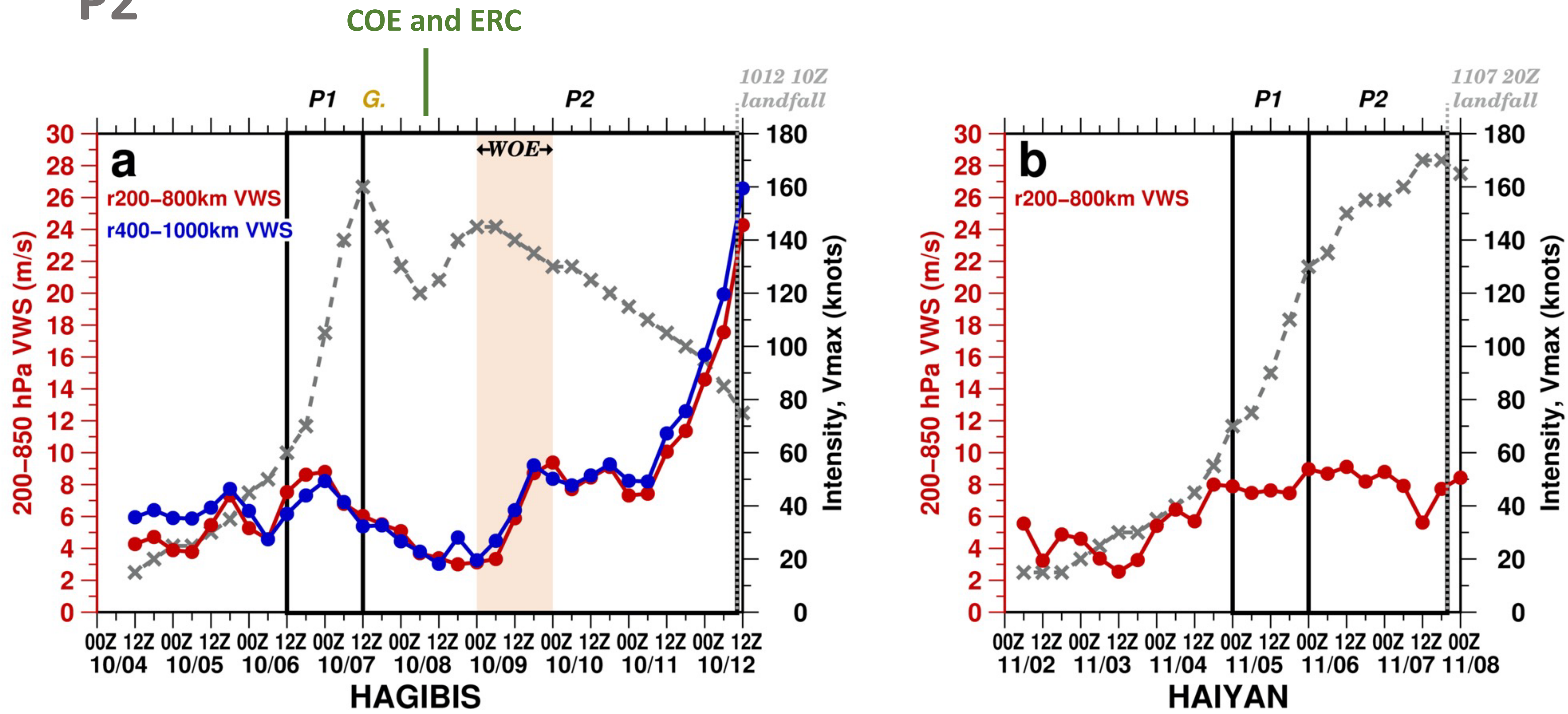




OHC 20191004
TD/TS
Cat.1
Cat.2
Cat.3
Cat.4
Cat.5
101100
100900
100700
P1
P2
kJ cm$^{-2}$
WOE
COE
101000
100900
100800
cm
SSHA: 20191004

# P2

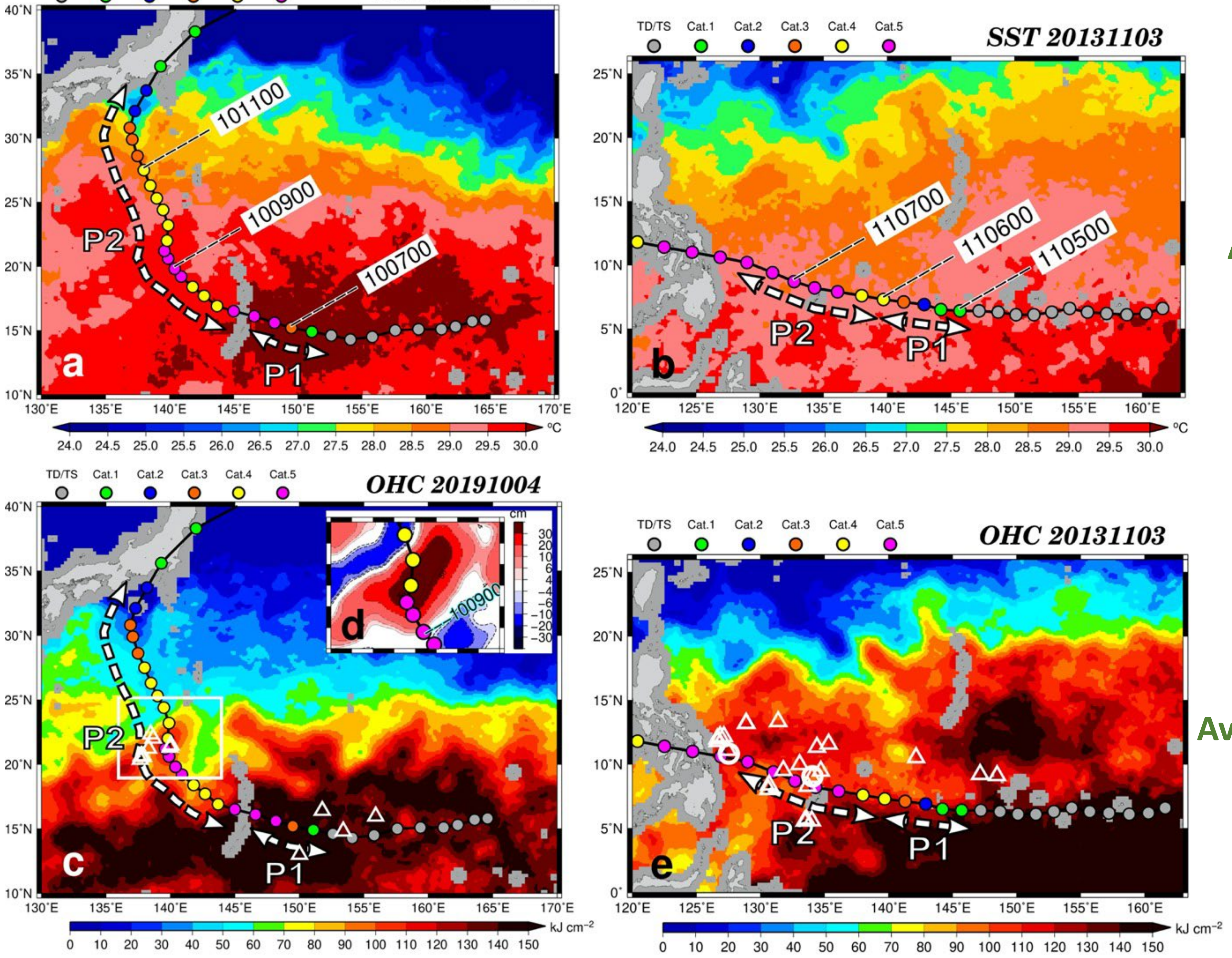



LMI: 160kts

LMI: 170kts

# P2

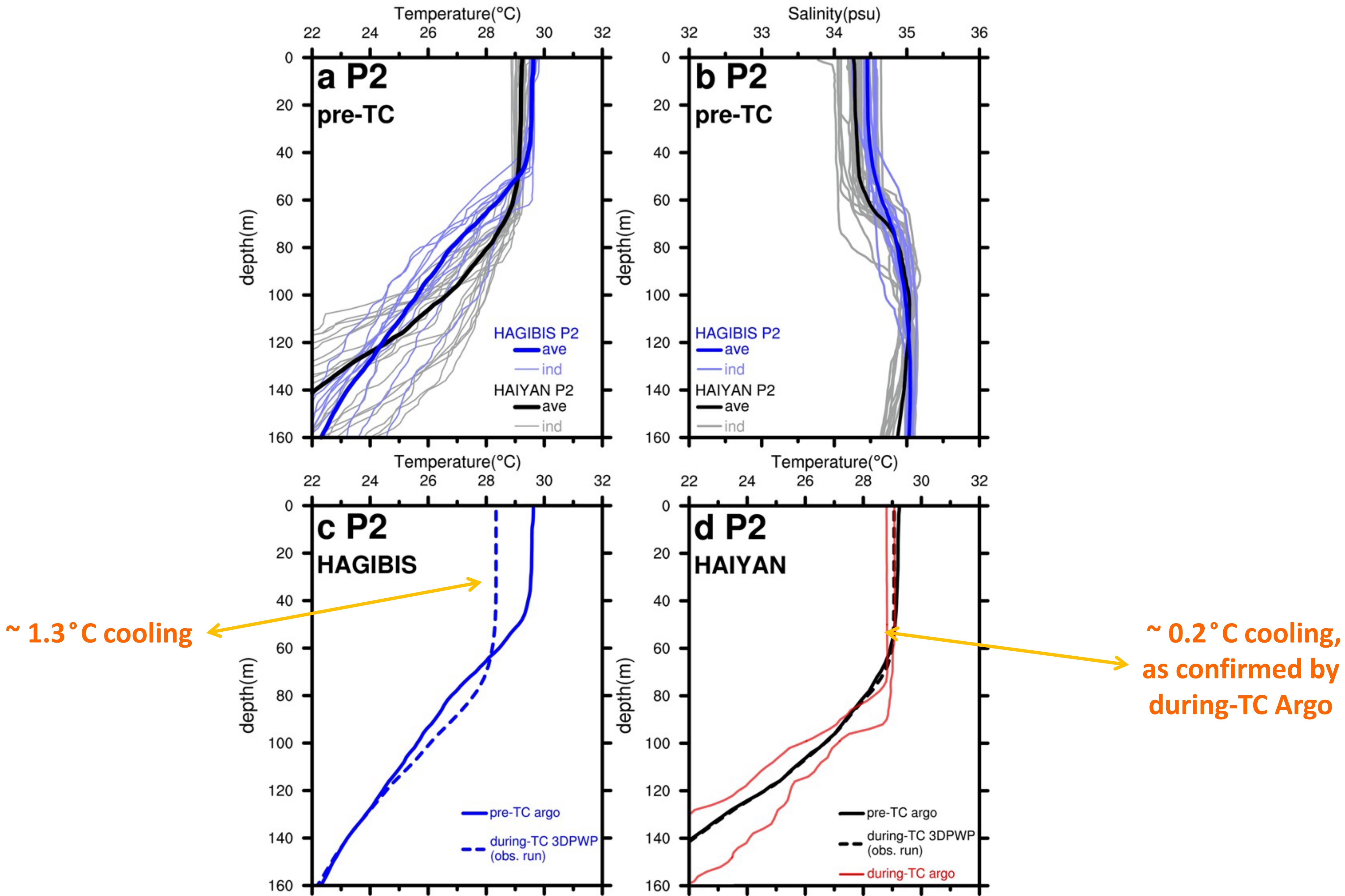
Over WOE
Avg. 29.6° C
Pre-TC SST



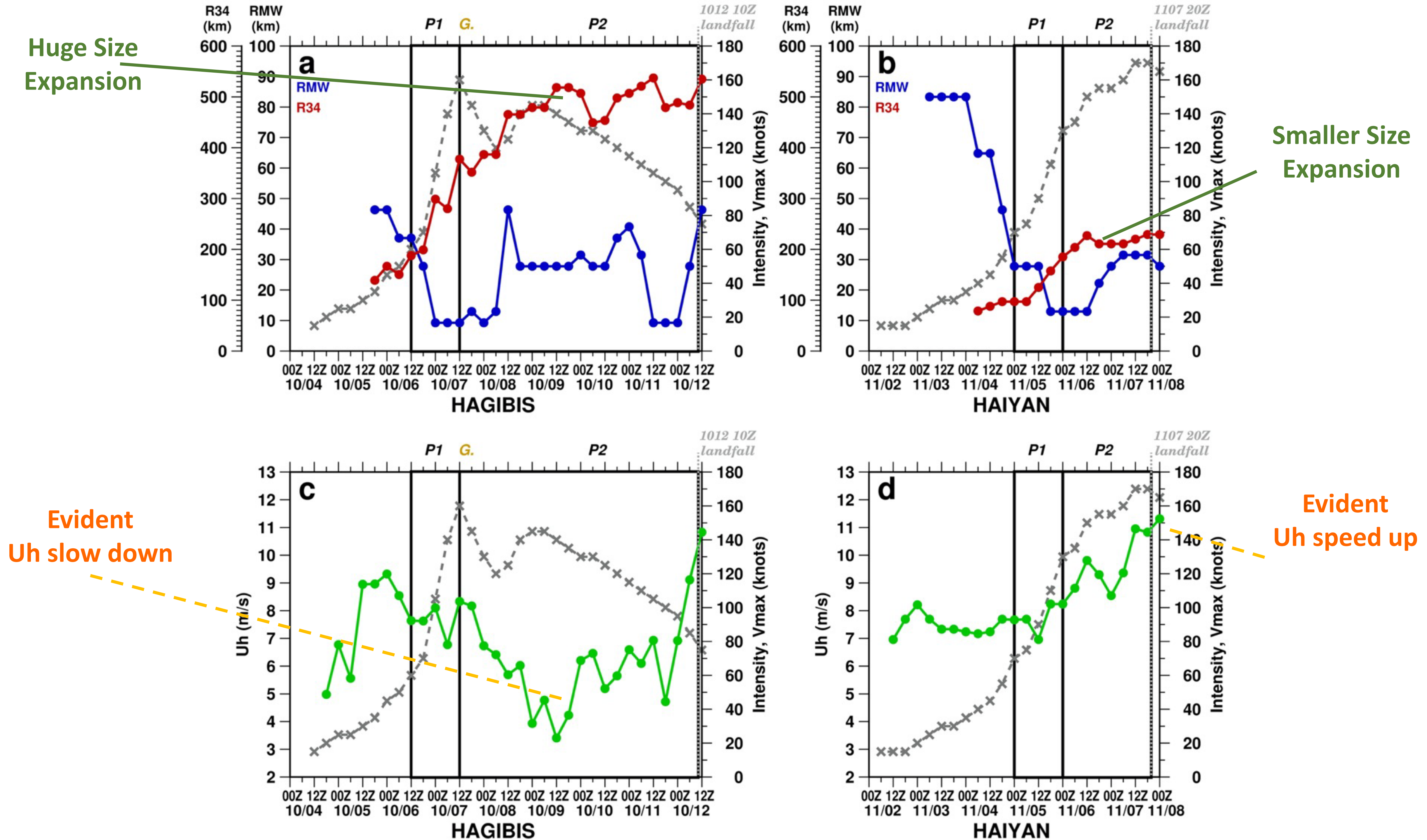

Avg. 29.1° C
Pre-TC SST

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

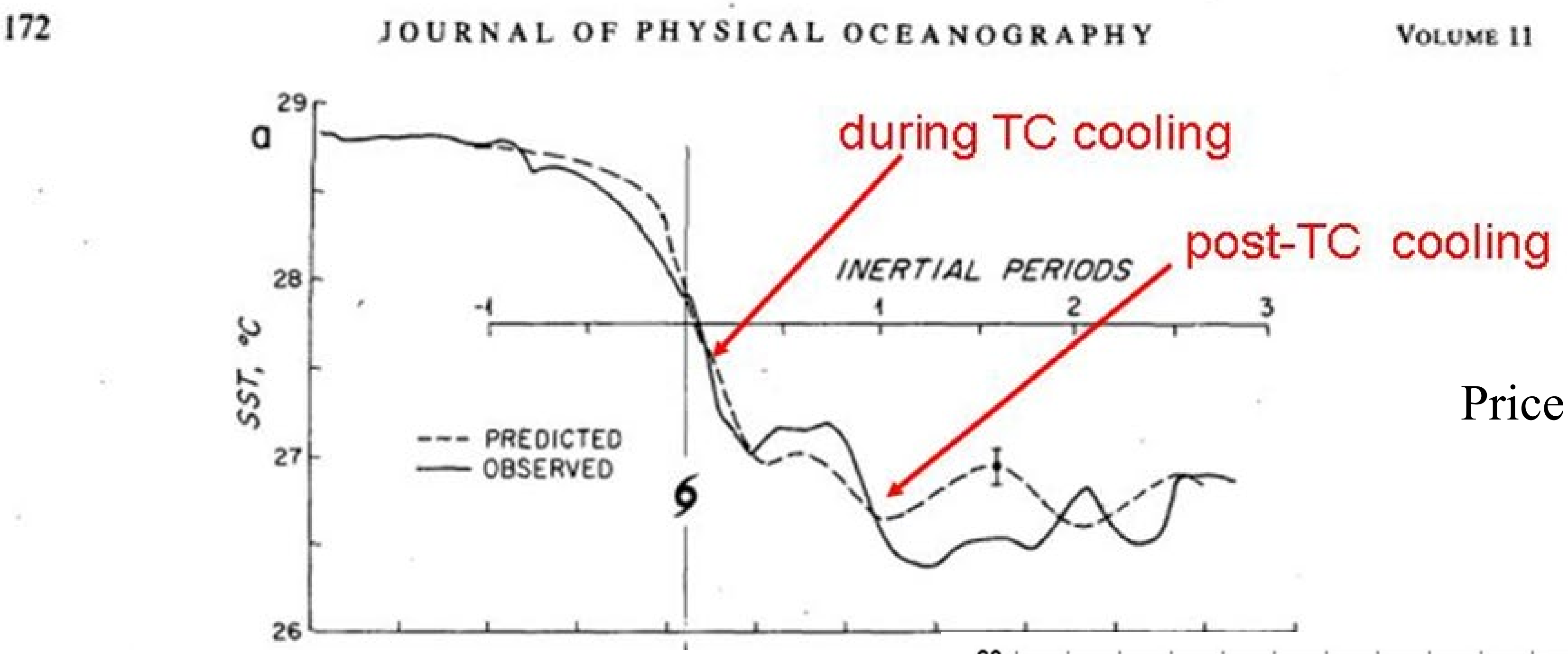
Avg. 109 kJ/cm2
Pre-TC OHC



Temperature(°C)
a P2
pre-TC
depth(m)
HAGIBIS P2
ave
ind
HAIYAN P2
ave
ind
Salinity(psu)
b P2
pre-TC
depth(m)
HAGIBIS P2
ave
ind
HAIYAN P2
ave
ind
Temperature(°C)
c P2
HAGIBIS
depth(m)
pre-TC argo
during-TC 3DPWP
(obs. run)
Temperature(°C)
d P2
HAIYAN
depth(m)
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



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

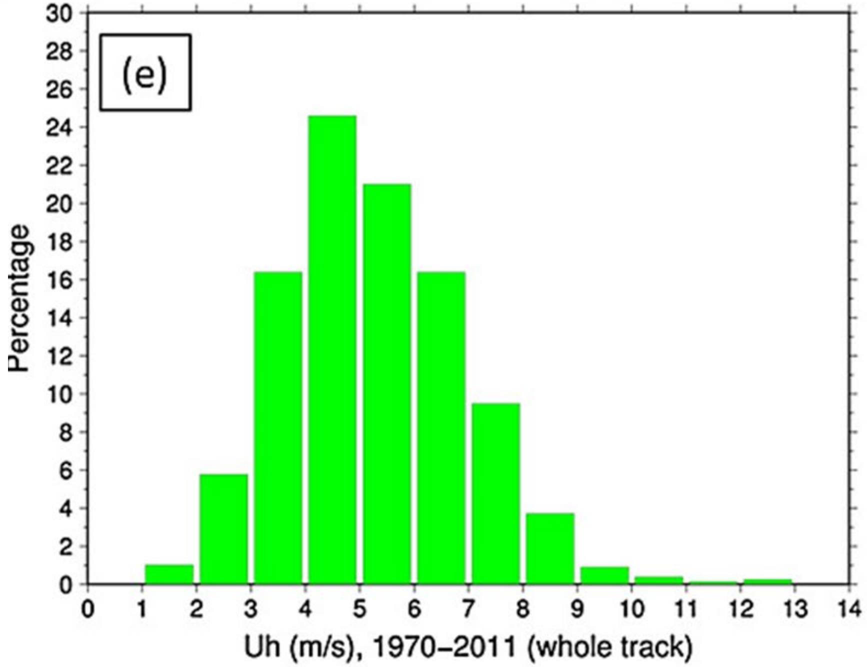



Price 1981

*4 factors affect the cooling effect*

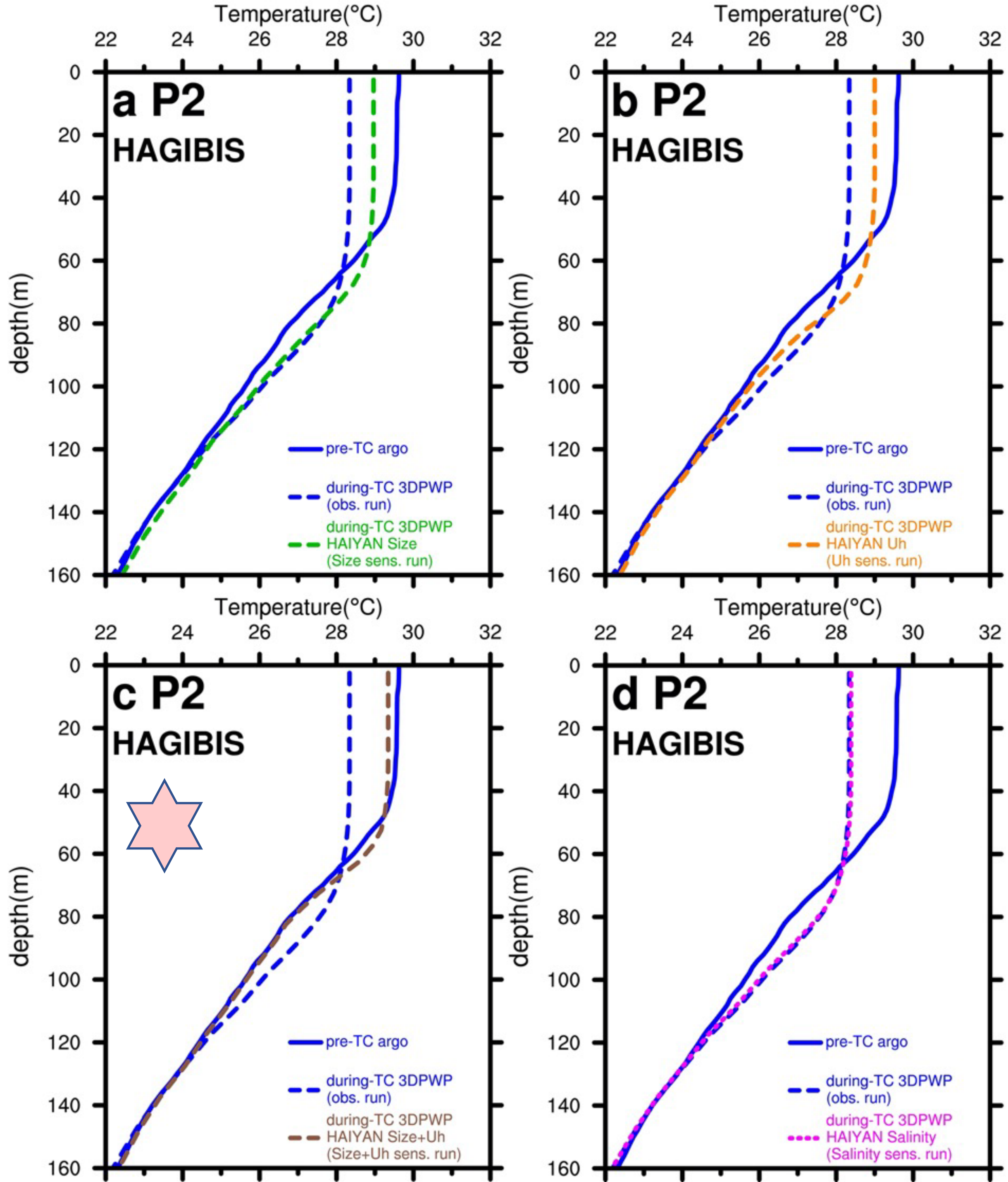
- *Pre-existing ocean T-S profile*
- *TC wind speed*
- *TC translation speed*
- *TC size*

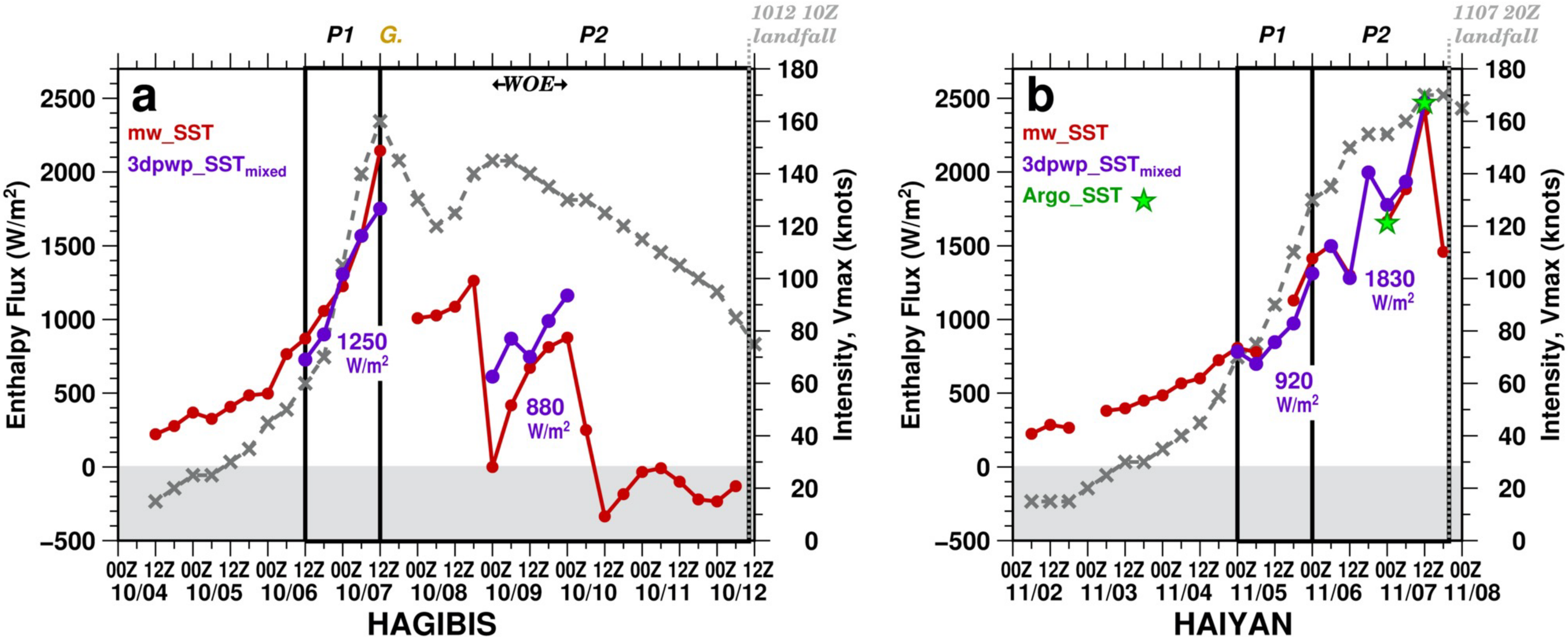
** TC_transit time = D/Uh*



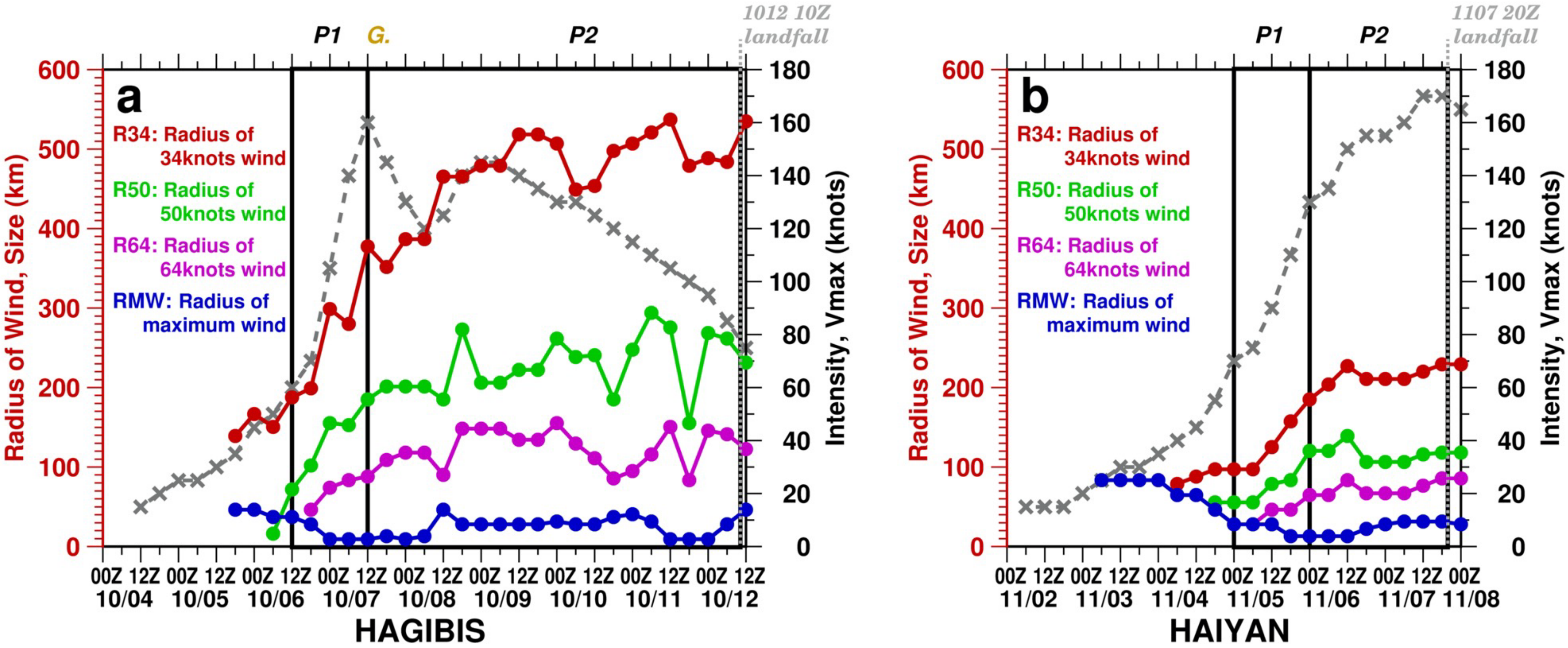

*Lin et al. MWR 2009; Lin JGR 2012*

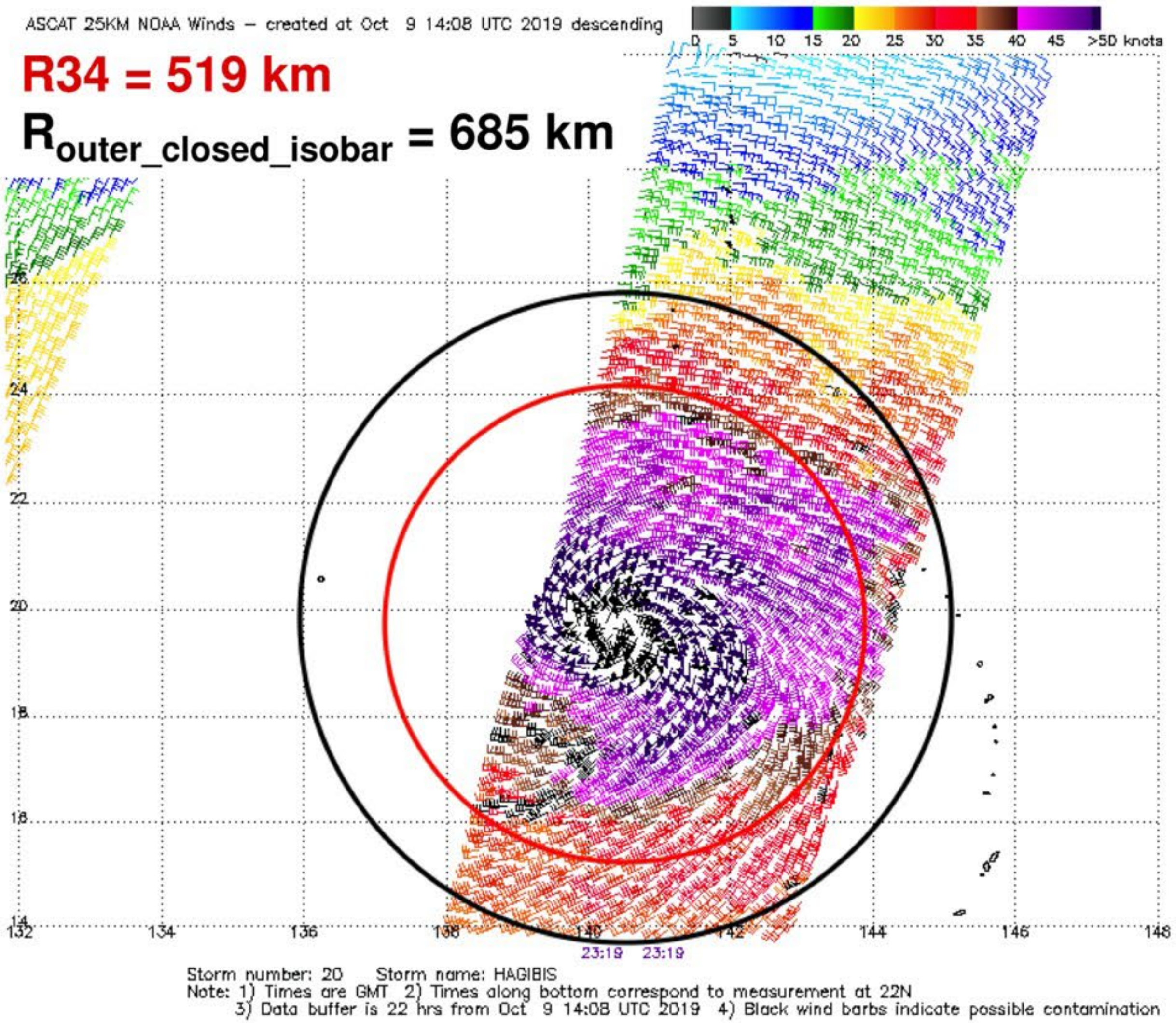
# *4 Sensitivity Experiments*

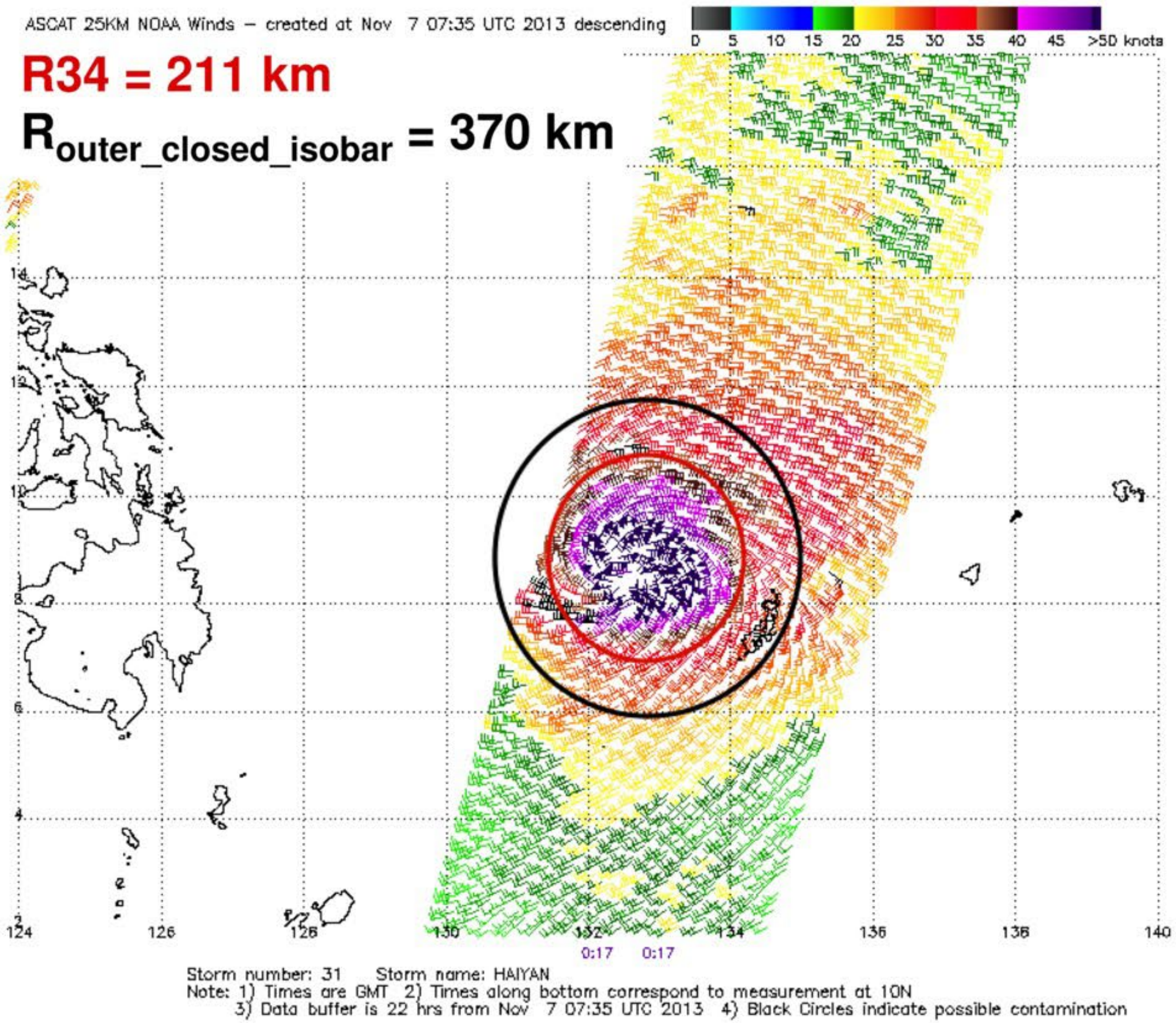


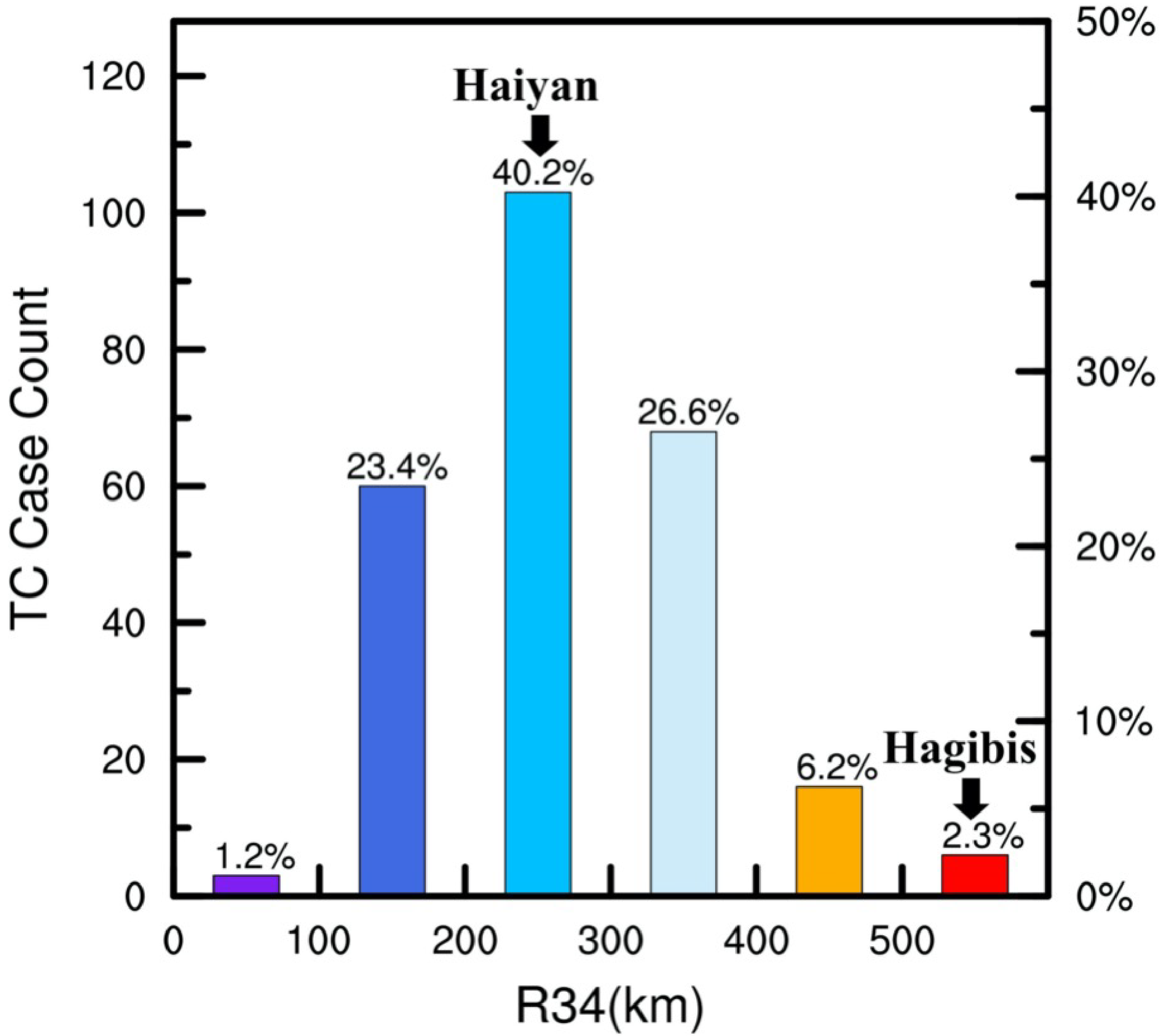


a
mw_SST
3dpwp_SST mixed
P1
G.
P2
↔WOE↔
1012 10Z landfall
1250 W/m2
880 W/m2
Enthalpy Flux (W/m2)
Intensity, Vmax (knots)
HAGIBIS
b
mw_SST
3dpwp_SST mixed
Argo_SST
P1
P2
1107 20Z landfall
920 W/m2
1830 W/m2
Enthalpy Flux (W/m2)
Intensity, Vmax (knots)
HAIYAN


a
b
P1
G.
P2
1012 10Z landfall
1107 20Z landfall
R34: Radius of 34knots wind
R50: Radius of 50knots wind
R64: Radius of 64knots wind
RMW: Radius of maximum wind
Radius of Wind, Size (km)
Intensity, Vmax (knots)
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
00Z 12Z
10/04 10/05 10/06 10/07 10/08 10/09 10/10 10/11 10/12
11/02 11/03 11/04 11/05 11/06 11/07 11/08
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
132 134 136 138 140 142 144 146 148
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
124 126 128 130 132 134 136 138 140
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

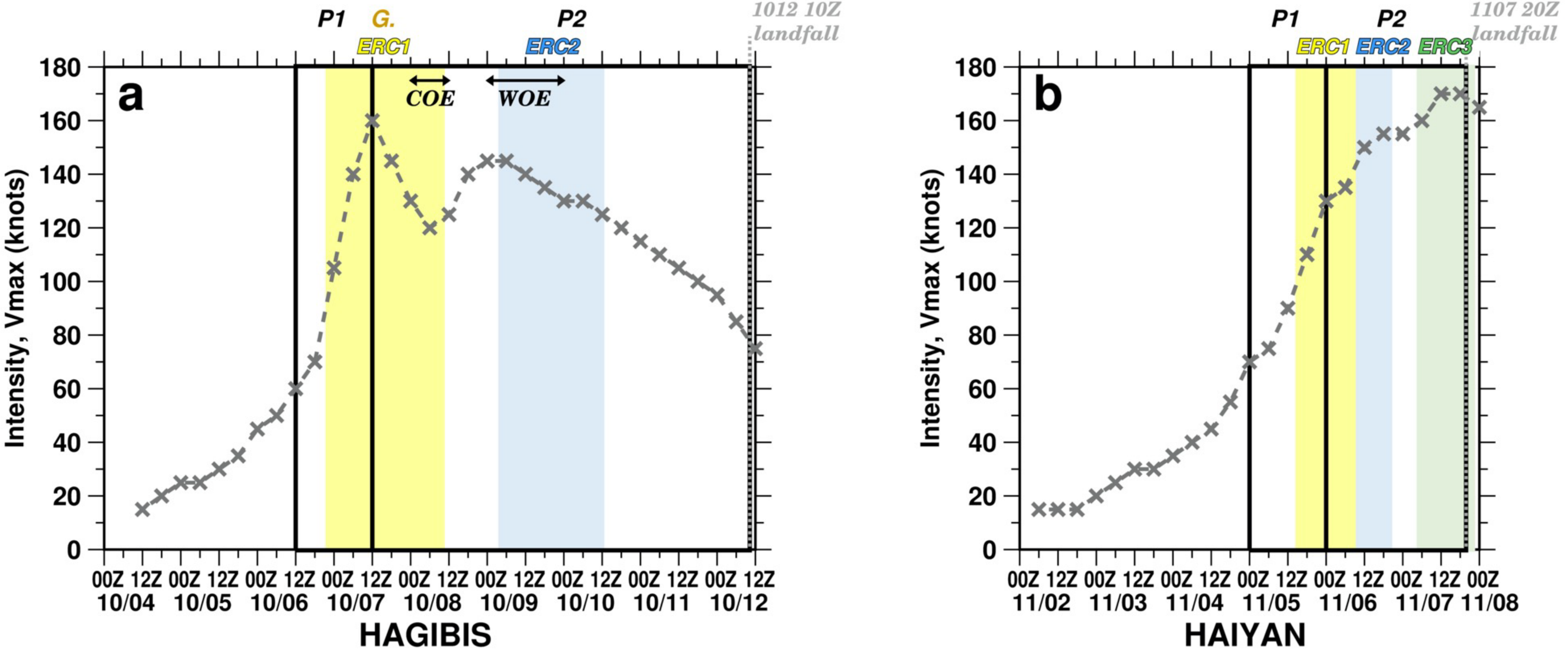



***17 Years (2003-2019) of 256 TCs (>= Cat.1)***
***Of JTWC Records***

**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)**

# Slower ERCs for larger-sized TCs



# Conclusions – Part 2

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**

# Pending Questions and Ideas

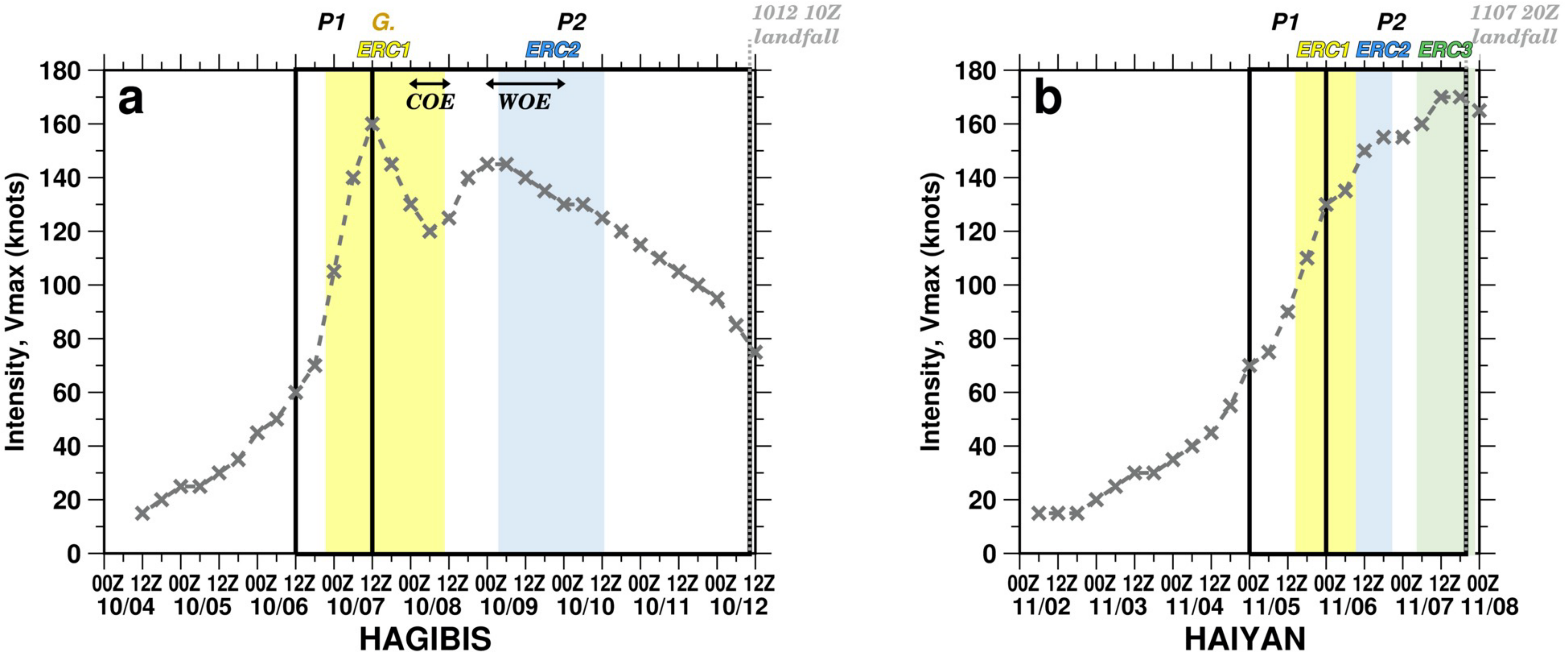
1. *Why Hagibis has such huge size?*

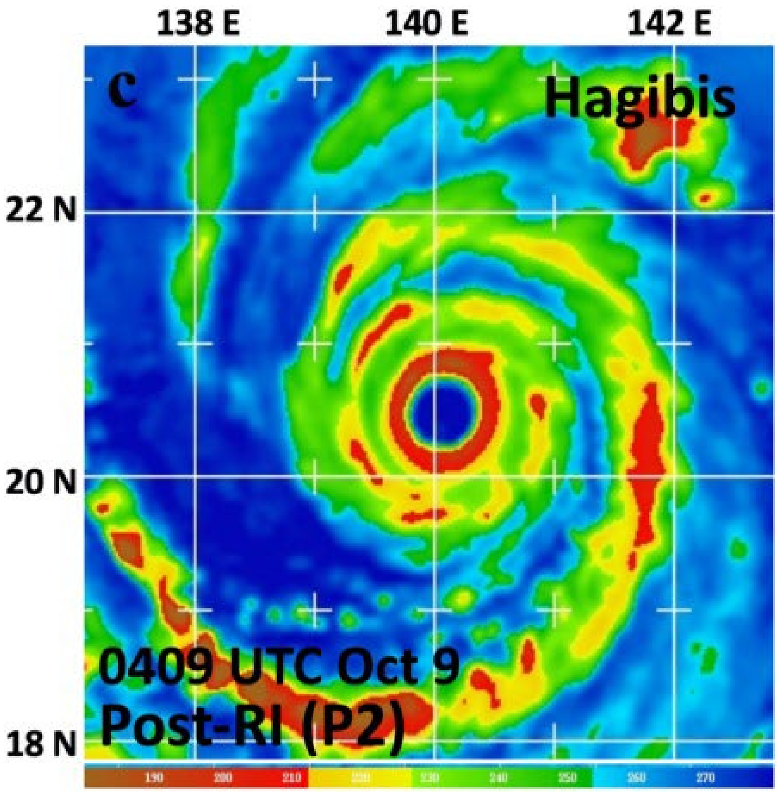
2. *Cold Ocean Eddy and Eyewall Replacement Cycle (ERC) on 8 Oct.?*

3. *ERC and RI (Fischer et al. MWR 2020)*

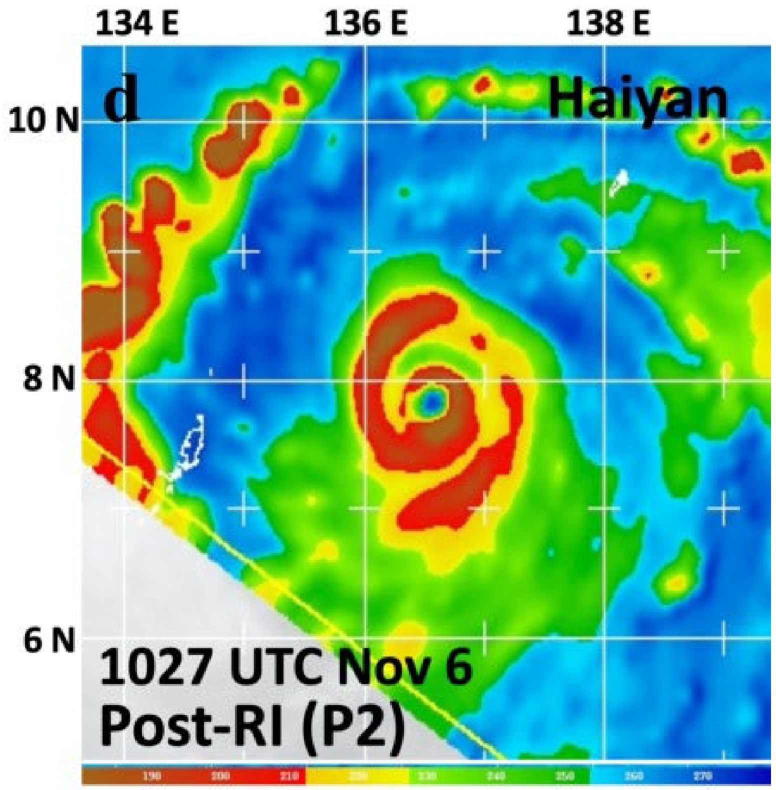
**Mahalo and Take Care!**

# ERC can occur during RI for both STYs (add new observations to Fischer et al. MWR 2020






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

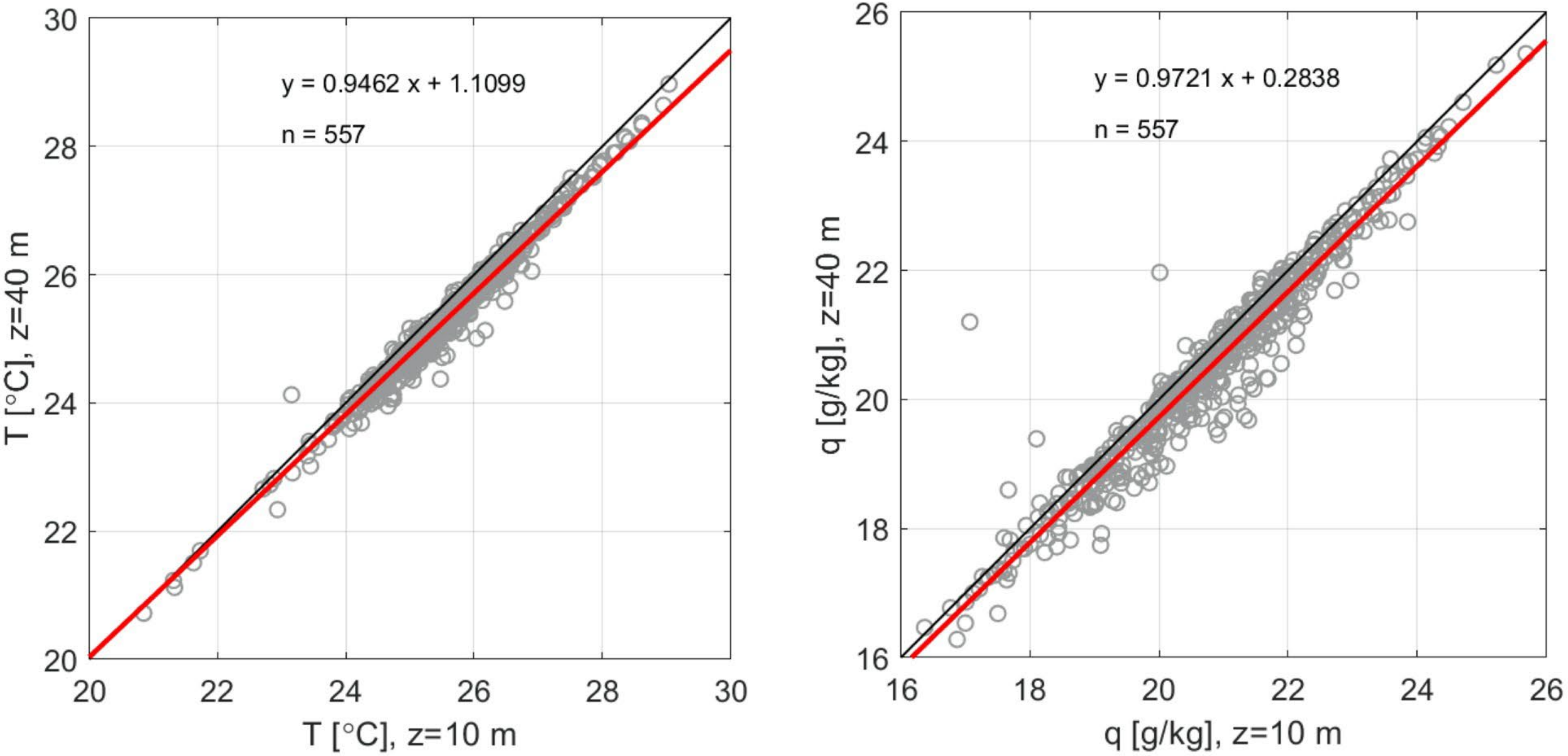



Haiyan remain compact
R34 ~ 250km

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

## 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 |




**Inner-Core dropsondes from NOAA HRD of Cat 4-5's Archive**

# Data and Method -1

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)**

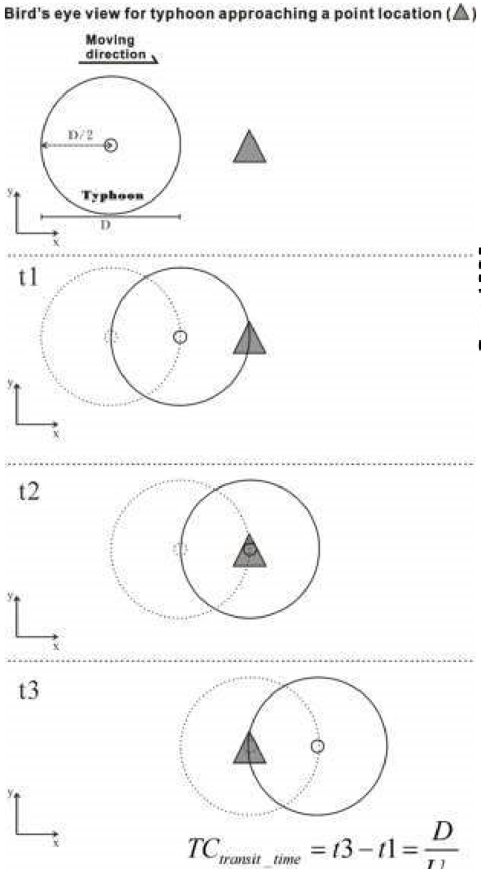
***Observational Data:***

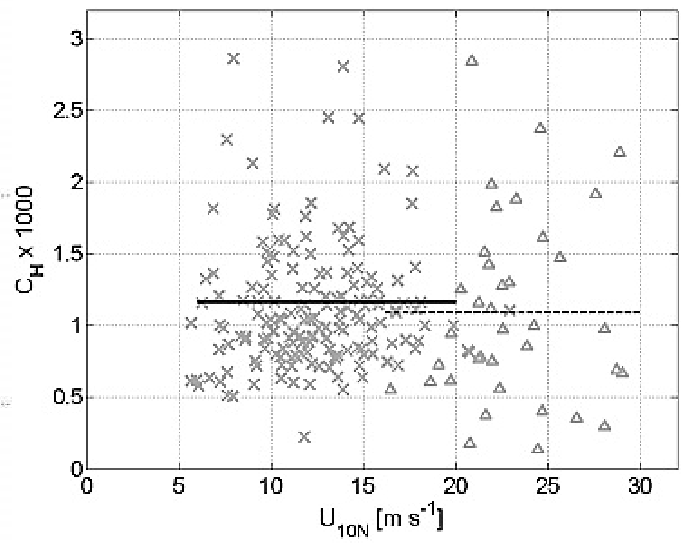
***NCEP-CFSR/6hrly, JTWC Best Track (including track, RMW, size, intensity, Uh), ASCAT wind, Satellite Altimetry SSHA (Sea Surface Height Anomaly), Microwave Sea Surface Temperature (SST), Argo in situ floats (pre, and during-TC), NRL microwave imagery, ARCHER ((Automated Rotational Center Hurricane 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***

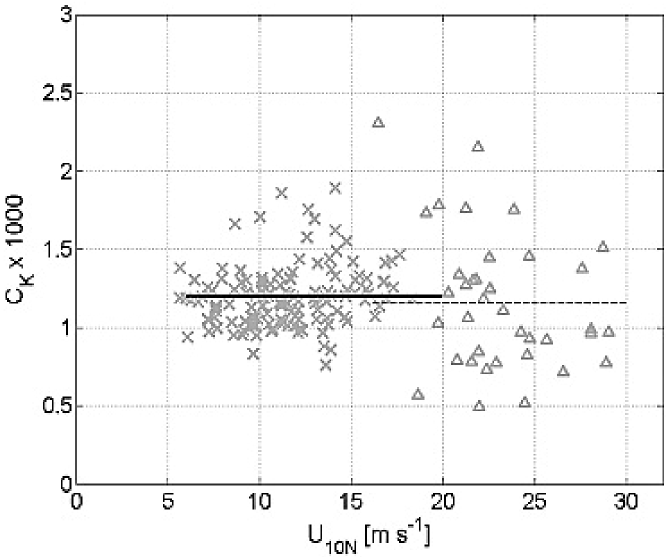
# Data & Method-2 : Numerical Simulations & Air-Sea Flux Estimation

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)

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

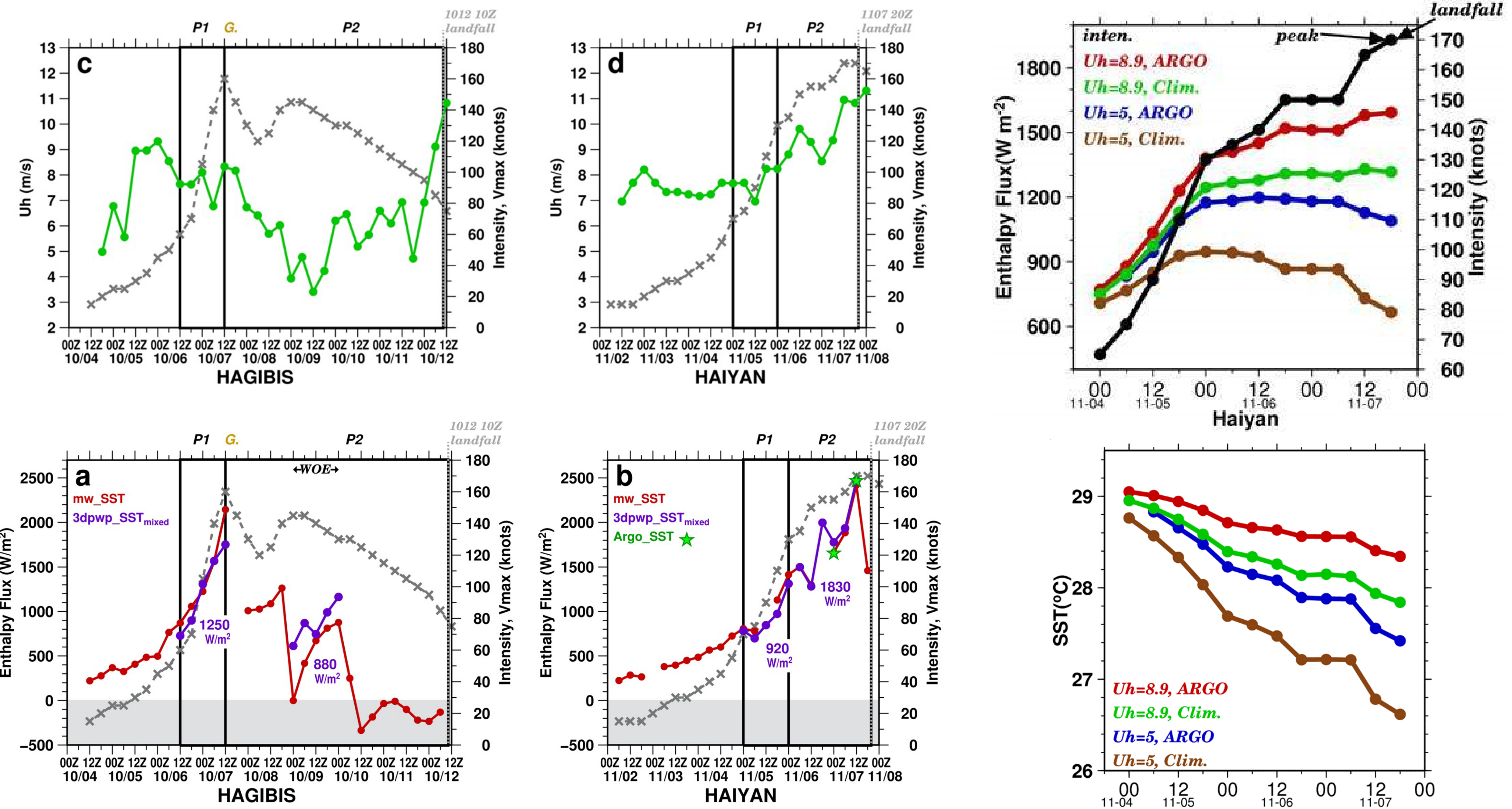
$$Q_L = C_E W (q_s - q_a) \rho_a L_{va}$$

Fcn. of during-TC SST

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

| 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 |




Lin et al. BAMS 2021; GRL 2014