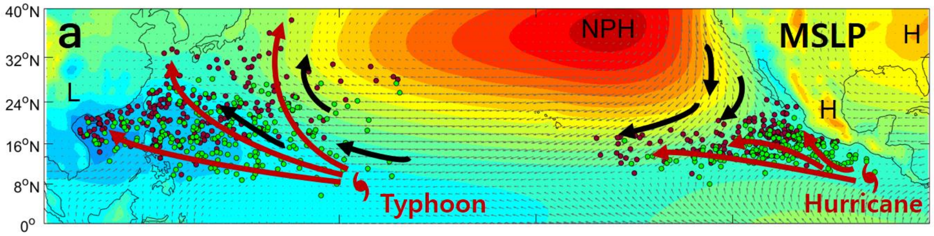

Moon et al. (2022, BAMS)

Why do eastern North Pacific hurricanes intensify more and faster than their western-counterpart typhoons with less ocean energy?

Jeju National University

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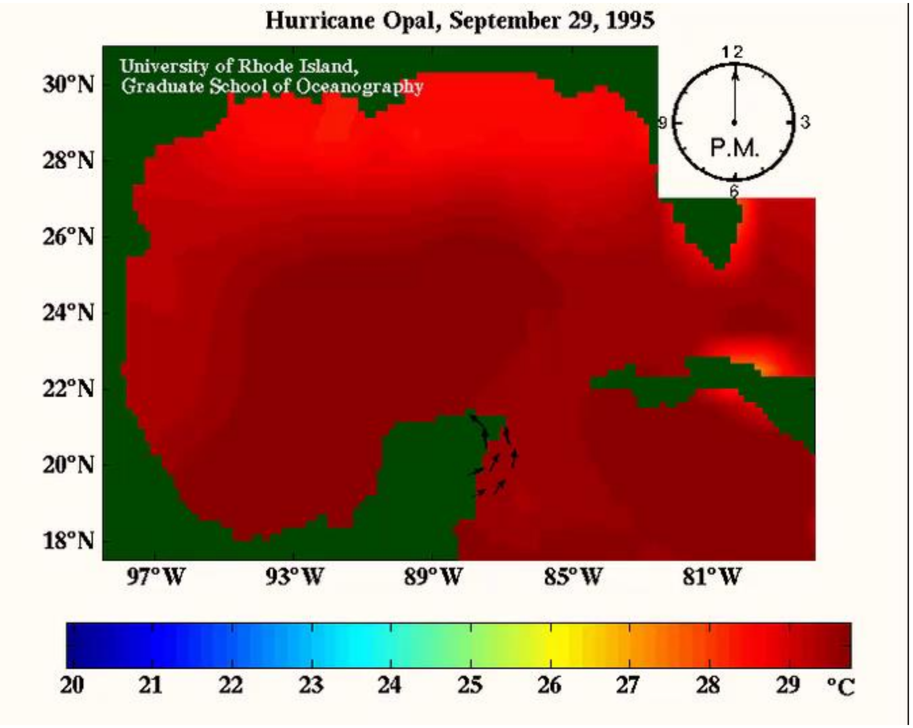
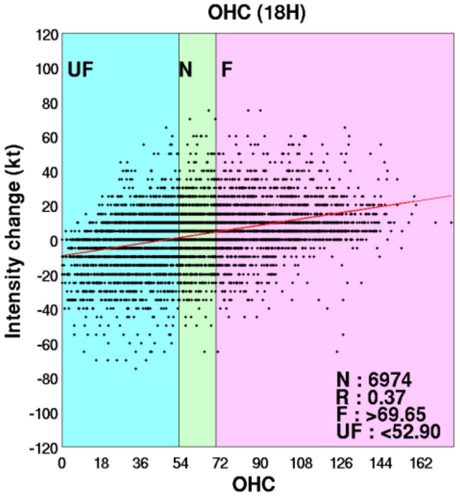
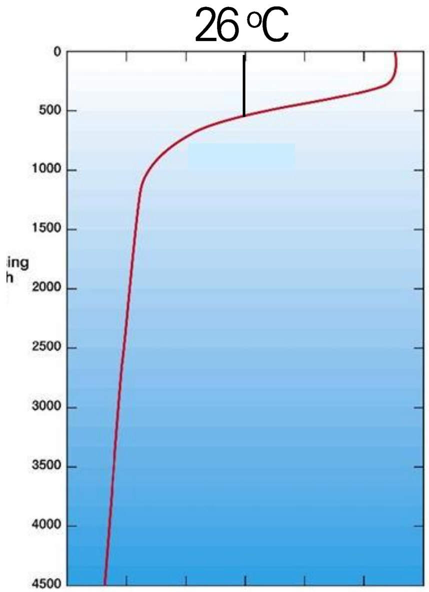
OHC and Tropical Cyclone (TC) intensification

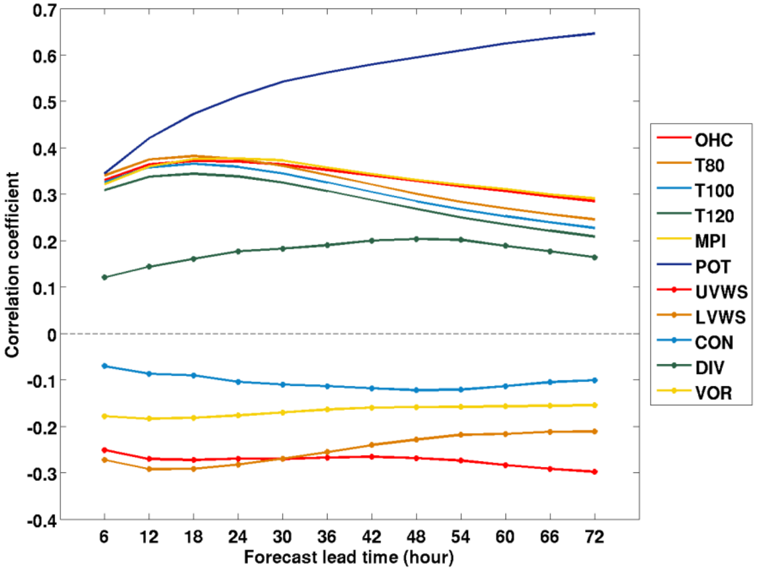
- **Ocean Heat Content** (OHC) : is known to be the most important oceanic predictor widely used in operational TC intensity forecasting

$$OHC = C_p \rho \int_{0m}^{d26} (T - 26)dz$$



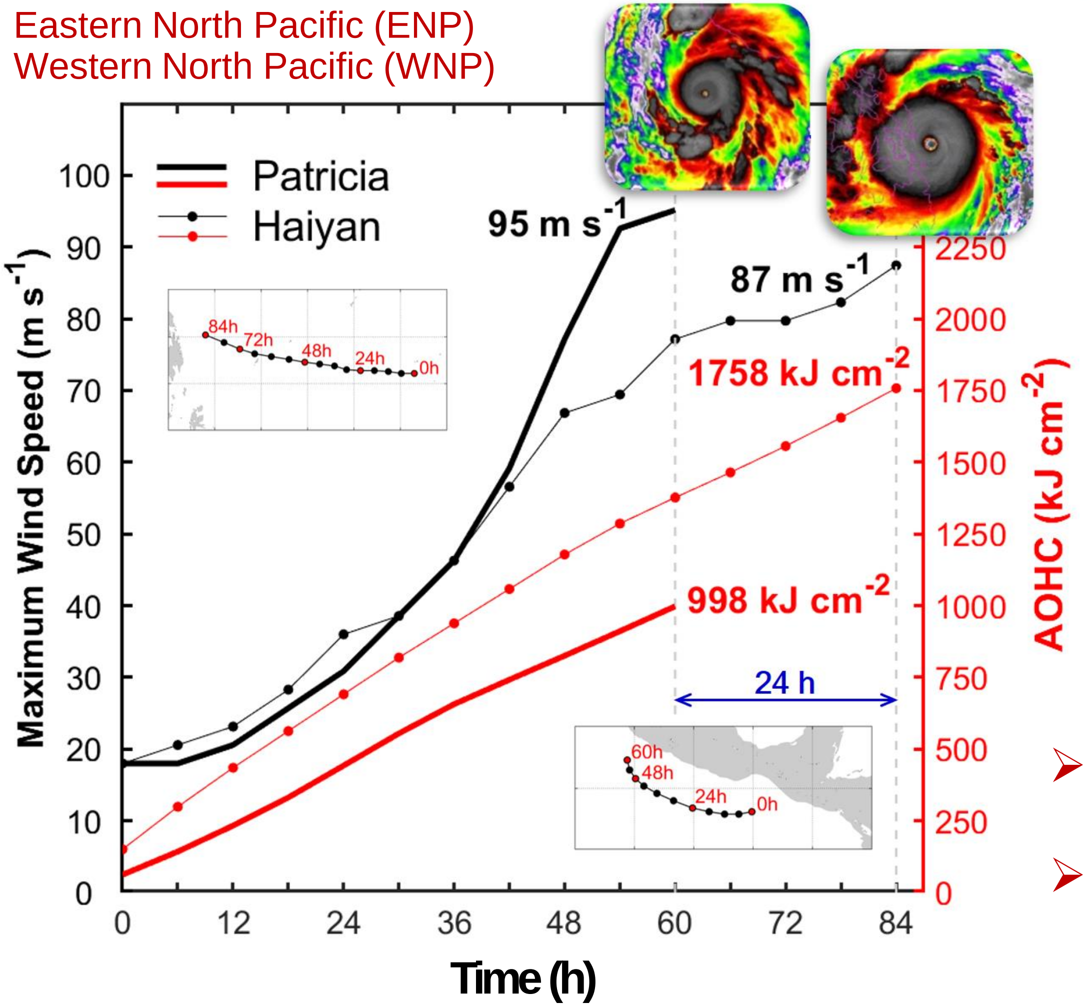






Comparison between Hurricane Patricia and Typhoon Haiyan

Eastern North Pacific (ENP)
Western North Pacific (WNP)



- **Accumulated ocean heat content (AOHC) from genesis to LMI**
- **Lifetime maximum intensity (LMI)**
- **LMI-reaching time (T_{LMI}; unit = h)**
- **Intensification Efficiency (IE)**
  = (LMI - 17) / AOHC : AOHC-based
  (LMI - 17) / ASSHC : SST-based
  (LMI - 17) / AFLUX : Flux-based

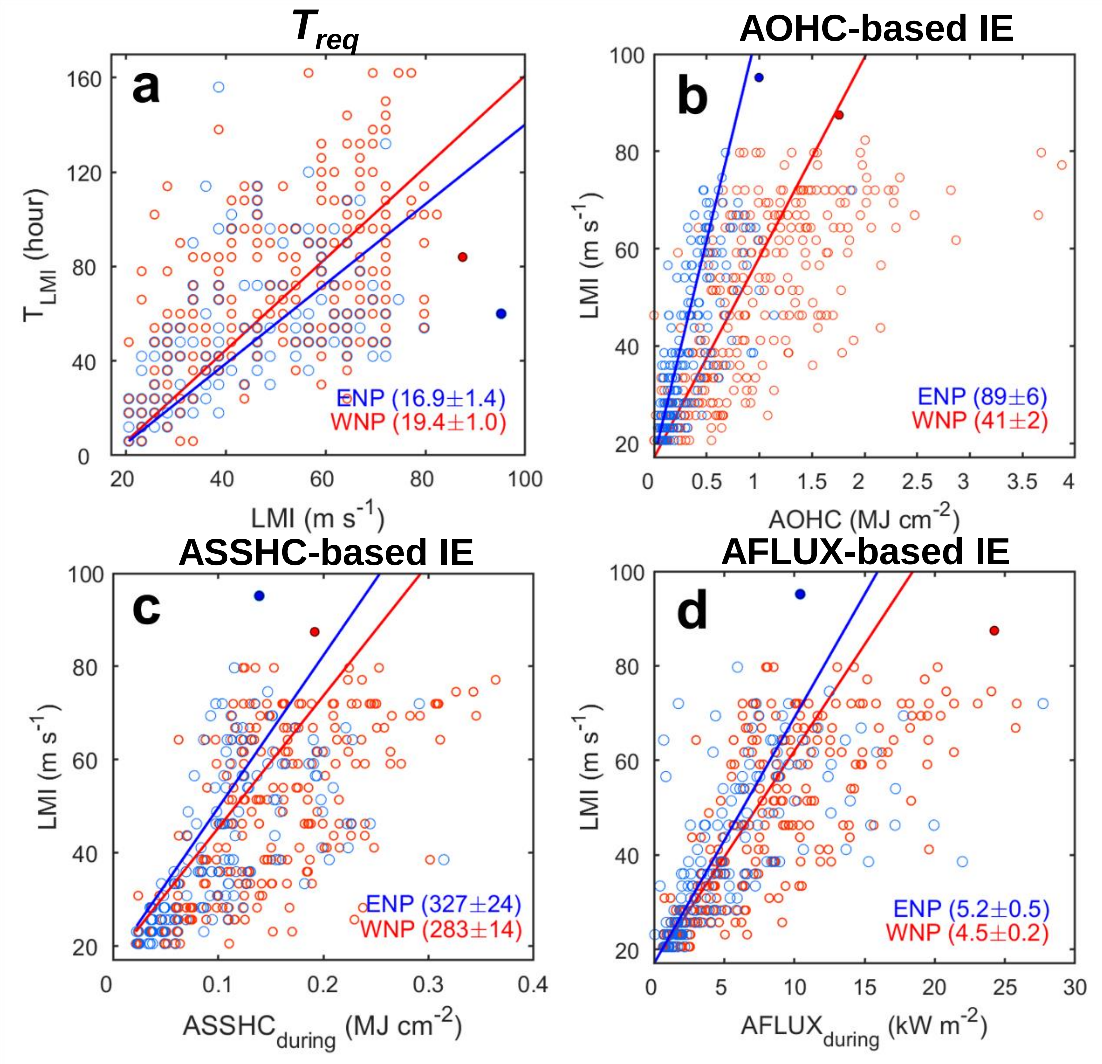
Fuel efficiency for car

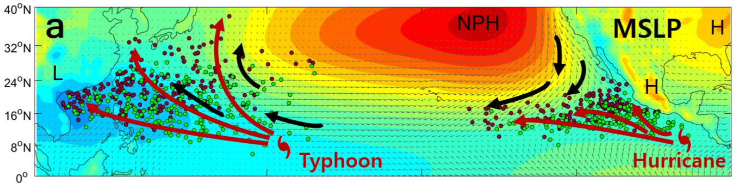
➢ Patricia's IE= (95 -17) / 1.0 = 78.3

➢ Haiyan's IE= (87-17) / 1.8 = 39.6

- ✓ Haiyan reached LMI (87 m s^{-1}) under the condition of high AOHC (1.8 MJ cm^{-2}) in 84 h
- ✓ Patricia reached an even higher LMI (95 m s^{-1}), 1.4 times faster (in 60 h), despite having 55% less AOHC (1.0 MJ cm^{-2}) than Haiyan
- ✓ The IEs of Patricia (78.3 m s^{-1} MJ^{-1} cm^{2}) are ~2 times higher than Haiyan (39.6 m s^{-1} MJ^{-1} cm^{2})

Comparison of T_{req} and IEs between ENP and WNP





For 500 TCs occurring in the ENP and WNP from 2001 to 2015

	T_{req}	IE		
		AOHC	ASSHC during	AFLUX during
WNP Typhoons	19.4	41±2	283±14	4.5±0.2
ENP Hurricanes	16.9	89±6	327±24	5.2±0.5
Difference (%)	2.5** (13%)	48** (117%)	44** (16%)	0.7** (16%)

What makes the differences in T_{req} and IEs between ENP and WNP?

1. Relationship between TC size and intensity

2. Roles of ocean waves

3. Background oceanic environments

4. Background atmospheric environments

5. Role of Latitudes

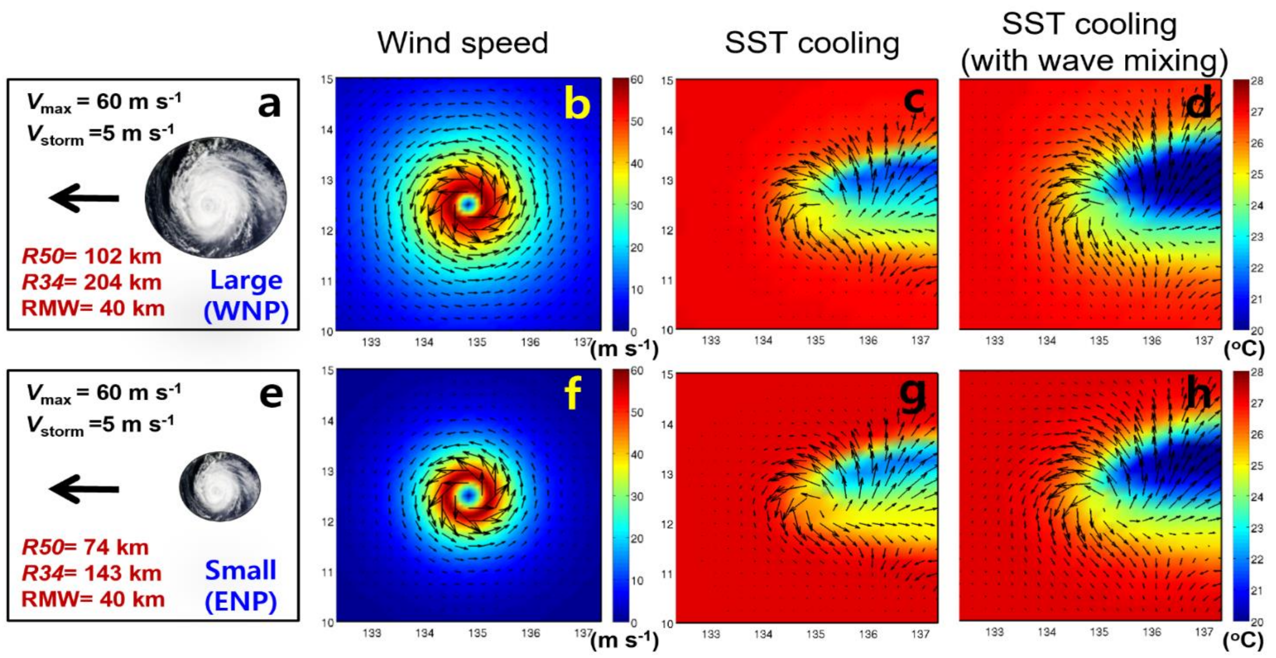
1. Relationship between TC size and intensity

	R34 (R_{init}, R_{LMI}, $r_{\Delta R}$)	R50 (R_{init}, R_{LMI}, $r_{\Delta R}$)	R64 (R_{init}, R_{LMI}, $r_{\Delta R}$)
Typhoons in the WNP	156km (100*/204**/ 104%/1.9)	75km (46/102**/ 120%/2.2)	52km (37**/65**/ 77%/2.2)
Hurricanes in the ENP	119km (92/143/55%)	61km (46/74/54%)	36km (31/42/36%)
Difference (%)	37km** (31%)	14km** (23%)	16km** (44%)

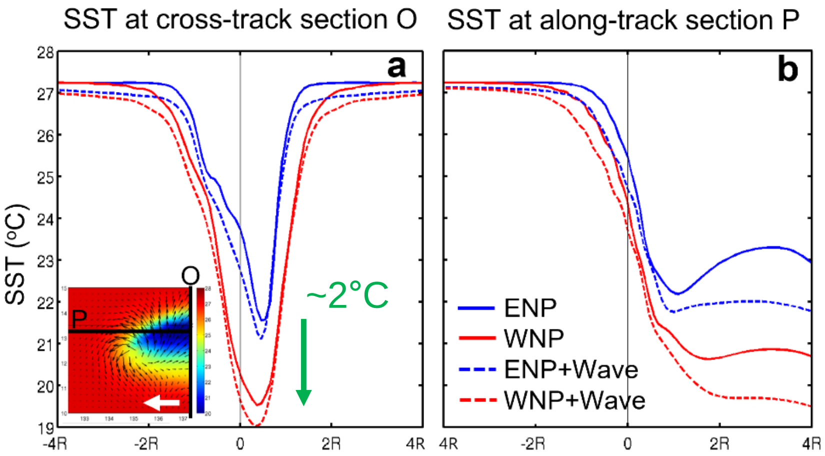
Values show TC size (*R34, R50, R64*; unit = km), averaged from the time of genesis to the lifetime maximum intensity (LMI) stage for all TCs that occurred in the ENP or WNP from 2001 to 2015. The parenthetical values for all metrics except TC size represent those at LMI stages. The first three parenthetical values for *R34, R50* and *R64* (denoted in the WNP and ENP) represent the mean radii (R_{init}, R_{LMI}) when TCs initially achieve (R_{init}) the wind speeds of each radius (*i.e.*, 34 kt, 50 kt, and 64 kt) or arrive at the LMI stage (R_{LMI}), and the increasing rate (in percentages, $r_{\Delta R}$) of size from the time of genesis to the LMI stage, respectively. The last parenthetical values for *R34, R50* and *R64* (denoted in the WNP) represent the ratio of $r_{\Delta R}$ between the two basins. For *R34, R50* and *R64*, the parenthetical percentages in the 'Difference' row are the ratio of the absolute difference (WNP−ENP) to the smaller value. Asterisks denote statistically significant separation in the differences (* = 95% confidence; ** = 99% confidence).

- ✓ The smaller the TC size, the faster the intensification
- ✓ Smaller TCs tend to have a greater pressure gradient near the eyewall than large TCs
- ✓ TC size has a strong negative correlation with the change in intensity

1. Relationship between TC size and intensity

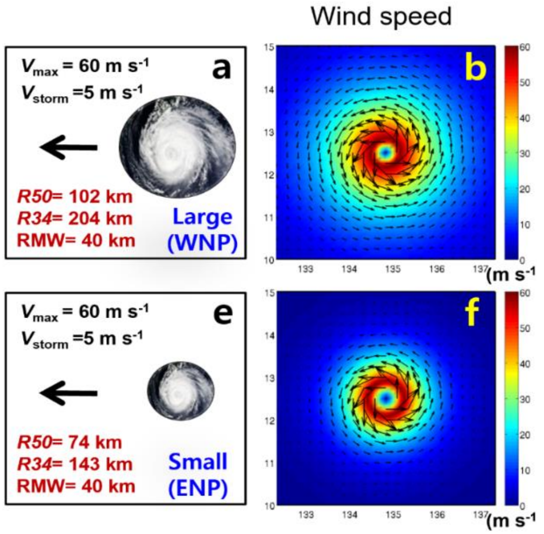


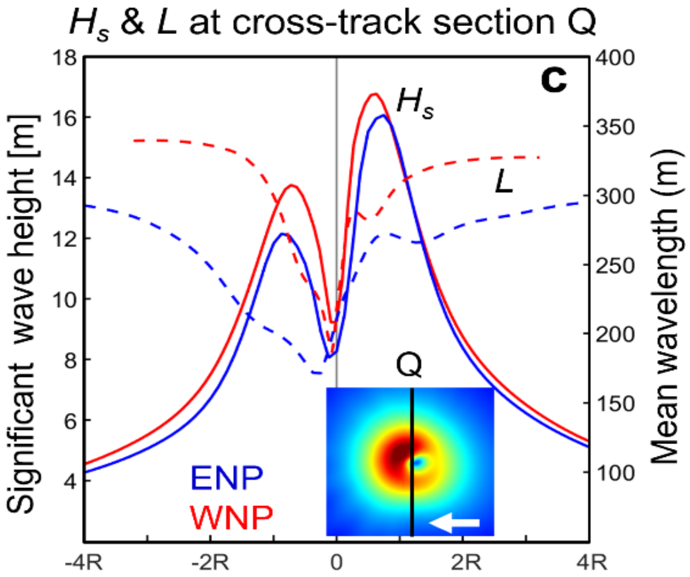
- ✓ The larger the TC size (*i.e.*, *R34*, *R50*, and *R64*), the stronger the sea-surface cooling, mainly due to the longer duration of intense TC winds for a given point in the ocean (Price, 1981; Pun et al. 2018; Lin et al. 2021).

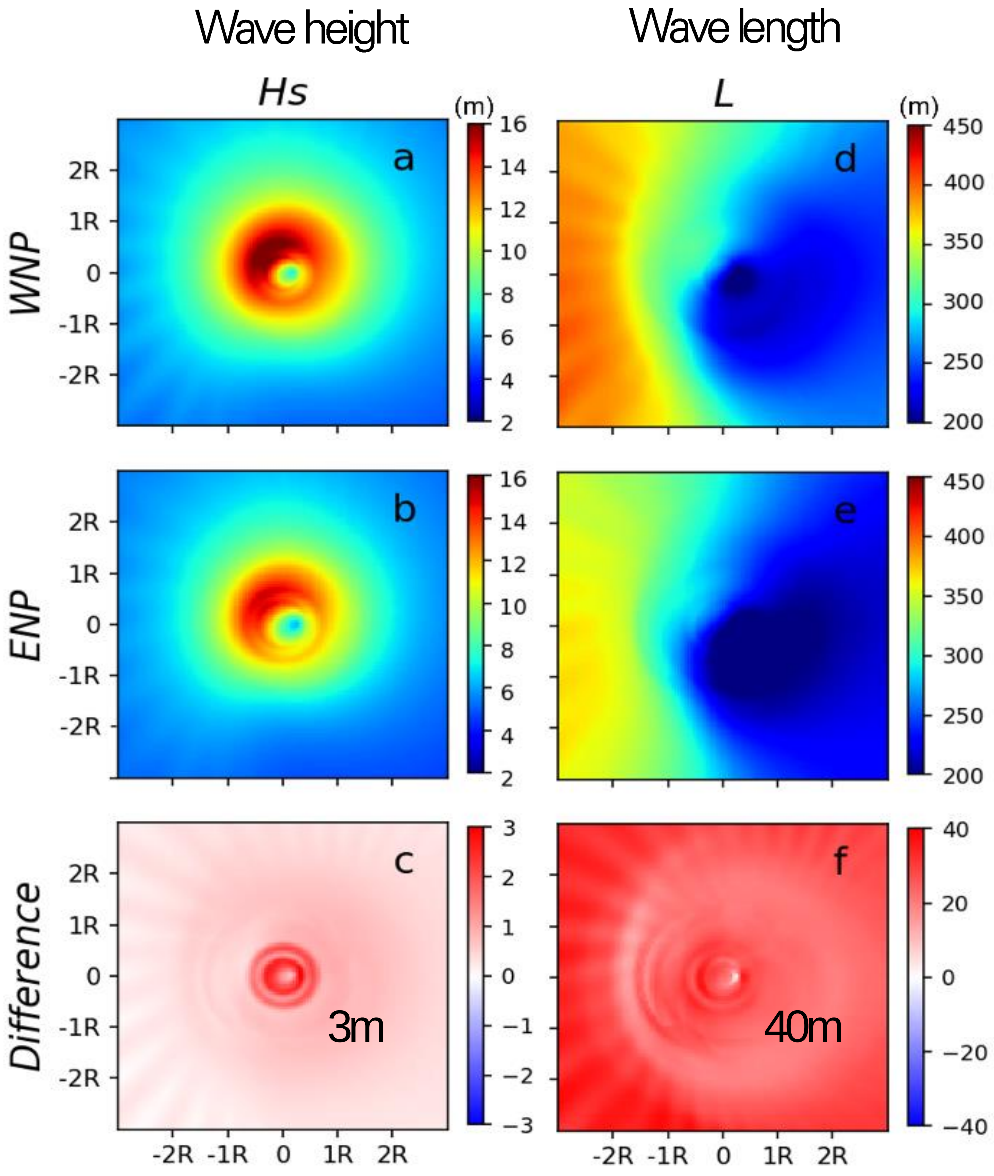


- ✓ A relatively smaller TC (like an ENP hurricane) produces a maximum sea-surface cooling of 6°C, while a relatively larger TC (like a WNP typhoon) produces cooling up to 8°C
- ✓ The ~2°C reduction in cooling for the (smaller) ENP hurricanes implies a crucial role for TC size in limiting to some extent the potentially large TC-induced surface cooling for ENP hurricanes that is due to factors such as the basin’s shallow mixed layer and steep thermocline

2. Roles of ocean waves



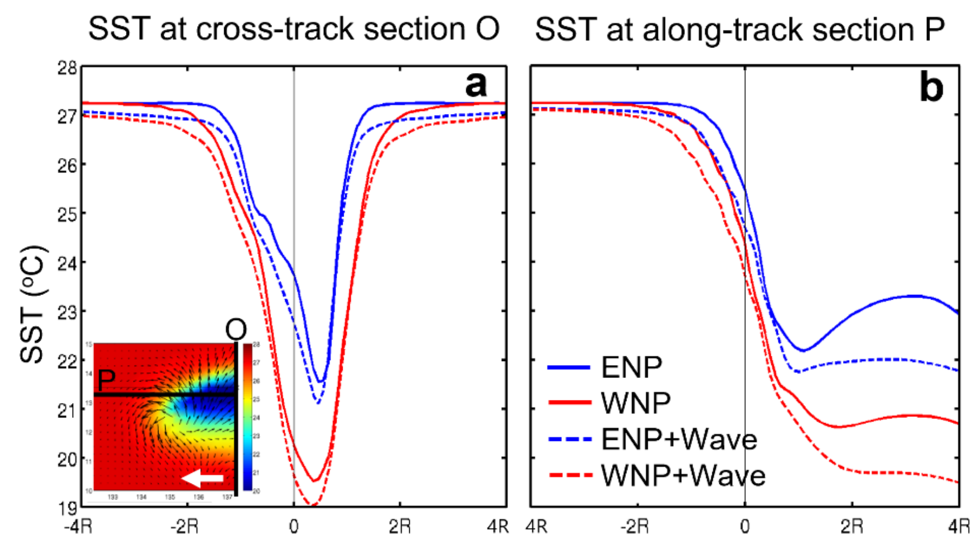


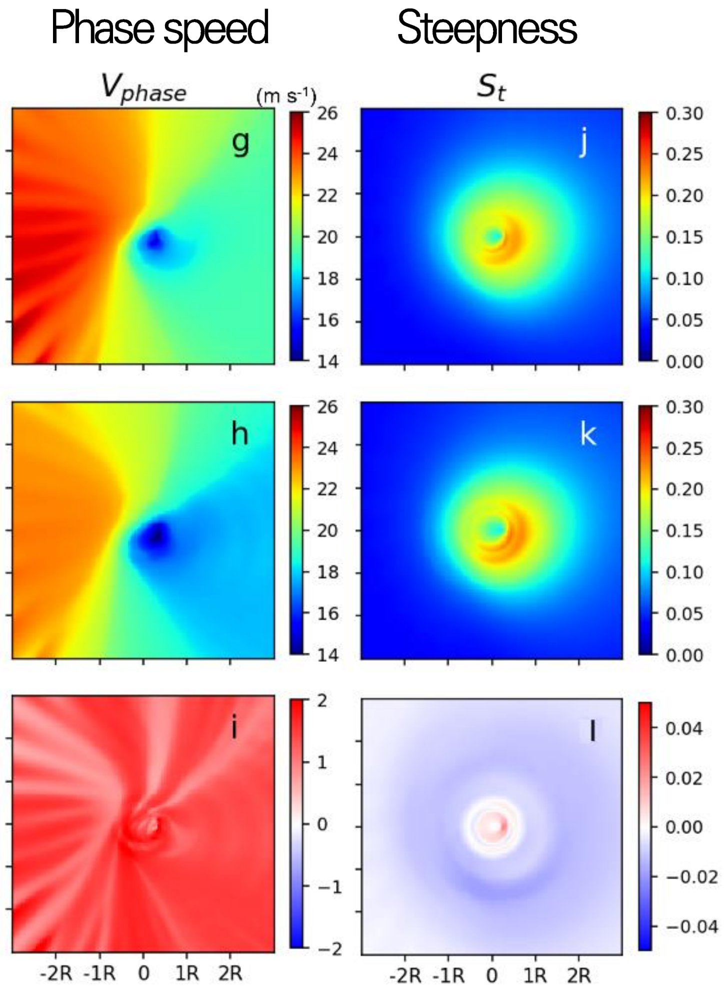


- ✓ The result of increased fetch and duration

2. Roles of *ocean waves*

- The increase of significant wave heights and wavelength can impact TC intensification through at least two physical processes: sea spray and wave-induced mixing.





1. An increase in the phase speed and a decrease in wave steepness -> unfavorable for sea spray generation -> negative feedback on intensification

2. Enhancing the TC-induced sea-surface cooling due to the additional wave-induced mixing from unbroken surface waves

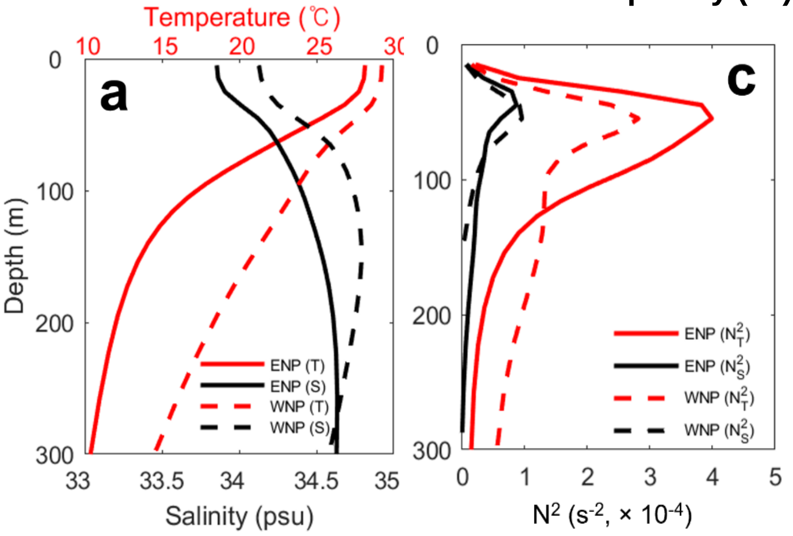
Both of these wave-related processes lead to less favorable conditions for the intensification of a large TC

3. Background oceanic environments

	OHC	SST_{pre}	SST_{during}	Cooling effect	T_{100}	PI_{pre}	PI_{during}	PI_{T100}	N^2	R_{SST}
WNP Typhoons	67.7 (51.0)	29.5 (29.5)	28.9 (28.6)	0.6 (0.9)	27.3 (27.3)	76.6 (75.8)	71.2 (67.0)	54.1 (53.3)	4.71 (5.18)	3.0 (2.6)
ENP Hurricanes	35.0 (24.2)	28.7 (28.5)	27.8 (27.0)	0.9 (1.5)	24.2 (24.1)	71.9 (70.1)	62.5 (53.8)	18.9 (17.6)	6.08 (5.71)	2.5 (1.9)
Difference (%)	32.7^{**} (26.8^{**})	0.8^{**} (1.0^{**})	1.1^{**} (1.6^{**})	0.3^{**} (0.6^{**})	3.1^{**} (3.3^{**})	4.7^{**} (5.7^{**})	8.7^{**} (13.2^{**})	35.2^{**} (35.7^{**})	1.37^{**} (0.53^{**})	0.5^{**} (0.7^{**})

Other values indicate ocean heat content (OHC; unit = kJ cm^{-2}), SST before the arrival of the TC (SST_{pre}, unit = °C), mixed ocean temperature to 100–m depth (T_{100}; unit = °C), SST underneath the TC (SST_{during}, unit = °C), cooling effect (SST_{pre}–SST_{during}, unit = °C), potential intensity based on SST_{pre}, SST_{during}, and T_{100} (PI_{SST}, PI_{during}, and PI_{T100}, respectively; unit = m s^{-1}), maximum oceanic Brunt–Väisälä frequency (N^2; unit = $10^{-4}×s^{-2}$), and relative SST, which is local SST relative to tropical mean SST (R_{SST}; unit = °C), averaged from the time of genesis to the lifetime maximum intensity (LMI) stage for all TCs that occurred in the ENP or WNP from 2001 to 2015. The parenthetical values for OHC, SST, Cooling effect, PI, N^2, and R_{SST} represent those at LMI stages. For T_{req} and IE, the parenthetical percentages in the 'Difference' row are the ratio of the absolute difference (WNP–ENP) to the smaller value. Asterisks denote statistically significant separation in the differences (* = 95% confidence; ** = 99% confidence).

Brunt–Väisälä frequency (N^2)



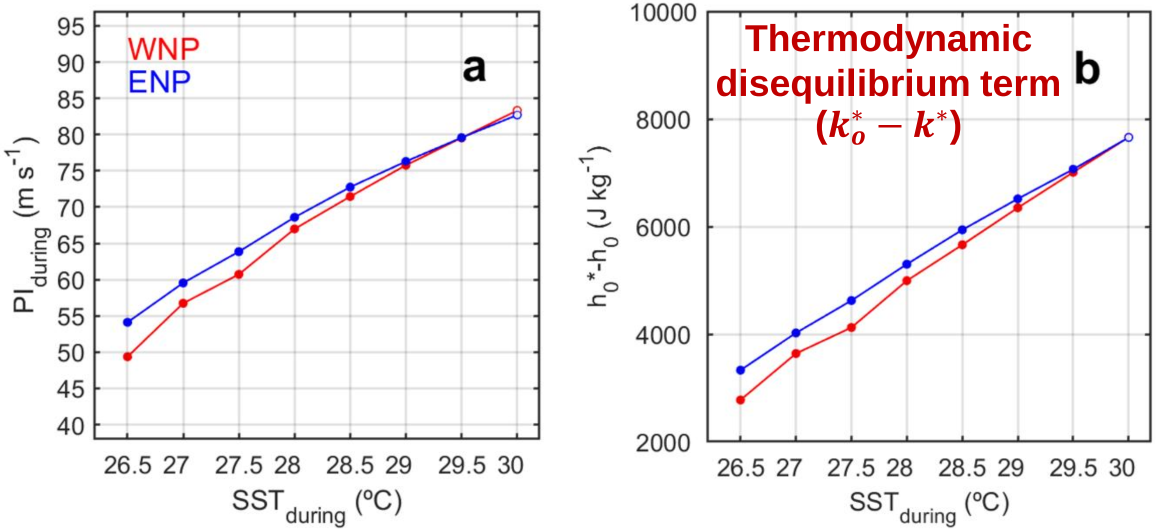
3. Background *atmospheric environments*

	LAT	V_{storm}	RT	VWS	IS	CAPE	SS	MSE	RH	q_s-q_a	$SST-T_a$
Typhoons in the WNP	17.7 (20.5)	5.0 (5.5)	14.3 (15.8)	7.7 (8.3)	8.7 (10.0)	652.7 (765.7)	177.9 (181.3)	338.6 (338.0)	63.5 (69.0)	1.10 (0.94)	11.28 (10.83)
Hurricanes in the ENP	15.2 (16.6)	4.6 (4.5)	11.3 (12.1)	6.0 (6.1)	7.7 (8.8)	328.6 (538.2)	178.1 (181.6)	336.9 (336.1)	61.3 (65.4)	1.48 (1.31)	11.37 (10.88)
Difference (%)	2.5^{**} (3.9^{**})	0.4^{**} (1.0^{**})	3.0^{*} (3.7^{**})	1.7^{**} (2.2^{**})	1.0^{**} (1.2^{**})	324.1^{**} (227.4^{**})	−0.2 (−0.3)	1.7^{**} (1.9^{**})	2.2^{**} (3.6^{**})	-0.38^{**} (-0.37^{**})	−0.09 (−0.05)

Some Values show latitude of TC center (LAT; unit = ^{0}N), storm translation speed (V_{storm}; unit = m s^{-1}), the residence time (RT; unit = h), vertical wind shear (VWS; unit = m s^{-1}), inertial stability (IS; unit = $10^{-4}\times s^{-2}$), convective available potential energy (CAPE; unit = J kg^{-1}), static stability (SS; unit = $10^{-6}\times s^{-2}$), moist static energy (MSE; unit = $10^{3}\times$kJ kg^{-1}), relative humidity (RH, unit = percent), the sea–air difference in specific humidity (q_s-q_a; unit = g kg^{-1}) and temperature ($SST-T_a$; unit = °C) at the air–sea interface, averaged from the time of genesis to the lifetime maximum intensity (LMI) stage for all TCs that occurred in the ENP or WNP from 2001 to 2015. Asterisks denote statistically significant separation in the differences (* = 95% confidence; ** = 99% confidence).

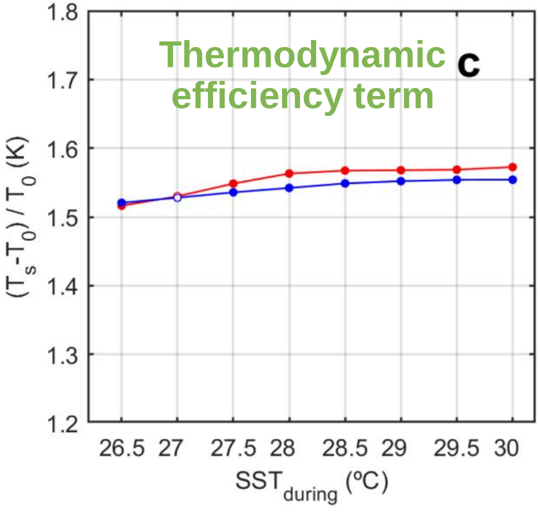
4. Background *atmospheric environments*

PI_{during} as a function of SST_{during}



$$\frac{g\,\left[\rho\,(z=-d) - \frac{-1}{d}\int_0^{-d}\rho(z)\,dz\right]d}{\rho_o\left(\frac{\tau}{\rho_o d}\frac{4R_h}{V_{storm}}S\right)^2} \geq 0.6$$

Price (1981)



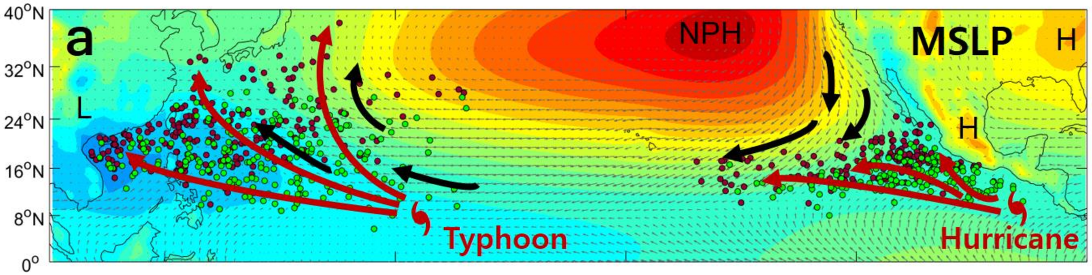
Thermodynamic efficiency term

Thermodynamic disequilibrium term $(h_o^* - h^*)$

$$PI_{during} = \boxed{\frac{SST_{during} - T_o}{T_o}}\,\boxed{\frac{C_k}{C_D}(k^* - k)}$$

5. Role of Latitudes

	LAT
Typhoons in the WNP	17.7 (20.5)
Hurricanes in the ENP	15.2 (16.6)
Difference (%)	2.5** (3.9**)



- ✓ It is known that TCs at low latitudes intensify more rapidly on average than those at higher latitudes.

- ✓ This is due to stronger and deeper friction-induced inflow under a lower planetary vorticity (small Coriolis parameter) environment and much larger diabatic heating rate, along with a larger radial gradient of diabatic heating above the boundary layer (Li et al. 2012; Smith et al. 2015).

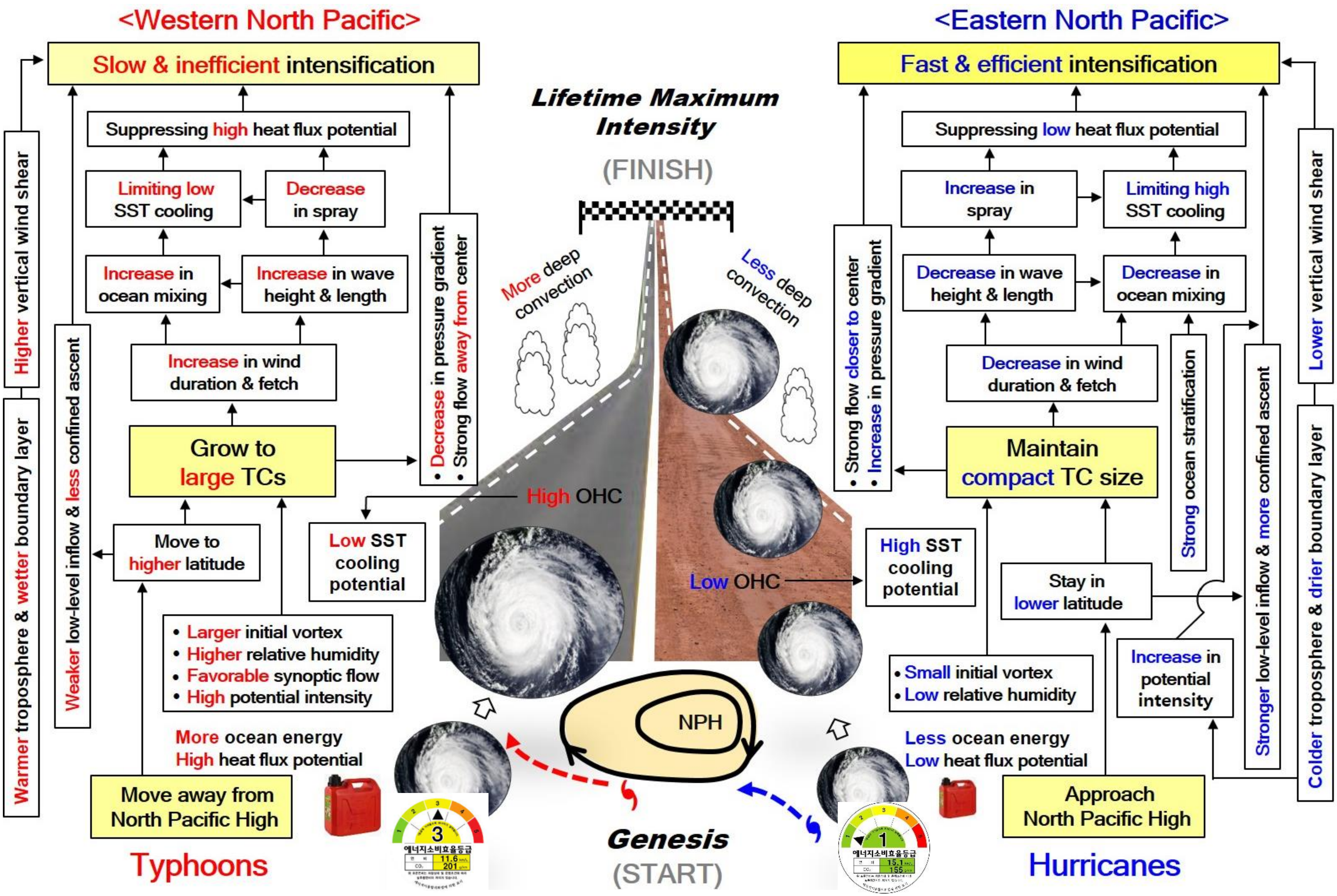
- ✓ In the ENP, once the TCs move away from the Mexican coast, their tracks mostly have a strong westward component and are confined to a relatively narrow low-latitude region south of 20°N.

- ✓ In the WNP, tracks are more distributed across a broad region meridionally, even reaching north of 30°N. This is due to the typical circulation around the North Pacific High (Wood and Ritchie 2015).

- ✓ The difference in the mean TC occurrence latitude between the two basins is 2.5° and reaches up to 3.9° at the LMI stage

- ✓ The higher average latitude of TC occurrence in the WNP basin thus may contribute to the larger TC sizes there relative to the ENP and through that mechanism may also contribute to the slower TC intensification in the WNP.

Why do eastern ENP hurricanes intensify more and faster than WNP typhoons with less ocean energy?



<Western North Pacific>

Slow & inefficient intensification

- Suppressing high heat flux potential
- Limiting low SST cooling
- Decrease in spray
- Increase in ocean mixing
- Increase in wave height & length
- Increase in wind duration & fetch
- Grow to large TCs
- • Decrease in pressure gradient
- • Strong flow away from center
- Move to higher latitude
- Low SST cooling potential
- • Larger initial vortex
- • Higher relative humidity
- • Favorable synoptic flow
- • High potential intensity
- Higher vertical wind shear
- Warmer troposphere & wetter boundary layer
- Weaker low-level inflow & less confined ascent
- More ocean energy
- High heat flux potential
- Move away from North Pacific High

Typhoons

<Eastern North Pacific>

Fast & efficient intensification

- Suppressing low heat flux potential
- Increase in spray
- Limiting high SST cooling
- Decrease in wave height & length
- Decrease in ocean mixing
- Decrease in wind duration & fetch
- Maintain compact TC size
- • Strong flow closer to center
- • Increase in pressure gradient
- Strong ocean stratification
- High SST cooling potential
- Stay in lower latitude
- • Small initial vortex
- • Low relative humidity
- Increase in potential intensity
- Lower vertical wind shear
- Colder troposphere & drier boundary layer
- Stronger low-level inflow & more confined ascent
- Less ocean energy
- Low heat flux potential
- Approach North Pacific High

Hurricanes

Lifetime Maximum Intensity

(FINISH)

More deep convection

Less deep convection

High OHC

Low OHC

NPH

Genesis

(START)

Discussions

- ✓ Highlight the importance of several factors, including TC size, latitude, and ocean waves

- ✓ Emphasizing the importance of accurate TC size prediction

- ✓ Limitation of TC size prediction skills

- ✓ Higher resolution models.

- ✓ Ocean wave coupling

감사합니다.

- ✓ We are recruiting postdoctoral researchers, graduate students, and visiting scientists to conduct research (open topic) related to tropical cyclones.
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