Global warming-induced warmer surface water over the East China Sea can intensify super typhoons like Hinnamnor

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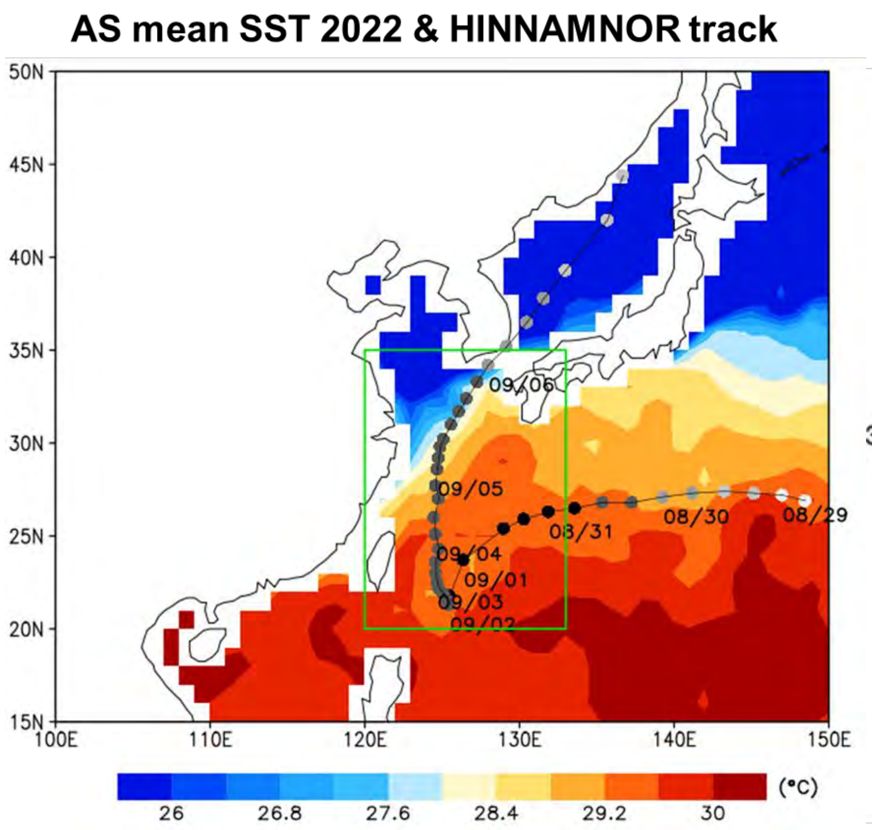
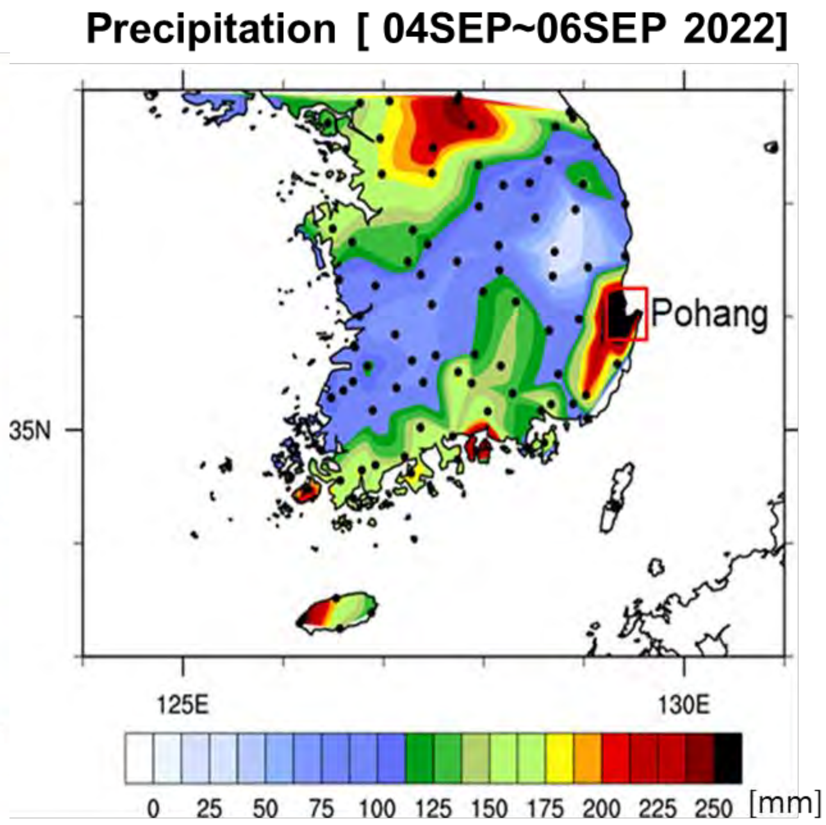
Kim et al. (2024, BAMS)

Typhoon Hinnamnor





- **First typhoon with Lifetime Maximum Intensity (LMI) recorded at the highest latitude (30°N)**
- **Strong Landfall intensity** (955.9hPa and 43.1m/s)
  → **record-breaking heavy precipitation**
  Pohang : 342.4mm/day
  Gyeongju : 212.3mm/day
- **Re-strengthened** while moving northward
- **SST remained above 29°C** in East China Sea (ECS) during 2022 August-September (AS)

Objective

Quantitatively assessing the contribution of human activities to the increase of SST and subsurface ocean heat content in the East Chia Sea (EAS) during Aug-Sep 2022 that led to re-intensification of typhoon like Hinnamnor

- Conduct an observational analysis to check the relationship between SST over ECS and TC intensities affecting the Korean Peninsula for 1982–2022

- Compare the probability of warm surface ocean exceeding the 2022 observed values between real and counterfactual world conditions using CMIP6 historical simulations with and without human influences (ALL vs. NAT)

- Estimate the associated future probability of Hinnamnor-like strong TC occurrences using CMIP6 future simulations (SSP1-2.6 vs. SSP2-4.5)

Data

TCHP (tropical cyclone heat potential)

$$Q_{TCHP} = \sum_{h=0}^{H} \rho_h C_p (T_h - 26) \Delta Z_h$$

ρ_h: density of the sea water
C_p: specific heat capacity
T_h : sea water temperature at each layer
ΔZ_h : thickness at each layer
H : vertical level of depth corresponding to the isotherm of 26°C
h : vertical level

Observations

- Best track : JTWC, RSMC, KMA
- SST : OISST v2, interpolation onto 1° x1° grids
- Potential temperature : NCEP GODAS to calculate TCHP
- Analysis period : 1982-2022
- Climatology period : 1991-2020

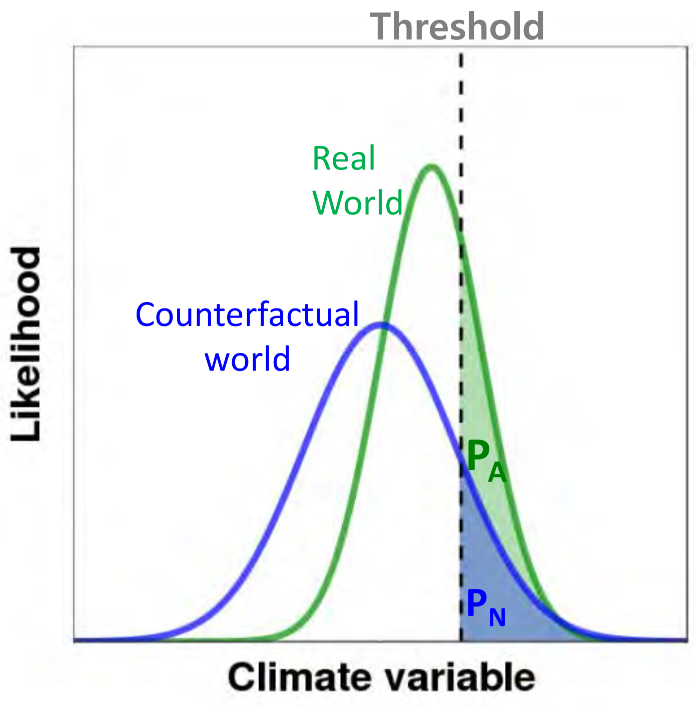
Model simulations

- GCM - 8 CMIP6 models (27 runs)
  - ALL (anthropogenic plus natural) historical + SSP2-4.5
  - NAT (natural only forcing)
  - SSP2-4.5 (fossil-fueled development-taking the high way)
  - SSP1-2.6 (Sustainability-taking the green road)
  - Analysis period : 2001-2020 (20 years)
  - No. of Ensemble : 540 (20 years ×27 runs)
  - Interpolation onto 1° x 1° grids
  - Anomalies in all CMIP6 simulations are relative to the 1991-2020 mean of ALL simulations

Model [Experiment]		No. runs	No. 41-yr chunks [CTL]
CMIP6 [ALL, NAT, SSP1-2.6, SSP2-4.5]	ACCESS-ESM1-5	3	21
	BCC-CSM2-MR	1	14
	CanESM5	10	24
	CNRM-CM6-1	3	12
	HadGEM3-GC31-LL	1	12
	IPSL-CM6A-LR	3	48
	MRI-ESM2-0	3	17
	NorESM2-LM	3 (1 for SSP1-2.6)	12
	total	27 runs (25 for SSP1-2.6)	160

Risk Ratio (RR) analysis

- Quantifying anthropogenic influence on extreme events (Stott et al. 2004, Nature)
- Comparing the probability of extreme events occurring in **a real world (with human influence)** **with that in a counterfactual world (without human influence)**



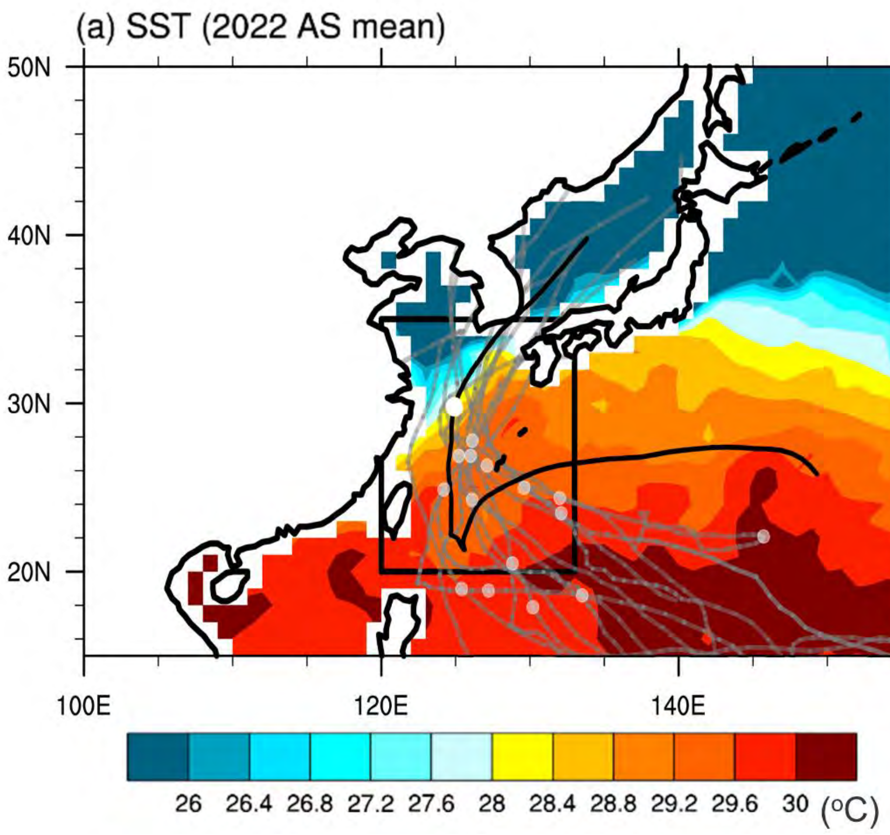
RR = P_A/P_N

P_N : Probability that extremes will occur exceeding the observed strength in **natural unforced conditions** (**NAT**)

P_A : Probability estimated in **anthropogenic forced conditions** (**ALL**)

- RR of 2 and 3 mean extreme event 2 and 3 times more likely.
- Confidence interval : likelihood ratio method (Paciorek et al. 2018)

TC selection for observational analysis

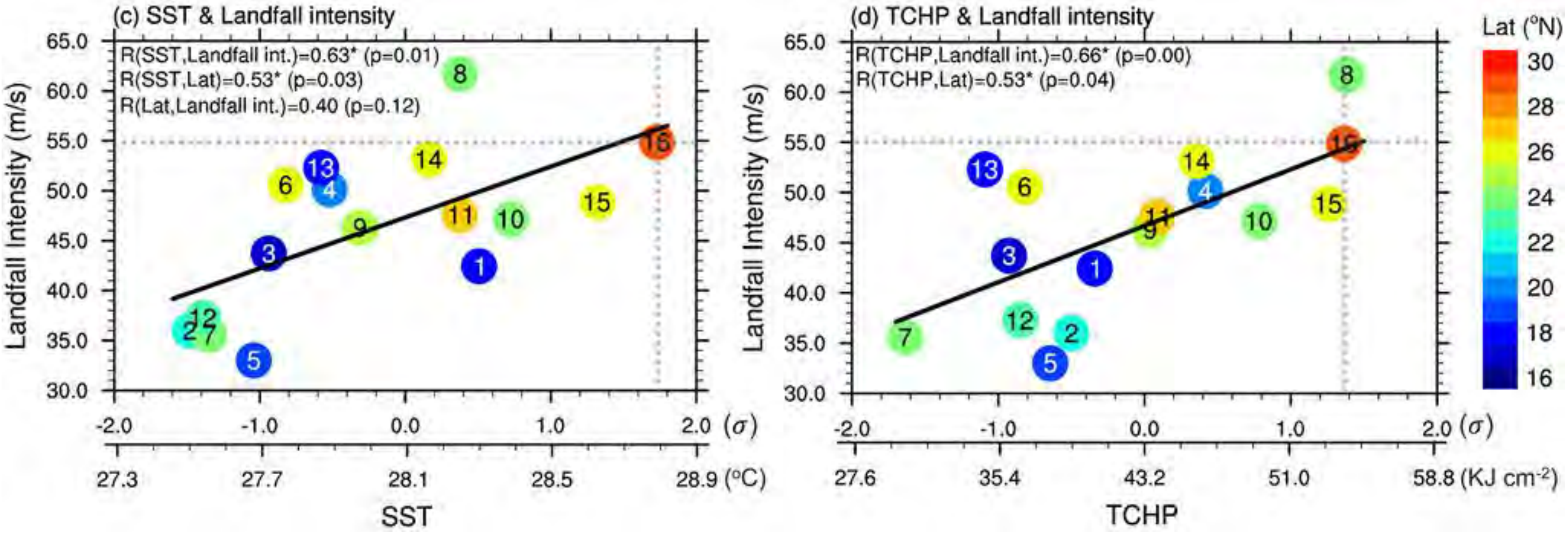


	TC name	year	LMI-lat (°N)	LMI [knot]	Landfall int. [knot]
1	FORREST	1983	18.6	150	82.5
2	VERA	1986	22.1	110	70
3	DINAH	1987	17.9	130	85
4	MIREILLE	1991	20.5	130	97.5
5	DOUG	1994	19	140	64.17
6	BART	1999	26.3	140	98.33
7	SAOMAI	2000	24.4	140	69.17
8	MAEMI	2003	24.3	150	120
9	SONGDA	2004	25	125	90
10	SHANSHAN	2006	24.9	120	91.67
11	NARI	2007	27.8	125	92.5
12	BOLAVEN	2012	23.5	125	72.5
13	GONI	2015	18.9	120	101.67
14	LINGLING	2019	26.9	120	103.33
15	MAYSAK	2020	26.9	120	95
16	**HINNAMNOR**	**2022**	**29.8**	**110**	**106.67**

During 1982 - 2022, In August and September, over Western Pacific

1) **Lifetime maximum intensity (LMI)** of TCs **exceeds 54 m/s** (“very strong” category in KMA’s classification)
2) **Landfall intensity** on the Korean Peninsular (center of TC ~3°) **exceeds 33 m/s** (“strong” category)
3) TCs **remain in the ECS for at least 72 hours**

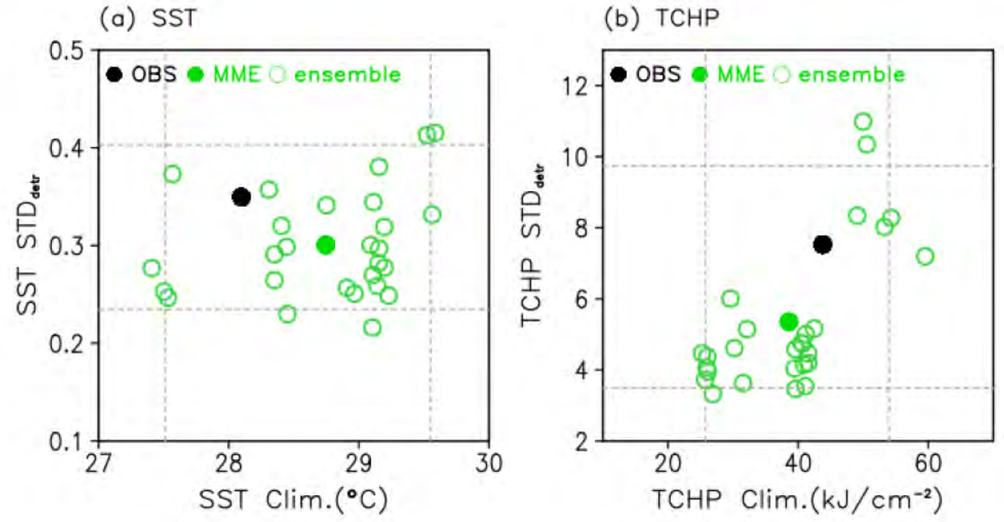
Relationship between SST & TCs

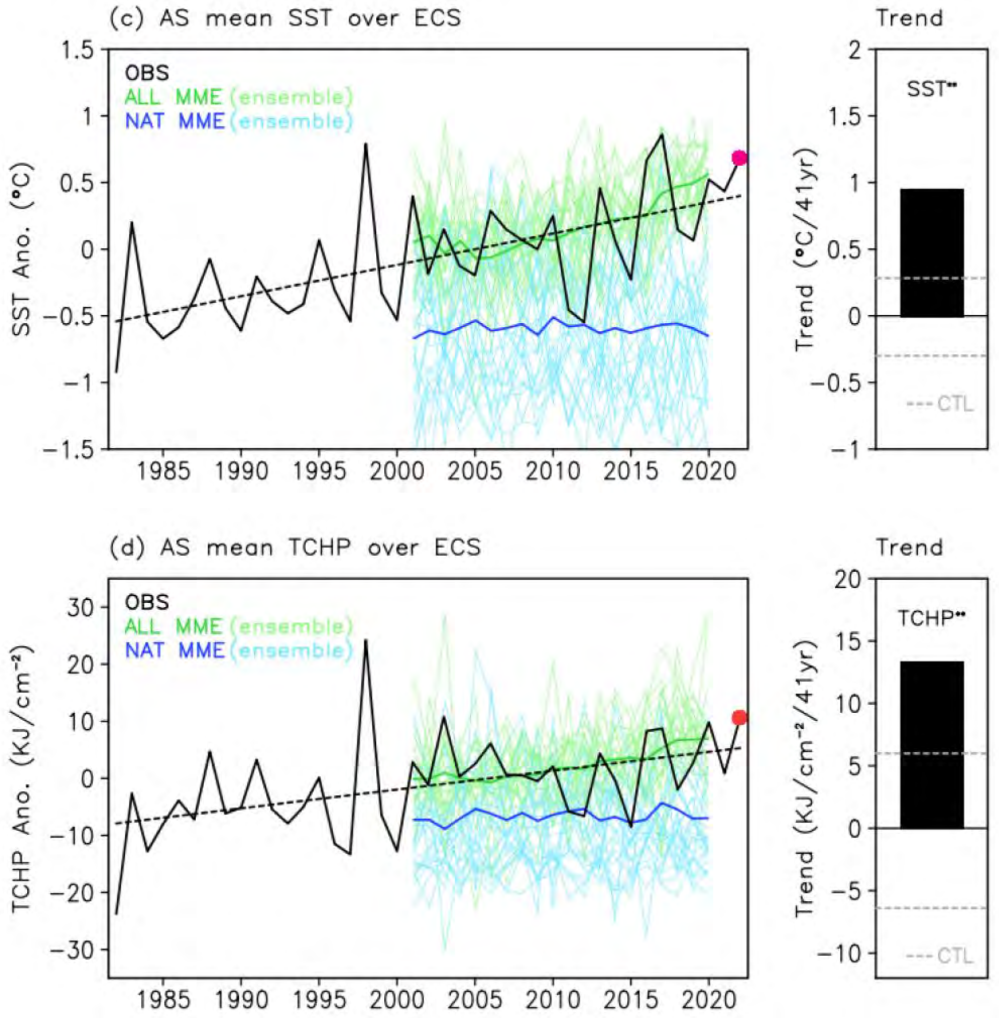


1. FORREST (1983) 2. VERA (1986) 3. DINAH (1987) 4. MIREILLE (1991) 5. DOUG (1994) 6. BART (1999)
7. SAOMAI (2000) 8. MAEMI (2003) 9. SONGDA (2004) 10. SHANSHAN (2006) 11. NARI (2007) 12. BOLAVEN (2012)
13. GONI (2015) 14. LINGLING (2019) 15. MAYSAK (2020) 16. HINNAMNOR (2022)

Warmer SST and higher TCHP over ECS
→ stronger landfall intensity & maximum intensification latitude
TCs intensifying at higher latitudes → stronger landfall intensity on the Korean Peninsula

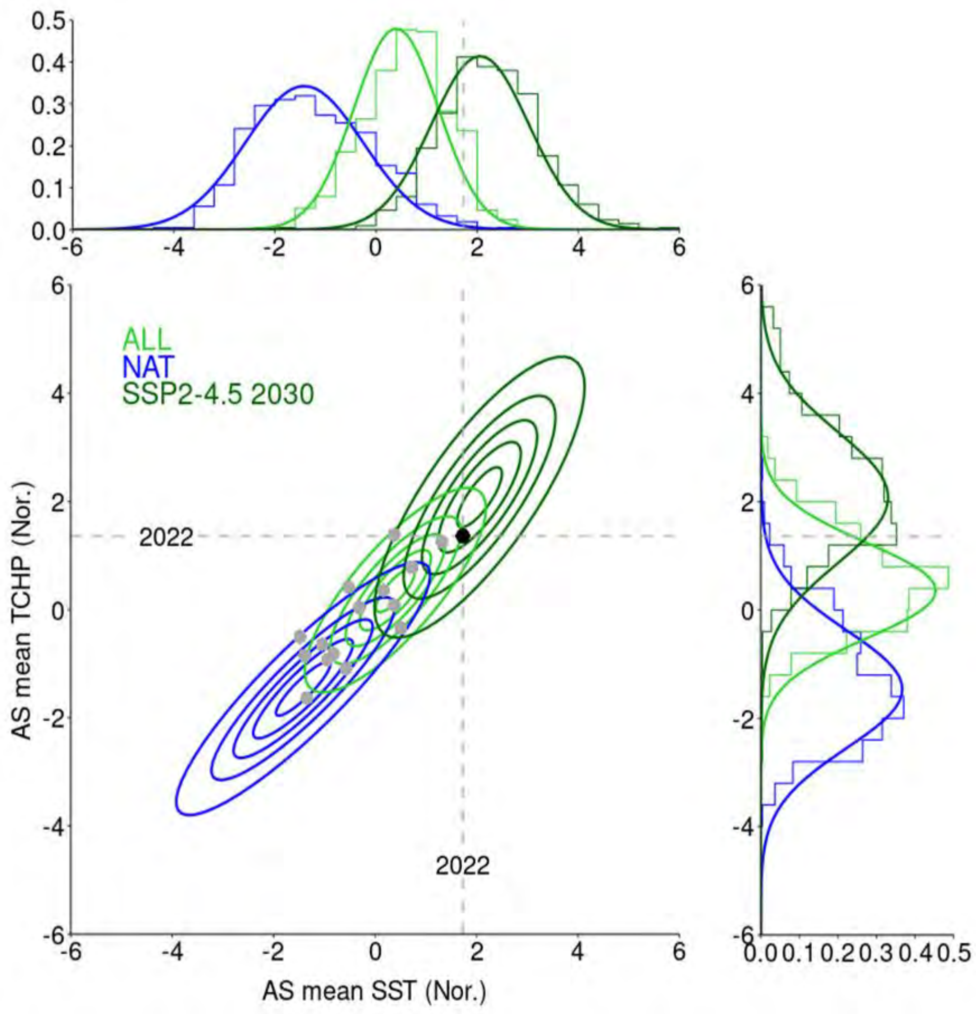
East China Sea SST





- CMIP6 models show reasonable skills for climatology and variability of SST and TCHP
- ALL runs capture the observed increasing trends in SST and TCHP trend, well beyond the internal variability range (estimated by CTL)

CMIP6-based attribution



	Observation (σ)	Probability of Occurrence		Risk Ratio
SST	1.73	P_{ALL}	5.0%	13.5 (4.8-58.4)
		P_{NAT}	0.4%	
TCHP	1.36	P_{ALL}	14.63%	26.3 (11.4-82.0)
		P_{NAT}	0.6%	
Joint	SST≥1.73 & TCHP ≥1.36	P_{ALL}	3.89%	21 (5.4-202.5)
		P_{NAT}	0.2%	

- The risk of 2022-like warm water over ECS has increased **at least five times** due to anthropogenic forcing

CMIP6-based projections

- **How often 2022-like warming will occur in the future based on SSP1-2.6 and SSP2-4.5 scenarios?**
- In the 2030s, 2022-like warming occurs about one in 2 years [new normal]
- After the 2050s, 2022-like warming will be experienced every year → **background warm water condition over ECS becomes enough to intensify TC once develop**
- Future probability of Hinnamnor-like strong TC occurrence = warm water return period x strong TC return period (2.56 year = 16 TCs during 41 years)
- **Hinnamnor-like strong TCs every five year in the 2030s, every 2-3 years after the 2050s**
- **Irrespective of emission scenarios**

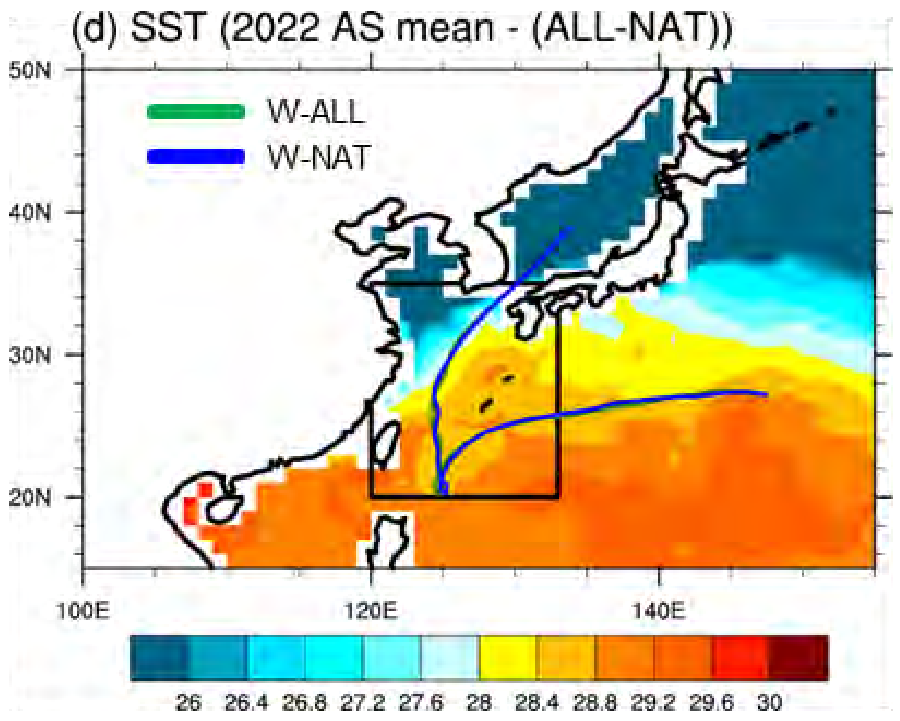
Summary

- TC Hinamnor has been reinforced during its northward movement over the unusually warm ECS.
- **2022-like warm surface water** has become **at least five times more likely due to human activities** comparing the ALL and NAT simulation from CMIP6 GCMs.
- This warm surface ocean is expected to become **normal in the 2030s under both SSP1-2.6 and SSP2-4.5** scenarios → **much higher chances of Hinnamnor-like super typhoons affecting East Asia with maintaining their intensities up to higher latitudes.**
- **Results are insensitive to emission scenarios**, emphasizing the urgency of immediate preparation of adaptation measures for strong TCs.
- Convection-permitting simulations with WRF model support that **warmer SST contribute to the intensity and long-duration of TCs**

WRF model experiment

<Model configuration>

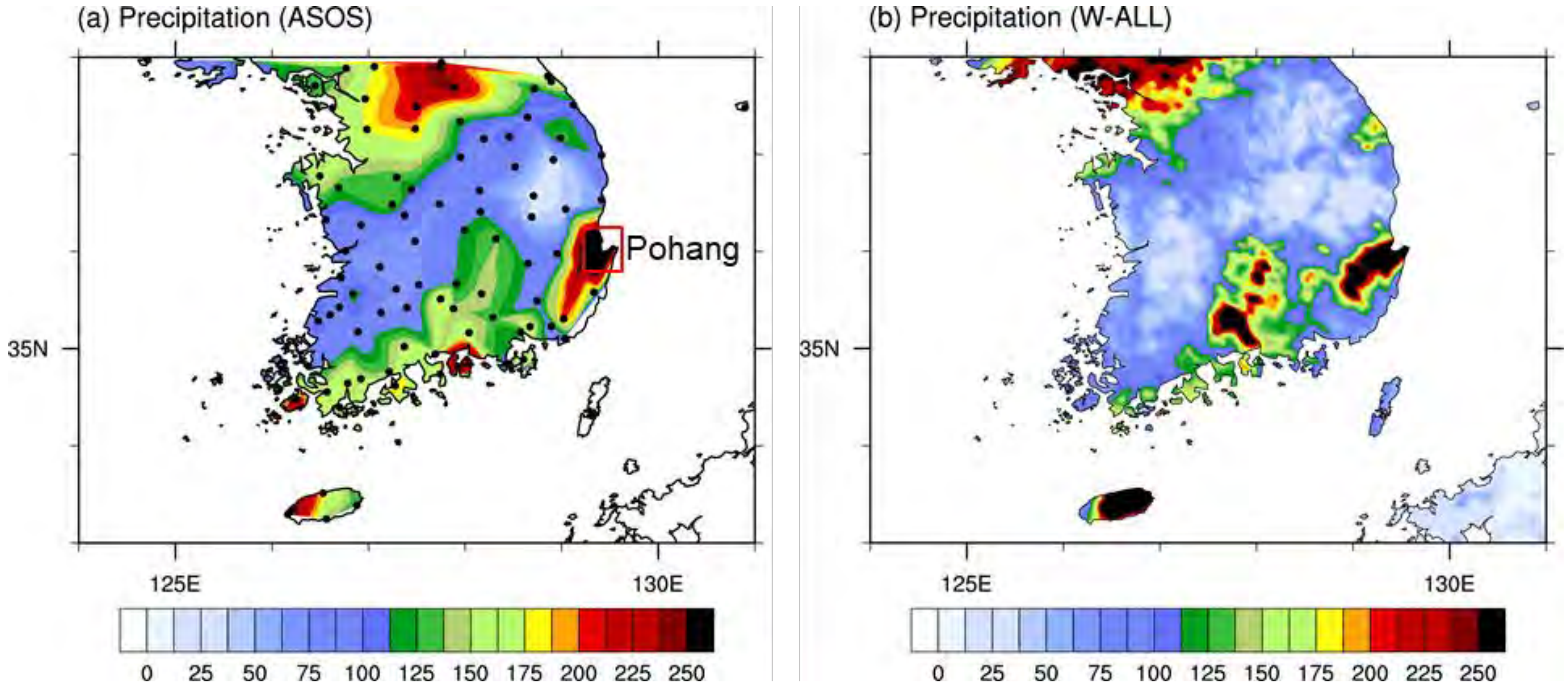
Model	WRF v4.0
Horizontal dimensions (lat x lon)	1801 x 2001
Horizontal resolution	3 km
Lateral boundary condition	ERA5
SST data	OISST
Vertical levels	50
Microphysics	WSM6
Planetary boundary layer	YSU
Convection scheme	Turn off



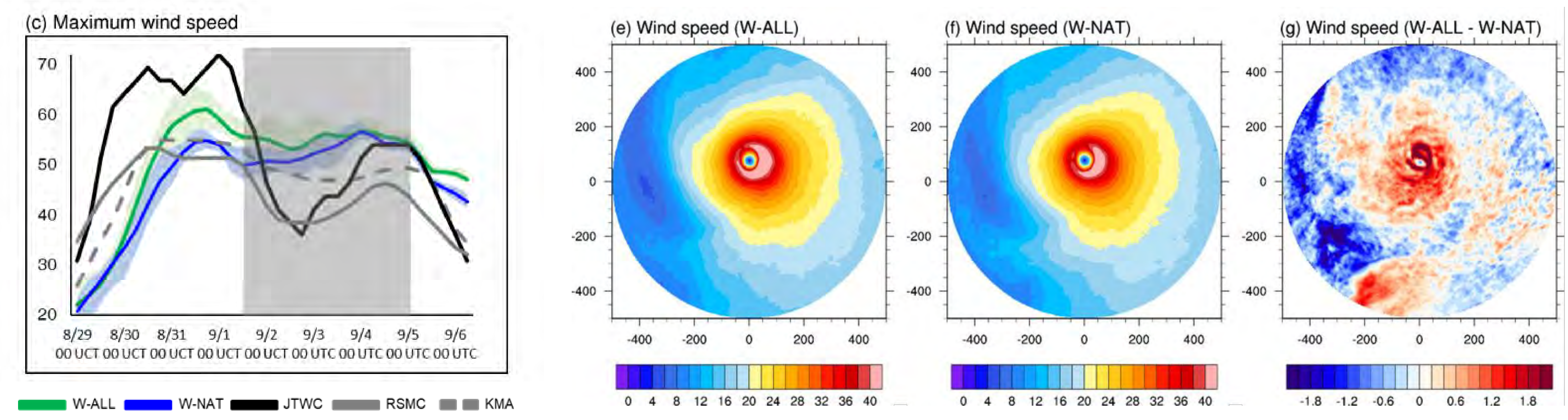
delta-SST : 0.68°C over ECS

Integration time : 06 UTC 28 AUG ~ 06UTC 06 SEP 2022
Spectral nudging technique is applied to keep the observed TC tracks
W-ALL : ERA5 & OISST
W-NAT : 2022 AS mean **SST, TAS, RH** – anthropogenic warming pattern (2011-2020 AS mean)
Anthropogenic warming pattern (delta) : ALL_{cmip6}-NAT_{cmip6}

WRF model evaluation [precipitation]



WRF model results



- **Increase in wind speed under warmer SST, more strongly near the eyewall**
- The early rapid intensification and subsequent weakening is underestimated
- TC landfall intensity does not show a significant difference between W-ALL and W-NAT
- Lack of air–sea interactions and no consideration of the climate change influence on TC tracks

→ **supporting the contribution of warmer SST on the intensity of TCs**