Explaining Extreme Events from a Climate Perspective

Global Warming–Induced Warmer Surface Water over the East China Sea Can Intensify Typhoons like Hinnamnor

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1. Introduction

In early September 2022, tropical cyclone (TC) Hinnamnor struck South Korea, resulting in 12 fatalities and tremendous socioeconomic damages. 1 Hinnamnor was the first super typhoon (lifetime maximum wind speed > 51 m s⁻¹) that maintained its strong intensity at a high latitude near 30°N (Fig. 1c) based on the observations since 1982. Hinnamnor’s landfall intensity was very strong (955.9 hPa and 43.1 m s⁻¹), bringing record-breaking heavy precipitation along the eastern coast of Korea such as Pohang (342.4 mm day⁻¹) and Gyeongju (212.3 mm day⁻¹) [Korea Meteorological Administration (KMA) 2023; Fig. 1b]. Unlike typical TCs, Hinnamnor restrengthened while moving northward. The unusually warm surface water over the East China Sea (ECS) seems to have contributed to its restrengthening (Cho et al. 2022). Indeed, the August–September (AS) 2022 mean sea surface temperature (SST) remained above 29°C in the large part of ECS (Fig. 1a), and this corresponds to the warmest record among the years when strong TCs having similar tracks affected South Korea (Fig. 1c; see below for selection categories). Given possible increases in long-lasting super typhoon affecting East Asia, assessing human contribution to the surface ocean precondition over ECS will provide useful insights into future projections and associated adaption measures.

This study aims at quantifying anthropogenic influences on the increase of SST and subsurface ocean heat content over ECS during AS 2022, which likely favored...
Hinnamnor's reintensification. We compare the probability of warm surface ocean exceeding the 2022 observed values between real and counterfactual world conditions by using multimodel simulations from phase 6 of Coupled Model Intercomparison Project (CMIP6) historical (ALL) and historicalNat (NAT) experiments, respectively.

2. Data and methods
To analyze the relationship between warm surface water over ECS and the TC track and intensity, we use best track datasets from the Joint Typhoon Warning Center (JTWC), Regional Specialized Meteorological Centers (RSMC), and KMA as observations during 1982–2022. The Optimum Interpolation Sea Surface Temperature (OISST), version 2.0 (Reynolds et al. 2002), is used after interpolation onto 1° × 1° grids for comparison with CMIP6 model simulations. To consider upper ocean heat content, we also analyze the tropical cyclone heat potential (TCHP),
which plays an important role in TC intensity and its intensification (Wada and Usui 2007). TCHP is defined as vertically integrated heat energy from the ocean surface to a depth of 26°C isotherm (Leipper and Volgenau 1972). Potential temperature data from the National Centers for Environmental Prediction (NCEP) Global Ocean Data Assimilation System (GODAS) are used for TCHP calculation, and its top layer (5-m depth) temperature shows good agreement with OISST during AS 2022 (not shown).

To assess anthropogenic influences on regional SST and TCHP, we use CMIP6 (Eyring et al. 2016) multimodel simulations (eight models providing 27 ensemble members, see Table ES1 in the online supplemental material) performed under historical (anthropogenic plus natural, ALL) and historicalNat (volcanic and solar forcing only, NAT) for 2001–20. The ALL simulations are extended to 2020 with the shared socioeconomic pathways (SSP; O’Neill et al. 2016) 2-4.5 scenario for 2015–20. Future simulations for 2021–2100 under the SSP 1-2.6 and 2-4.5 scenarios are also used. We use 20-yr periods from current and future simulations (moving windows), which yield 540 samples (20 years × 27 ensemble members) for each experiment or scenario. The anomalies in all CMIP6 simulations are relative to the 1991–2020 mean of ALL simulations. The ALL simulations on average capture the observed climatology and interannual variability of ECS mean SST and TCHP (Figs. ES1a,b) although there are large intermodel differences. To consider possible influences of model biases, we normalize observed and simulated values of SST and TCHP with respect to corresponding interannual standard deviations obtained from the reference period (1991–2020). Nevertheless, when repeating our analysis using absolute magnitude of SST, main results remain unaffected (not shown). NAT and future simulation values are normalized based on ALL climatology.

To quantify the influence of human activities on SST and TCHP, we calculate a risk ratio (RR), which is defined as $RR_{ALL/NAT} = \frac{P_{ALL}}{P_{NAT}}$ (Fischer and Knutti 2015). The probability of the extreme events under a real-world condition ($P_{ALL}$) is compared to that under a counter-factual world condition without human influences ($P_{NAT}$). The RR is also calculated for joint probability for SST and TCHP exceeding the 2022 thresholds. The 90% confidence intervals of RR are estimated by the likelihood ratio method (Paciorek et al. 2018).

To further evaluate regional warm water influence on TC, we conduct Weather Research and Forecasting (WRF) Model experiments to simulate Hinnamnor under the observed SST and cooler conditions by removing anthropogenic warming (refer to the supplemental text for details).

3. Results

We first conduct an observational analysis to check the relationship between SST over ECS and TC intensities affecting the Korean Peninsula during AS for 1982–2022. Fifteen TCs are selected based on their tracks and land-fall intensities: lifetime maximum intensity of TCs exceeds 54 m s$^{-1}$ (“very strong” category in the KMA’s typhoon classification, Kim et al. 2022), landfall intensity on the Korean Peninsula exceeds 33 m s$^{-1}$ (“strong” category), and TCs remain within the ECS (black box in Fig. 1a) for at least 72 h. Here, landfall intensity is defined as the intensity when the center of TC approaches within 3$^\circ$ from the Korean Peninsula. Although other environmental factors like relative humidity and vertical wind shear can affect the TC intensity, we focus our analysis on SST and TCHP which exhibit most noticeable increases in line with anthropogenic warming. Results show that warmer SST (averaged over the whole ECS) is associated with stronger landfall intensity (Fig. 1c, $r = 0.63$) and the maximum intensification latitude ($r = 0.53$), which are statistically significant at 5% level. The same analysis using the observed TCHP shows similar results (Fig. 1d), with higher TCHP significantly contributing to the TC intensification at higher latitudes ($r = 0.53$) and the stronger landfall intensity ($r = 0.66$). TCs intensifying at higher latitudes...
tend to exhibit stronger landfall intensity on the Korean Peninsula ($r = 0.40$) although their correlation is not significant. When applying different thresholds for landfall intensity ($25 \text{ m s}^{-1}$; “normal” typhoon based on the KMA’s classification) or minimum duration time over ECS ($48 \text{ h}$), these relations remain largely unaffected (not shown). Note that the regression lines do not indicate anthropogenic warming component alone due to the possible influences of natural variability (Vecchi et al. 2008).

CMIP6 results show that the observed warmer conditions over ECS during 2001–20 are reproduced only when including human influences (Figs. ES1c,d). Using 540 samples from ALL and NAT simulations, we compare the probability of occurrences of warm SST and TCHP events in ECS exceeding the observed condition in AS 2022 ($1.73\sigma$ and $1.36\sigma$, respectively). Figure 2a illustrates the joint probability distribution of ECS mean SST and TCHP obtained from ALL (green) and NAT (blue) runs. The probability of normalized SST and TCHP higher than the observed 2022 values is 5.0% and 14.63% in ALL ($p_{\text{ALL}}$) and 0.4% and 0.6% in NAT ($p_{\text{NAT}}$), respectively (Table 1). The corresponding RR is 13.5 (4.8–58.4, 90% confidence interval) for SST and 26.3 (11.4–82.0) for TCHP. The RR of the joint probability of SST and TCHP is 21 (5.4–202.5), indicating that the risk of 2022-like warm water over ECS has increased at least five times due to anthropogenic forcing. Note that since SST and TCHP are highly corrected ($r = 0.84$), the joint probability remains as large as those in univariate cases (Table 1). The observed trends of ECS mean SST and TCHP during 1982–2022 are statistically significant and well beyond the naturally driven ranges (Fig. ES1c) in line with the warm pool expansion under global warming (Weller et al. 2016; Roxy et al. 2019).

We have further checked how often 2022-like warming will occur in the future based on the SSP1-2.6 and SSP2-4.5 scenarios. Figure 2b displays changes in return periods for the...
2022-like AS mean SST and TCHP estimated from 2010s (2001–20) to 2090s (2081–2100). In both scenarios, 2022-like warming occurs about one in 2 years around 2030s, representing a new normal (dark green lines in Fig. 2a; Lewis et al. 2017). After 2050s, such events will be experienced every year, indicating that the background surface condition over ECS becomes warm enough (i.e., exceeding the 2022 observations) to intensify TCs once they develop. To estimate the associated future probability of Hinnamnor-like strong TC occurrences, we have multiplied the return periods of warm water by the return period of strong TCs passing through the ECS and affecting South Korea (2.56 years = 16 TCs during 41 years, see Fig. 1a). Results indicate that even though we assume no future increases in the frequency of strong TCs affecting East Asia, we are expected to have Hinnamnor-like strong TCs every 5 years around 2030s and every 2–3 years after 2050s (numbers over the bars in Fig. 2b), irrespective of emission pathways. We note that this simple projection is based on the assumption that the statistical relation between the ECS mean SST and TCHP and the TC landfall intensity (Figs. 1c,d) will remain in the future, which may not be the case due to the impacts of other factors (e.g., Vecchi et al. 2008).

We have further checked the impact of regional warm water on TC intensification using five-member ensemble simulations using a high-resolution (3 km) WRF Model under real and counterfactual world conditions (W-ALL and W-NAT, respectively; refer to the supplemental text for details). Results show that observed heavy precipitation is reproduced realistically in W-ALL (cf. Fig. ES2a with Fig. 1b). While both W-ALL and W-NAT experiments capture the observed TC tracks (Fig. ES2b) due to the use of spectral nudging, temporal evolution of TC intensities is hardly reproduced. In particular, the early rapid intensification and subsequent weakening during 29 August–2 September are underestimated (Figs. ES2c,d), which may be partly due to the omission of the influence of low-salinity waters of the Yangtze River in the East China Sea (Hong et al. 2022; Oh et al. 2023) and the TC-generated surface cooling effect (Huang et al. 2015; Chu et al. 2020). Further, TC landfall intensity does not show a significant difference between W-ALL and W-NAT (based on a paired t test). Nevertheless, TC wind speed averaged during the TC’s northward path through ECS (gray shading in Figs. ES2c,d) shows an increase under warmer SST, especially near the eyewall (Figs. ES2e–g). These WRF-based results suggest the contribution of warmer SST on the intensity of TCs although caveats remain due to the lack of air–sea interactions and no consideration of the climate change influence on TC tracks. In addition, since the WRF-based results assume the existence of a set of historical typhoons under climate warming conditions, the model results do not address the question of the influence of anthropogenic warming on the frequency of TCs in the ECS region or affecting Korea.

### Table 1. Probability of occurrence of the AS mean SST and TCHP averaged over ECS exceeding the observed 2022 threshold and corresponding RR. Values in parentheses indicate 90% confidence intervals of RR.

<table>
<thead>
<tr>
<th>Observation ($\sigma$)</th>
<th>Probability of occurrence</th>
<th>RR</th>
</tr>
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<tbody>
<tr>
<td>SST 1.73</td>
<td>$P_{\text{ALL}}$ 5.0%</td>
<td>13.5 (4.8–58.4)</td>
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<td></td>
<td>$P_{\text{NAT}}$ 0.4%</td>
<td></td>
</tr>
<tr>
<td>TCHP 1.36</td>
<td>$P_{\text{ALL}}$ 14.63%</td>
<td>26.3 (11.4–82.0)</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{NAT}}$ 0.6%</td>
<td></td>
</tr>
<tr>
<td>Joint SST $\geq$ 1.73 and TCHP $\geq$ 1.36</td>
<td>$P_{\text{ALL}}$ 3.89%</td>
<td>21 (5.4–202.5)</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{NAT}}$ 0.2%</td>
<td></td>
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4. **Concluding remarks**

Our analysis based on observations and CMIP6 multimodel simulations indicates that the long-lived TCs like Hinnamnor tend to approach the Korean Peninsula with stronger intensities
when they pass over warmer ECS and that the 2022-like warm surface water has become at least five times more likely due to human activities. This warm surface ocean is expected to become a new normal around 2030s irrespective of low (SSP1-2.6) or intermediate (SSP2-4.5) emission scenarios. Our results suggest that anthropogenic SST warming in the region could produce stronger intensities for the typhoons that do occur, but our analysis does not establish whether Hinnamnor-like super-typhoons affecting East Asia will become more or less frequent under global warming.

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