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Increasing risk from landfalling tropical cyclone-heatwave compound events to coastal and inland China

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Abstract
Tropical cyclones (TCs) and heatwaves are amongst the most deadly and costly natural hazards. Despite considerable advances in understanding each of them, their occurrences in rapid sequence (e.g. in a week) that introduce disproportionately large impacts to infrastructure and human health have received far less attention. Based on dynamical downscaling simulations, we project that currently rare landfalling TC-heatwave compound events would be five to ten times more frequent in coastal Southeast China, and migrate northward and westward to the intact interior. It is the substantial increase in heatwaves that contributes most to the projected increase in frequency and novel emergence of compound events. There would be higher fraction of severer compound events composed of either intense TCs (in the top 10% historically) or exceptional heatwaves (above the historical 99.9th percentile), with coastal Southeast China even bracing for out-of-ordinary combinations of the two. On top of the unprecedented frequency, intensity and land exposure, future emergence of unseasonal compound events in South and Southeast China would further overwhelm local adaptive capacities.

1. Introduction
Tropical cyclones (TCs), combining strong winds, heavy rainfall and storm surges, are among the most catastrophic weather extremes (Peduzzi et al. 2012). The western North Pacific (WNP) is particularly vulnerable to TCs, not only because of frequent TC genesis but also due to high exposure of population and infrastructure in surrounding nations (Basconcello and Moon 2022). Understanding variabilities and changes in TCs is fundamental to risk assessment and disaster preparedness for the region. Existing TC datasets show multi-decadal variations in basin-wide TC frequency and intensity in the WNP, with some features becoming particularly prominent since the 1980s. These include intensification of landfalling TCs (Mei and Xie 2016), increase in the fraction of stronger TCs (Kossin et al. 2020), slowdown of translation speed (Kossin 2018, Lai et al. 2020), and poleward (Kossin et al. 2014, Murakami et al. 2020, Studholme et al. 2022) and coast-ward migration (Wang and Toumi 2021). These property changes might aggravate TCs’ impacts. For instance, slower-moving TCs produce larger volume of precipitation, worsening TC flooding in Southeast China (Utsumi and Kim 2022); while the re-distribution of TCs could place unprepared regions (e.g. northern latitudes) at uncharted risks (Chen et al. 2021).

In addition to altering the profile of TCs themselves, anthropogenic climate change is also
magnifying TCs’ impacts through increasing their spatiotemporal proximity to other extremes to bring compound events (Zscheischler et al. 2020). Given ever increasing sea levels with warming, it is reasonable to expect, and actually observed, higher chance of concurrent extreme sea level and TCs leading to widespread floods (Woodruff et al. 2013, Strauss et al. 2021). A sequence of TC and heatwave gripping the same place constitutes another type of compound events (Lin 2019, Matthews et al. 2019), with the TC-caused blackout and infrastructure damages substantially enhancing vulnerability of the affected communities to ensuing heatwaves. The combination therefore leads to surprisingly higher mortality and morbidity than expected from each of hazards striking alone, as unfortunately showcased in Puerto Rico after Hurricane Maria (Santos-Lozada et al. 2020) and southwest Louisiana in the wake of Hurricane Laura (Stancil 2020). Despite the great impacts, TC-heatwave events have received far less attention compared to other types in the compound event portfolio.

Given projected increases in both intense TCs and hot extremes in the populous WNP (Knutson et al. 2020, Perkins-Kirkpatrick and Lewis 2020, Wu et al. 2022), we should no longer ignore the increasing chance of their configuration. But, the projection information on this emerging type of hazards remains too sparse to inform adaptation planning. To our best knowledge, the studies from Matthews et al. (2019) and Feng et al. (2022) are the only two projecting TC-heatwave compound events. The former one, assuming no change in TCs and independence of two extremes, might underestimate future increases in compound hazards related to TC increases and/or tighter TC-heatwave linkage, and miss those ‘black-swan’ events occurring at unprecedented magnitudes, time and space. The latter study, applying synthetic storms generated by a deterministic-statistical TC model, is informative to local stress testing against future TCs, but still unable to resolve the underlying physics for TC-heatwave coupling at synoptic-to-multidecadal time scales.

To address aforementioned gaps, we for first time use high-resolution (∼25 km) dynamical downscaling simulations, i.e. a physically coherent modeling framework, to provide a more complete picture of future risks of TC-heatwave compound events. Here, we pay major attention to landfalling TC-heatwave compound events in China, acknowledging that the densely-populated coastlines suffered severely from repeated hits by landfalling TCs in recent decades.

2. Data and methods

2.1. Observations and simulations

For observational TC tracks, we use six-hourly best track data during 1980–2005, secured from the International Best Track Archive for Climate Stewardship (IBTrACS v03r10, Knapp et al. 2010). The dataset assembles information from different regional TC centers, and the one from the World Meteorological Organization sanctioned forecast agencies (IBTrACS_wmo) is used here. As with daily temperature observations, we use two datasets, including the widely-adopted gridded CN05.1 that incorporates site observations in more than 2000 stations covering mainland China at a 0.25° × 0.25° resolution (Wu and Gao 2013), and the Berkeley Earth land air temperature of a 1° × 1° grid spacing (Rohde et al. 2013a, 2013b). We also use 0.25° × 0.25°-grid temperature records from the European Centre for Medium Range Weather Forecasts Reanalysis 5 (ERA5, Hersbach et al. 2020). Multiple temperature datasets are employed to evaluate influences of re-gridding uncertainties related to resolutions and latitude-longitude boundaries on the identification of compound events, to better serve model validation.

For model simulations, the latest generation of Abdus Salam International Centre for Theoretical Physics regional climate model (RegCM4) is used (Giorgi et al. 2012). The simulations were performed as part of Phase II of the CORDEX-East Asia domain at a 25 km resolution enclosing the entire territory of China, neighboring lands over East Asia and broad swathes of the WNP (https://cordex.org/domains/region-7-east-asia/). We follow Gao et al. (2016), Gao et al. (2017) for physical parameterization schemes. Initial and temporally-evolving lateral boundary conditions used to drive the regional model are obtained from five CMIP5 (Taylor et al. 2012) global climate models (GCMs), including CSIRO-Mk3.6.0 (Rotstayn et al. 2010), EC-EARTH (Hazeleger et al. 2010), HadGEM2-ES (Collins et al. 2011), MPI-ESM-MR (Jungclaus et al. 2013, Stevens et al. 2013) and NorESM1-M (Bentsen et al. 2013, Iversen et al. 2013). They were selected because of availability of required variables, relatively high resolution in the CMIP5 archive, and high skill in simulating present climates over China (Jiang et al. 2016). The down-scaled outputs are abbreviated as GdR, EdR, HdR, MdR and NdR, respectively. The lateral boundary conditions scheme was carried out using an exponential relaxation technique (Giorgi et al. 1993) and updated every 6 h along with the prescribed SSTs taken from the corresponding GCMs. The simulations span from the present-day period of 1968–2005 forced by realistic greenhouse gas concentrations to a future period of 2006–2098 under an intermediate emission scenario—RCP4.5 (Moss et al. 2010), which is largely consistent with the ongoing international mitigation efforts (Hausfather and Peters 2020).

2.2. Methods

We employ the TSTORMS (Detection and Diagnosis of Tropical Storms in High-Resolution Atmospheric Models) software (www.gfdl.noaa.gov/tstorms/) to detect and track TCs in simulations.
Our previous works confirmed that the statistics of storms (e.g. genesis and occurrence frequencies, track density) in the WNP identified by the software using downscaled simulations or reanalysis data are comparable to those from the IBTrACS dataset (Wu and Gao 2019, Wu et al. 2022). Following the China National Standard No. GB/T19201-2006 adopted in operational forecasting and warning services, TCs are categorized by wind speeds into tropical depression (TD, <17.1 m s$^{-1}$), tropical storm (TS, 17.2–24.4 m s$^{-1}$), strong tropical storm (STS, 24.5–32.6 m s$^{-1}$), typhoon (TY, 32.7–41.4 m s$^{-1}$), strong typhoon (STY, 41.5–50.9 m s$^{-1}$) and super typhoon (SuperTY, $\geq$51 m s$^{-1}$).

A heatwave is defined as a period of at least three consecutive days with either of daily maximum temperature ($T_{\text{max}}$) or minimum temperature ($T_{\text{min}}$) above the seasonal 95th percentile, which is obtained by pooling and ranking the reference period (1986–2005) samples. Here, the considered season spans from May to October—the entire active TC season. By requiring either of extreme $T_{\text{max}}$ and $T_{\text{min}}$, this definition acknowledges and emphasizes health impacts of daytime-only, nighttime-only, and day-night sustained heat (Wang et al. 2021). All temperatures are interpolated onto 2° × 2° grids.

On this basis, a TC-heatwave compound event is considered when a heatwave occurs within 7 d after the passage of a landfalling TC of the TS level at least, in the same 2° × 2° grid. Though the simulated landfalling TCs are detected on a 0.25° basis, their outer spiral rainbands and strong wind zones could slash a much larger spatial extent; meanwhile, heatwaves are typical of spatially-extensive extremes determined by its dynamic origin from large-scale tropospheric anticyclones. This is why we consider the event sequencing at a 2° × 2° grid scale instead of at exactly the TC landfalling point. A 7 d interval represents a relatively short timespan for recovery of the affected community and infrastructure to complete from the preceding TC. If multiple TCs collide with the same heatwave or a TC is followed by multiple heatwaves within the prescribed timespan, the event is counted once. The choice of milder thresholds for intensity and length of timespan in-between guarantees against missing high-consequence events that result from the combination of moderate extremes (van der Wiel et al. 2020).

3. Results

During the reference period (1986–2005), despite with several landfalling TCs and heatwaves observed each year, there is basically zero chance for their collision within the same week across the majority of China, except for very limited patches over South and Southeast sectors seeing 1–2 such compound events in total (figures S1(a) and (b)). The downscaled simulations well capture the spatial pattern with simulated frequency comparable to the observation (figures S2(a)–(e)). The occurrence of TC-heatwave compound events, however, seems more frequent along Southeast coasts (coastal bias) and more extensive to the adjacent interior (inland bias) in models (figures S2(a)–(e)). The coastal bias might by partly caused by the loss of (near) coastal grids (including Taiwan Island) due to the re-gridding of land-only observations (CN05.1 and the Berkeley data). When simulations are compared to events identified based on reanalysis data that contains both terrestrial and marine surface air temperatures, the coastal bias is largely mitigated (figure S1(c)).

Overall, future compound events are projected to be more frequent and more widespread across China compared to the present (figures S2(f)–(j)). Specifically, the five downscaled models consistently project five-to-tenfold increases (even over tenfold in some coastal areas) in TC-heatwave compound events in most of Southeast China at the end of the 21st century (figure 1, shading). These models also agree on the tendency that compound events would be possible to slash historically intact inland areas (west of 115°E) of southern China and northern latitudes (north of 35°E, Circum-Bohai Bay), despite uncertainties in the projected extent of such novel emergence because of the inland bias in simulation. The emergence of novel hazards in these hitherto-unexposed regions might translate into disastrous consequences because of the lack of experience in dealing with them.

The time-slice analysis cannot tell the nature of projected frequency changes as a systematic response to warming or a stark expression of natural variability. We further examine event frequencies and spatial extent of land exposure throughout the entire century (figure S3). For the region as a whole, the directional and monotonic increases in these two indictors, in terms of both ensemble-mean and individual simulations, suggest the dominance of anthropogenic warming in driving future frequency changes in TC-heatwave compound events. While, at a grid (local) scale, the modulation of internal variability on compound events is more pronounced, as evidenced by several-decade differences amongst grids in the timing to see the largest 20 year frequency (figure S4).

The nailed nature of projected regional increases in compound events, along with the well-known stronger response of hot extremes than TCs to warming (IPCC 2021), motivates us to speculate a dominant role of substantial increases in heatwaves in elevating the odds of temporal proximity between the two extremes. We verify this hypothesis within an Even Coincidence Analysis framework (Donges et al. 2016; Supplementary Text-1). We firstly compute the grid-scale lagged coincidence rate, which approximates the fraction of landfalling TCs followed by a heatwave within a week in all identified
Figure 1. Frequency ratio and novel emergence of TC-heatwave compound events. The ratio is calculated as the 20-year event number over 2079–2098 divided by the 1986–2005 value, expressed by shading. The novel emergence, where no compound events are simulated during 1980–2005 but at least one event is projected throughout 2006–2098, is denoted by black dots. (a)–(e) show individual downscaled outputs; where (f) shows ensemble-mean ratio and emergence where at least four models have non-zero ratio or agree on the emergence, respectively. In the calculation of emergence, a longer historical period starting at 1980 is considered to better evaluate the historical rareness of compound events.

landfalling cases there. At present, less than 10% of landfalling TCs evolve into compound events at most grids (figures 2(a)–(e)); while the end-of-century percentage would soar up to 50%–90% (figures 2(f)–(j)). As a matter of fact, the past absence of compound events in most areas (figures 2(a)–(e)) is not due to few occurrences of landfalling TCs (figure S5); rather, relatively sparse heatwaves and asynchronous seasonal cycles of the two extremes (see below) are to blame. In particular, the future northward and westward migration of TCs (white crosses in figures 2(f)–(j)) also contributes to the emergence of compound events in patches of northern and western inner lands. Following Poschlo et al. (2020)’s scheme of removing the general warming signal, we alternatively adopted the adjusted 95th temperature percentiles obtained from the 2079–2098 samples to re-define future heatwaves as synoptic
Figure 2. Lagged coincidence rates between landfalling TCs and heatwaves during the reference period (a)–(e), at the end of the 21st century (f)–(j). White crosses in (f)–(j) locate grids which register no landfalling TCs during the reference period but at least one at the end of the 21st century. The calculation of lagged coincidence rates is detailed in Supplementary Text-1.
Figure 3. Fraction of compound events constituted by TCs and heatwaves of different intensity levels during the reference period (a) and the difference in event fractions between future and reference periods (b). The intensity levels of TCs are measured by reference-period percentiles of winds of all simulated TCs considered (tropical storm category at least) across the study domain, and the intensity for heatwaves is measured by the percentile of simulated maximum $T_{\text{max}}/T_{\text{min}}$ during the heatwave. The vertical and horizontal bold lines highlight the percentiles beyond which TCs and heatwaves are classified into as ‘intense’ and ‘exceptional’ levels, respectively. The symbol ‘X’ labeled at the end of x- and y-axis represents any percentiles higher than the 99th for TCs and 99.9th for heatwaves.

disturbances relative to non-stationary background climates. The re-calculated lagged coincidence rates show no sign of strengthened coupling between the two types of extreme weather disturbances in the future (figure S6).

Given that the magnitudes for precipitation and wind extremes are proportional to TC intensities, the recovery (e.g. restoration of power grids and shelters) from stronger TCs takes longer. So heatwaves preconditioned by intense TCs are more dangerous, calling for research and adaptation priority devoted to the configuration. The 25 km grid spacing, however, is still struggling to resolve dynamics and thermodynamics of intense TCs in the WNP (Wu et al 2022). To minimize influences of this bias on projections, we turn to relative intensity levels stratified by percentiles for simulated winds of the considered TC population (cases of TS level at least) in each model during the reference period, and configure TCs of different relative intensities to heatwaves similarly measured by the percentiles for their maximum $T_{\text{max}}$ or $T_{\text{min}}$. The use of percentile-based thresholds also makes model-specific identifications more comparable to each other, thus allowing to pool all simulated cases into one ensemble. As shown in figure 3, in comparison to historical TC-heatwave configurations, a future warmer climate is projected to elevate the fraction of compound events constituted by either an exceptional heatwave (above the 99.9th percentile) or an intense TC (above the 90th percentile, analogous to the ‘Strong Typhoon’ Category in observational TC records of the same probability). As the most concerning case, the fraction of intense TC—exceptional heatwave compound events soars from around 5% up to approximately 15%, with the extra land exposure largely concentrated along south-southeast coasts (figure S7). Though compound events are not novel to these regions (figures and S2(a)–(e)), the configuration of events of such exceptional magnitudes is so rare (figures S7(a)–(e)) that the emergency response system built upon historical moderate cases might be quickly pushed to the limit or even overwhelmed. Interestingly, even subject to the removal of the general warming signal in heatwaves (Poschlod et al 2020), the fraction of events starting with intense TCs still rises, with the fraction of strongest 1% TC—hottest 1% heatwave combination increasing by around 4% (figure S8). This implies that in the future, the passage of intense TCs might physically prime the atmosphere for the escalation of follow-up heatwaves. The underlying dynamic and thermodynamic mechanisms deserve further exploration.

Apart from events occurring in unexpected locations and with extraordinary magnitudes, those showing up in unusually early or late season represent another stressor to our socioeconomic systems that have long been acclimatized to the current event seasonality. Historically, landfalling TCs and heatwaves are characteristics of asynchronous seasonal cycles, with the former peaking during late-July to mid-September and the latter concentrating before mid-August. So the overlapping regime, i.e. July to mid-August, is the typical season fostering compound events. These features are largely reproduced by simulations (figure S9). During the conventional season, the regionally-aggregated number of future TC-heatwave compound events would be about five times the current level on average (multi-model mean, figure S10). Slightly earlier
arrival of landfalling TCs and the remarkable extension of heatwave season in a warmer world jointly favor occurrences of unseasonal compound events, i.e. before 10th June or after 20th September (figures 4 and S10). Coastal South and Southeast China would bear the brunt of these unseasonal TC-heatwave compound events (figure S11).

4. Discussion

Though our definition strictly follows the impact-centric rule (Leonard et al 2014), identified events still only inform the hazard aspect in risk assessments (Zscheischler et al 2018), i.e. an emerging climatic impact-driver which could—yet not necessarily—induce and amplify impacts (IPCC 2021). Formal impact quantification needs a multi-disciplinary collaboration through data sharing and knowledge exchanging. Considering ‘feel-like temperature’ that incorporates both air temperature and relative humidity (RH) would enhance impact relevance of the defined events to public health (Matthews et al 2019). The current lack of homogenized gridded RH observations in the region for model validation (Freychet et al 2020) and uncertain TC—heavy rainfall—RH relationship in simulations prevent us
from moving forward in this regard. The diversity of humid heat indices and an arbitrary selection further add uncertainties to the projection of TC-humid heatwave compound events. We also realize that the intensity and temporal interval thresholds critical to infrastructure upgrading against this imminent climatic impact-driver might vary substantially by region. It might be wise and feasible to leverage high-profile past events as a conservative benchmark to sort out meteorological anomalies for guiding definition of impactful compound events (Bevacqua et al 2021).

There are a variety of mechanisms that potentially provide a physical linkage between TCs and heatwaves. At a local scale, the release of diabatic heating from TC heavy precipitation bolsters the formation and longevity of an upper-tropospheric warm pool, which then stimulates an upper-level ridge to dynamically drive heatwaves on the heel of TCs (Hart et al 2007, McTaggart-Cowan et al 2007). Enhanced diabatic heating from wetter storms (Knutson et al 2020) accordingly sets up a plausible pathway of strengthening the linkage between the two extremes. Originating from air-sea interactions at lower latitudes, northwestward propagating intraseasonal oscillations are capable of modulating daily weathers over East Asia (Lee et al 2013) with the intrinsic biweekly mode supporting back-to-back occurrences of TCs and hot extremes within a week (Chen and Zhai 2017). The response of the mode to warming and its implications on future TC-heatwave compound events remains to be explored. Additionally, there is emerging evidence on that as the climate warms, Rossby waves at mid-high latitudes would become increasingly wavy (Sussman et al 2020), in favor of more frequent, hotter and longer-lasting heatwaves across broad swaths of mid-latitudes including eastern China (Mann et al 2018, Rousi et al 2022). This changing dynamic could also promote the sequencing of TCs and heatwaves, even if TCs change little.

Another caveat of our projections pertains to the under-sampling of internal variability. Unforced intrinsic atmospheric-oceanic modes spanning from sub-synoptic to multi-decadal scales could considerably modulate frequency, intensity, seasonality and location of TCs in the WNP (Wang and Zhai 2019, Dai et al 2022). In this regard, internal variability-dominated variations, especially at shorter time scales (∼20 years) and local-to-regional spatial scales, could amplify or mask anthropogenically-forced increases in TC-heatwave compound events. The downscaling of five different GCMs, however, provides limited realizations of internal variability modes plausibly compatible with future warming. Moreover, the projection length (∼100 years) from each realization is too short to give a robust estimate for statistics of low-likelihood cases (e.g. intense TC—exceptional heatwave) that are most concerning to policy-making. Single-model initial-condition large ensembles offer a promising way forward (Deser et al 2020), though the current resolution of the data archive remains too coarse to characterize intense TCs. Additionally, the unrealistically strong radiative cooling due to inaccurate representation of aerosol reduction over East Asia in the emission scenario (Wang et al 2021) might also lead to underestimation of risks from unfamiliar TC-heatwave compound events in terms of magnitudes or occurrence locales (Murakami 2022).

5. Conclusions

Different from previous studies focusing on TCs and heatwaves in isolation, we are concerned about their sequential occurrence within a week as an emerging compound hazard. Such rapid transition between the two extremes used to be rare in China, with limited cases confined to Southeast coasts. Under an intermediate emission scenario (RCP4.5), five GCMs, downscaled to a 25 km resolution, consistently project five-to-tenfold increases in TC-heatwave compound events in these previously-exposed areas and new exposure of Circum-Bohai areas, parts of the Yangtze-Huai River Valley and the interior of southern China. The compound event is also projected to intensify across the domain, as evidenced by larger fractions of cases involving either an intense TC (historically top-10%) and an exceptional heatwave (historically top-1‰), or even aligning both (mainly in southeast coasts). Also unfamiliar to southeast coasts is the possible emergence of unseasonal TC-heatwave compound events, i.e. those possibly occurring before early June or after late September.

The projected sharp increases in frequency and intensity of TC-heatwave compound events, as well as their emergence in historically unexposed regions and calm seasons, underscore the importance and urgency of incorporating the compound event perspective into future disaster preparedness in populous China. Our attribution results also underpin the benefit of achieving the committed carbon-neutral goal in constraining TC-heatwave compound risks by means of suppressing heatwave increases.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no competing interests.

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