Explaining Extreme Events of 2019 from a Climate Perspective

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EXPLAINING EXTREME EVENTS OF 2019 FROM A CLIMATE PERSPECTIVE

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Cover: Ruins and rubble are all that are left of homes destroyed by Hurricane Dorian viewed from a U.S. Customs and Border Protection rescue helicopter 5 September 2019 in Marsh Harbour, Abaco, Bahamas. Dorian struck the small island nation as a Category 5 storm with winds of 185 mph. (credit: Planetpix/Alamy Stock Photo)

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Has Global Warming Contributed to the Largest Number of Typhoons Affecting South Korea in September 2019?

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A multimodel analysis indicates that the 2019 September record high number of typhoons affecting South Korea was contributed to mostly by the very strong convection over northwestern India with no discernible anthropogenic contribution.

During 2019, seven typhoons [i.e., tropical cyclones (TCs)] hit South Korea, resulting in tremendous damages on the country's infrastructure and economy through heavy rain and high winds (reported in *The Korea Herald*^{1,2}). This is the largest number of annual TCs affecting South Korea since 1959; in particular, it was the first time since records began in 1904 that three typhoons struck South Korea during September (Figs. 1a,c). While warm sea surface over the western North Pacific is important for overall typhoon activities (e.g., Zhang et al. 2016), the western North Pacific subtropical high (WNPSH) is known to strongly modulate typhoon land-fall over East Asia since typhoons usually move northward along its western boundary (Ho et al. 2004; M. Lee et al. 2019; Zhou and Lu 2019). In September 2019, the WNPSH was unusually strong with an extreme northwest

¹ <http://www.koreaherald.com/view.php?ud=20190908000142>.

² <http://www.koreaherald.com/view.php?ud=20190922000168>.

Fig. 1. (a) September 2019 typhoon tracks and WNPSH (western North Pacific subtropical high) boundary location. (b) Spatial patterns of anomalous geopotential height at 200 hPa (H200; shading), steering winds (vectors; only for wind speed $\geq 4 \text{ m s}^{-1}$), and OLR (outgoing longwave radiation; blue contours; only for $\leq -20 \text{ W m}^{-2}$). Green boxes indicate two regions used to define G200 (H200 gradient index; see text for its definition). Yellow dots and cyan hatches represent record high H200 and OLR, respectively. Time series of (c) numbers of TCs affecting South Korea (n_{TC}) and anomalous zonal and meridional steering winds (u , v) averaged over the East China Sea area [$120^{\circ}\text{--}140^{\circ}\text{E}$, $25^{\circ}\text{--}35^{\circ}\text{N}$; black box in (b)], and (d) G200 and area-mean OLR anomalies over northwestern India (OLR_{nd}). Pearson correlation (r) and Spearman's rank correlation coefficients (r_s) are provided. (e) Boxplots of G200 anomalies from CMIP6 and HadGEM3-A-N216 runs for strong and weak northwestern Indian convection in comparison with the 2019 (red solid) and 1999 (red dotted) observed values. Composites of H200 anomalies (gpm) from (f) NCEP1, (g) CMIP6, and (h) HadGEM3-A-N216 (HG3) from years with stronger convection over northwestern India (black box) during 1981–2010; 30p and 70p represent 30th and 70th percentile, respectively. Black cross marks in (g) indicate more than 70% intermodel agreement in sign.

shift, as indicated by 5,880-gpm contours in Fig. 1a, which are typically used to depict its boundary (Liu and Chan 2013). The extreme development of the WNPSH was associated with anomalous anticyclonic circulation developed in the upper troposphere from northeast China to Japan (Fig. 1b), which intensified southeasterly steering winds (mass-weighted horizontal winds from 850 to 300 hPa) over the East China Sea area (black box in Fig. 1b), guiding the typhoons toward the Korean Peninsula (cf. Zhou and Lu 2019). Both the zonal and meridional components of the area-mean steering flows are significantly correlated with the TC numbers affecting South Korea at 5% level (Fig. 1c, based on Spearman's rank correlation using years with non-zero TCs). Given the observed and projected intensification of TCs landfalling over the northwest Pacific under warming (e.g., Mei and Xie 2016; H. Lee et al. 2019), the present study attempts to answer the question of whether global warming has contributed to the anomalous extreme steering winds.

During September 2019, there was strong convection in northwestern India [Figs. 1b,d, based on outgoing longwave radiation (OLR) anomalies] related to the strong Indian monsoon and its delayed withdrawal (reported in *The Indian Express*³). The strong convection over northwestern India is known to induce anomalous upper-troposphere highs over South Korea during summer through the Rossby wave propagation mechanism (Kim et al. 2019, 2020; Yeo et al. 2019; Min et al. 2020). A similar teleconnection pattern was observed in September (Figs. 1d,f), which can be reproduced by the models (Figs. 1g,h; Fig. ES1). This suggests that the unusually strong Indian monsoon may have contributed to the extreme number of TCs affecting South Korea.

The present study assesses anthropogenic and natural contributions to the September 2019 atmospheric circulation pattern conducive to the record high number of typhoons affecting South Korea using CMIP6 multimodel simulations as well as HadGEM3-A large-ensemble simulations performed with and without anthropogenic forcing (see below for details). Using a standard risk ratio (RR) approach to event attribution (Stott et al. 2016; Otto 2017), we compared the probabilities of occurrence of the TC-related circulation pattern between real and counterfactual conditions (to assess anthropogenic contribution) as well as between strong and weak tropical convection conditions (to assess natural contribution).

Data and methods.

Observational data include monthly mean geopotential height and horizontal winds throughout the troposphere for 1951–2019 from NCEP1 reanalysis (Kalnay et al. 1996), TC information for 1951–2019 from the Korea Meteorological Administration (KMA; <https://data.kma.go.kr/>), monthly mean OLR for 1974–2019 (https://psl.noaa.gov/data/gridded/data.interp_OLR.html).

Multimodel datasets from phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016) are used, which include historical (natural plus anthropogenic, called ALL), natural-only (NAT), and greenhouse-only forcing (GHG) simulations (see Table ES1 in the online supplemental material). The data for 2010–19 from each experiment were used, assuming similar climate to 2019 conditions. Historical simulations (2010–14) were combined with corresponding Shared Socioeconomic Pathway (SSP) 2–4.5 scenarios (2015–19). High-resolution large-ensemble HadGEM3-A simulations performed for 2019 (referred to as HadGEM3-A-N216; Ciavarella et al. 2018; Vautard et al. 2019) were also used (Table ES2), which provide 525 members for real world (ALL) and counterfactual world (NAT) conditions. The observed 2019 SST and sea ice concentrations from HadISST1 (Rayner et al. 2003) was prescribed for ALL simulations. For NAT simulations, adjusted SST and sea ice concentrations were prescribed after removing anthropogenic SST changes (delta-SST) from HadISST1. The delta-SST was estimated from four CMIP5 models (as ALL–NAT) and an observed trend, each of which have 105 ensemble members (Table ES2). Observations and all model simulations were interpolated on the same $2.5^\circ \times 2.5^\circ$ grids of NCEP1 reanalysis. All variables were normalized prior to analysis using mean and standard deviation of each data obtained from 1981–2010 for robust comparison between observations and models (see below for sensitivity tests to model samples). NAT and GHG runs were normalized based on ALL climatology of each model.

As a proxy of anomalous southeasterly steering wind over the East China Sea area, we defined a gradient index of 200-hPa geopotential height anomalies (hereafter, G200) between the East Sea (Sea of Japan) area and the southern China area (green boxes, Fig. 1b). The resulting observed G200 has significant correlations with steering winds, northwestern Indian convection (Fig. 1d), and also with the number of TCs affecting South Korea ($r_s = 0.50$). G200 indices were calculated for CMIP6 and Had-

³ <https://indianexpress.com/article/explained/india-monsoon-rainfall-bihar-patna-floods-6054167/>.

GEM3-A-N216 simulations (Fig. 1e) and the RR was obtained for the 2019 G200 value in two ways. One ($RR_{ALL/NAT}$) is to calculate the ratio of the probability of occurrence of 2019-like positive G200 events between ALL and NAT, which quantifies human impacts on TC-related atmospheric circulation patterns. The other ($RR_{SC/WC}$) is to calculate the probability ratio between model samples with strong and weak Indian convection for ALL, NAT, or GHG separately (Fig. 1e) in order to examine Indian monsoon influences on the extreme G200 events. For this analysis, using normalized OLR (for CMIP6, based on each model) or precipitation (for HadGEM3-A-N216, due to data availability) averaged over northwestern India (black box in Fig. 1f), we selected samples with OLR $\leq$ 30th percentile for strong convection (SC), with OLR $\geq$ 70th percentile for weak convection (WC), and vice versa for precipitation. To test RR sensitivity to a less extreme G200 threshold, we used the value observed in 1999 (dashed line in Fig. 1e), when two TCs affected South Korea. The 5%–95% confidence intervals of RRs were estimated using the likelihood ratio method following Paciorek et al. (2018).

Results.

Figure 2 illustrates the Gaussian kernel density function of the normalized G200 for ALL, NAT, and GHG simulations from CMIP6 and for ALL and NAT runs from HadGEM3-A-N216. CMIP6 results show that the probability of extreme G200 events exceeding the observed 2019 value is 2.97%, 3.24%, and 2.97% in ALL (P_{ALL}), NAT (P_{NAT}), and GHG (P_{GHG}), respectively (Table 1), indicating that the 2019-like extreme southeasterly flows occur rarely with similar probability across different forcings. The corresponding $RR_{ALL/NAT}$ is about 0.92 (5%–95% confidence interval is 0.46–1.81; Fig. 2f), suggesting no detectable human influences. HadGEM3-A-N216 results present P_{ALL} and P_{NAT} as 1.33% and 2.86%, respectively (Table 1), resulting in $RR_{ALL/NAT} = 0.47$ (0.21–0.96). A simple analysis (Fig. ES3a) indicates that relatively low probability of ALL runs from HadGEM3-A-N216 is partly due to the identical SST forcing prescribed, as opposed to the NAT runs, which include five different SSTs (see Table ES2). When applying the 1999 observed threshold, $RR_{ALL/NAT}$ remains close to unity for both model ensembles (Table 1). This result indicates that the September 2019 TC-related extreme circulation pattern is not attributable to human-induced global warming.

To assess the possible contribution of strong northwestern Indian convection on the extreme TC-related circulation pattern, we compared the probabilities of occurrence of the extreme G200 events between model samples with SC and those with WC. Results reveal that when the northwestern Indian convection is stronger, G200 density distri-

Table 1. Probability (%) of occurrence exceeding the observed G200 values from total samples (P_{TOT}) and subsample with strong and weak convection over northwestern India (P_{SC} and P_{WC} , respectively). RR is calculated between ALL and NAT ($RR_{ALL/NAT}$) as well as between strong and weak convection ($RR_{SC/WC}$). The 5%–95% uncertainty ranges of RR are provided in brackets.

Model	Observed year	Experiment	P_{TOT} (%)	P_{SC} (%)	P_{WC} (%)	$RR_{SC/WC}$	$RR_{ALL/NAT}$
CMIP6	2019	ALL	2.97	7.27	0.00	∞ [5.49– ∞]	0.92 [0.46–1.81]
		NAT	3.24	8.11	0.00	∞ [6.24– ∞]	
		GHG	2.97	5.41	1.80	3.00 [0.89–14.02]	
	1999	ALL	6.76	14.41	2.70	5.33 [2.15–17.17]	0.83 [0.54–1.28]
		NAT	8.11	17.12	0.90	19.00 [4.97–182.47]	
		GHG	7.30	14.41	2.70	5.33 [2.15–17.17]	
HadGEM3-A-N216	2019	ALL	1.33	1.90	1.27	1.50 [0.34–7.76]	0.47 [0.21–0.96]
		NAT	2.86	6.96	0.63	11.00 [2.71–107.64]	
	1999	ALL	4.95	7.59	3.80	2.00 [0.92–4.70]	0.74 [0.49–1.12]
		NAT	6.67	11.39	3.80	3.00 [1.47–6.80]

Fig. 2. Kernel density functions of normalized G200 for (a)–(c) CMIP6 ALL, NAT, and GHG simulations and (d), (e) HadGEM3-A-N216 (HG3) ALL and NAT simulations, respectively. The thick solid lines indicate results from all simulations and thin and dashed lines represent subsampled results with stronger convection (SC) and weaker convection (WC) conditions, respectively. Black solid and dashed vertical lines represent the 2019 and 1999 observed values from NCEP1. (f) RR (mark) and its 5%–95% confidence intervals (error bars) obtained (left) between P_{sc} and P_{wc} ($RR_{sc/wc}$) and (right) between P_{all} and P_{nat} ($RR_{all/nat}$) for CMIP6 and HG3 models. Solid and dashed error bars indicate RR results for the 2019 and 1999 observed thresholds, respectively. Refer to Table 1 for corresponding RR values and Fig. ES2 for corresponding return periods.

butions shift to right both for CMIP6 and HadGEM3-A-N216 (Fig. 2). The resulting P_{all} , P_{nat} , and P_{ghg} clearly increase upon the stronger convection (Table 1), which can also be seen when applying the 1999 G200 threshold. WC samples exhibit the opposite results with decreased probability of extreme G200 events. $RR_{sc/wc}$ for CMIP6 is found to be at least 3 (based on best estimates), implying that the unusually strong northwestern Indian convection has contributed to the increased risk of September TCs affecting South Korea by intensifying anomalous southeasterly steering winds. HadGEM3-A-N216 results also show that P_{all} and P_{nat} are increased upon stronger convection and vice versa. Compared to CMIP6, however, $RR_{sc/wc}$ from this model is generally lower and its confidence interval includes unity in ALL simulations. This can be associated with the narrower ensemble spread related to the single SST prescribed as discussed above. When applying the 1999 observed threshold, $RR_{sc/wc}$ and its confidence intervals are increased, supporting the contribution of the extreme northwestern Indian convection to the record high number of TCs affecting South Korea by increasing the probability of occurrence of extreme steering flow patterns. Overall results can be interpreted based on the corresponding return periods (Fig. ES2). Sensitivity tests support the robustness of our results to different sampling of models based on model skills for the Indian convection and teleconnection response (see Table ES1 and Figs. ES3b–e for details) although more comprehensive model evaluations are needed.

Concluding remarks.

Our multimodel event attribution analysis indicates no discernible anthropogenic influences on the September 2019 extreme steering winds over the East China Sea region, which were closely associated with the record high number of typhoons affecting South Korea. It is rather found that the unusually strong September monsoon over northwest India could well have contributed to the extreme circulation patterns, increasing the probability of a 2019-like event by at least 3 times in CMIP6 models and about 1.5 times in the HadGEM3-A-N216 ensemble. Further investigation is warranted to better understand details of how anomalous northwestern Indian convection induces extreme circulation patterns over Northeast Asia (e.g., Kim et al. 2019, 2020) and also to quantify human and natural contribution to the intensified Indian monsoon (cf. Menon et al. 2013; Lee et al. 2018). Finally, it should be noted that linking the extreme circulation pattern to actual TCs affecting South Korea remains difficult because of no consideration of TC genesis, large uncertainty in TC track data during pre-satellite period (e.g., Moon et al. 2019), and a lack of objective determination of TCs affecting South Korea.

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