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On Uncertainty in Extreme Weather Forecasts in a Changing Climate: August 2022 Floods in South Korea

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ABSTRACT

In August 2022, South Korea experienced massive and large-scale flooding, preceded by the highest record in 80 years. The torrential rain over several consecutive days caused devastating flooding events and landslides in Seoul, and underestimated rainfall forecasts forced several hundred people to evacuate, leaving infrastructures damaged substantially. In this study, we use high-resolution observational reanalysis data to investigate spatial and temporal evolutions of atmospheric and oceanic conditions during the 2022 August flooding events. We show that a prolonged dipole atmospheric system, with low in the north and high pressure in the south, reinforces a persistent and strong stationary front causing succeeding rain. Given the prominent westerly winds accompanied by the dipole pressure system, which acts as a channel of westerly winds across middle Korea, anomalously warm sea surface temperature (SST) over the Yellow sea located west of Korea plays a key role in supplying moisture and heat for the rainfall events. The principal component analysis and SST trend results suggest that the intensity of distinct dipole modes of atmospheric pressure and Yellow sea SST have significantly increased over the recent decades as known consequences of global warming. Our findings indicate that climate change may increase uncertainties in climate and weather extremes forecasts; thus, further efforts and attempts to improve our understanding of current and future climate systems are highly important.

INTRODUCTION

In August 2022, South Korea (SK) was devastated by floods as it faced its highest rainfall in 80 years, over 2,800 buildings were destroyed, hundreds of people were displaced, and nine people died (Roh, 2022) (Figures 1a-c). Unfortunately, this incident was only one in a larger series of disastrous floods. The Southern and Southwestern United States were hit by flash floods in July and August, and Pakistan had been facing floods since June. Even this month, floods have continued to endanger people, displacing hundreds of people in Australia. Heavy rains have caused hundreds of people to lose their lives in Venezuela over the past few months. Floods have caused the largest portion of losses among all natural disasters, especially during recent decades, with global losses totaling around $60 billion USD in 2016 alone (Aerts et al. 2018).

Likewise, the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report also confirmed an increasing number of heavy precipitation events over the past 50 years(Jung et al. 2011). Additionally, global exposure to floods is expected to triple by 2050 due to population increase and the concentration of assets in flood-prone areas (Aerts et al. 2018). In recent decades, global flooding disasters and extreme precipitation events have intensified and increased in frequency as a result of extreme precipitation events growing with global warming, and global conditions are only expected to get worse (Williams et al. 2022) (Tabari, 2020) (Jung et al. 2009).

Flooding is defined by the Intergovernmental Panel on Climate Change (IPCC) as "the overflowing of the normal confines of a stream or other body of water or the accumulation of water over areas that are not normally submerged." Floods are affected by precipitation, the intensity, amount, duration, timing, and whether it comes down as rain or snow (Seneviratne et al. 2012). Typically, precipitation is the largest factor affecting flood risk, with higher levels of intense precipitation causing favorable conditions for floods. Additionally, the effects of climate change in increasing Earth's temperature create warmer conditions facilitating the evaporation of water into the atmosphere. This water continues to collect until a holding capacity is reached and the moisture comes down as precipitation (Tabari, 2020).

Aside from the loss of life, floods can have long-lasting effects on infrastructure especially, as network robustness may take extended periods of time to even return to a baseline level. This is because roads are being blocked due to downed trees, power lines, hazardous waste, and other debris which can take months to remove before full reconstruction efforts can be launched (Dong et al. 2022). Floods will continue to pose a risk to people and property, and their danger is only on the rise.

South Korea's Hydroclimate

In terms of extreme precipitation, this study focuses entirely on South Korea. Resting on the tip of the Korean Peninsula, South Korea is bordered on three sides by the East Sea (Sea of Japan), Yellow Sea, and East China Sea, near the Pacific Ocean (Figure 1c). The Korean Peninsula is located in the mid-latitudes (30°N/S-60°N/S), an area with a strong energy gradient due to the temperature imbalance in between the Arctic to the north and the equator to the south (Choi, 2020). In addition, South Korea's hydroclimate is strongly influenced by summer monsoons, characterized by a strong seasonal shift in the tropical rainbelt bringing heavy rains into East Asia (Lim et al. 2019). In South Korea, this period is known as "jangma", and usually occurs in June to mid-July.

As previously stated, South Korea has recently faced a destructive flooding event caused by several days of persistent precipitation that destroyed thousands of buildings and displaced dozens of people (Roh, 2022). Although, when compared with past Augusts in South Korea, the accumulated daily precipitation may not seem all that high (Figure 1a), when taking the 4-day accumulated precipitation (Figure 1b), it is clear that the persistence of rainfall was a major factor in setting this event apart from others in South Korea's history. This is owing to the prolonged levels of high precipitation over several consecutive days.

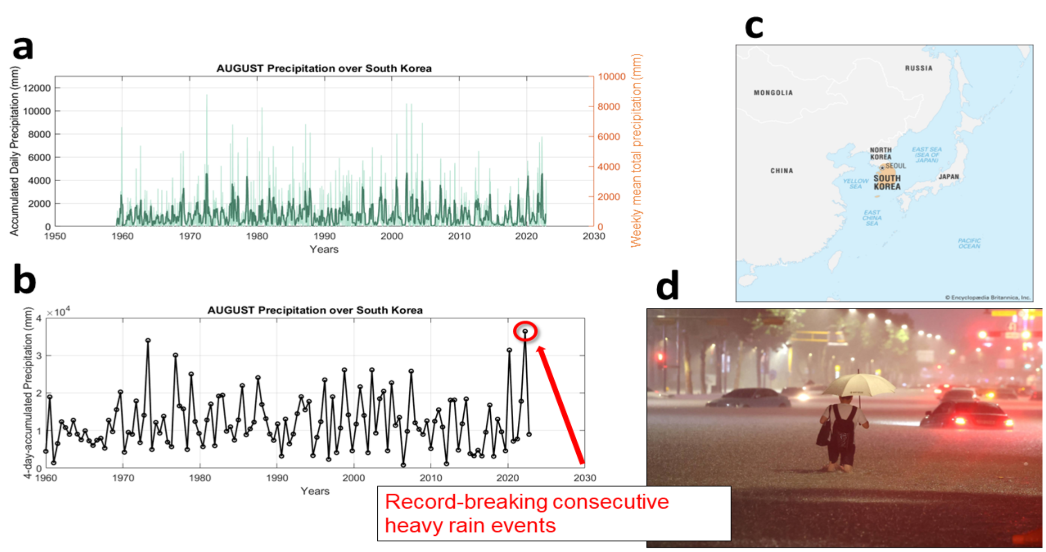

Figure 1. Daily Accumulated August Precipitation over South Korea Within Different Timeframes (1 day, 4 days, 7 days). Accumulated daily precipitation data for the month of August in South Korea from 1959-2022. The darker green lines represent the weekly mean precipitation while the lighter lines are the accumulated daily precipitation (mm). **(a)** 4-day accumulated precipitation data for the month of August in South Korea from 1959-2022. **(b)** Map of East Asia with South Korea highlighted. *Credit: Encyclopedia Britannica*. **(c)** A man walks through a flooded street in Seoul, August 2022. *Credit: Reuters*. **(d)** Figures a and b provided by the student.

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In the future, the Korean peninsula is projected to face higher levels of precipitation with an increase in the frequency and intensity of heavy precipitation events, especially during the summer months (Jung et al. 2011). The summer precipitation also coincides with the typical Korean rainy season, "jangma". However, a 2004 study showed a 20% decrease in July precipitation and a 54% increase in August precipitation in the east and southeast parts of Korea (Lee and Kwon, 2004). A similar trend was observed between August and April, with August seeing an increase in precipitation while April saw a decrease. These trends were likely contributing factors to the extreme flooding event this past August (Jung et al. 2011) (Tabari, 2020).

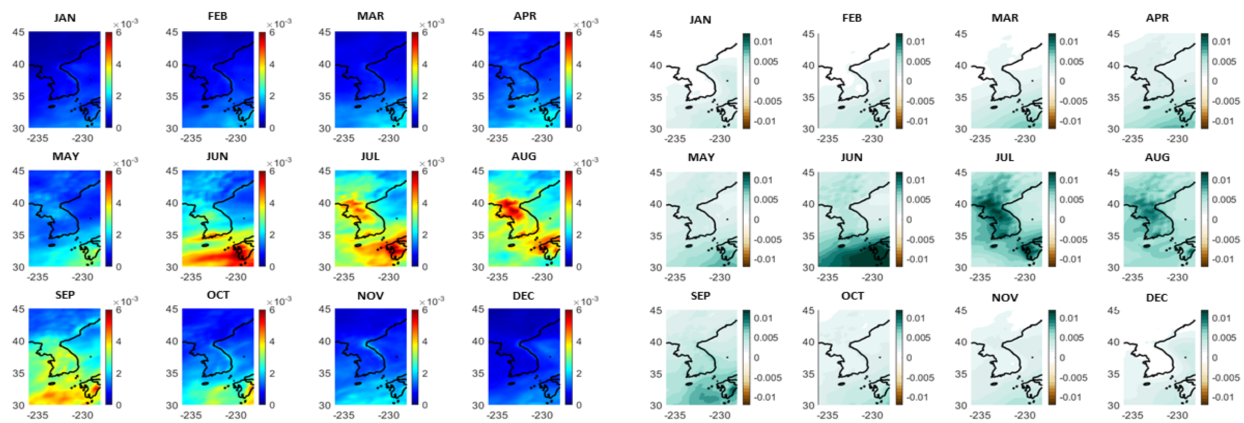

Figure 2. Monthly mean precipitation and standard deviation of precipitation over Korea, 1979-2022. (a) The standard deviation of the precipitation (mm) around the Korean peninsula from 1979-2020. **(b)** The mean monthly levels of precipitation around the Korean peninsula from 1979-2020. Figure provided by the student.

STATEMENT OF PURPOSE

In August 2022, I was in South Korea. I arrived on August 7, just as intense precipitation was beginning to cause the formation of large-scale floods near the capital city of Seoul. Seeing the devastation that this disaster brought to people motivated me to ask "why couldn't this have been mitigated?" or "why are these kinds of events happening everywhere?" This experience led me to develop my research goals and questions.

Although previous studies have analyzed the conditions favoring flooding and how those conditions are changing in various parts of the world. No studies, at the time of this writing, have analyzed the recent August 2022 floods in South Korea.

The primary goal of the study was to understand why forecasting failed in August 2022 and propose changes to remedy those problems. By reviewing past studies into Korea's hydroclimate and forecasting system (Jung et al. 2011) (Park et al. 2018), I hypothesize that Korea's forecasting system failed due to global warming exacerbating changes in Korea's precipitation cycle and South Korea's strong regional variability for its weather.

The secondary goal of this study was to understand the underlying causes of the August 2022 flooding in South Korea and relate this to climate change if applicable. Again, based on prior studies in this field, I hypothesize that climate change induced global warming is a factor in changing monthly trends and increasing precipitation rates in the month of August and that it also caused an increase in extreme precipitation due to an increased atmospheric water concentration.

METHODOLOGY

This study uses hourly and monthly data of precipitation, sea-level pressure (SLP), sea surface temperature (SST), and wind patterns over South Korea from the period 1959-2022. Monthly data was used as they give an idea of larger trends while also including seasonal variability, as opposed to yearly data. Hourly data was used to give a closer insight into specific events, such as the August 2022 flooding, which occurred over around four days. Public observational data was obtained through the Copernicus Climate Data Store (CDS), managed by the European Commission, and the National Oceanographic and Atmospheric Administration (NOAA).

For analysis of the Korean peninsula and surrounding areas, the coordinates (25°N–50°N, 122°E–105°E) are used, and for analysis of the Yellow Sea, the coordinates (33°N–39°N, 126°E–120°E) are used. The time series for analysis of the Yellow Sea SST was (1980-2022).

All data was analyzed, and all figures were created by the student using MATLAB R2022a. Empirical orthogonal function (EOF) analysis was performed to determine spatial patterns in regards to SLP. EOF analysis, also known as principal component analysis (PCA), is a statistical technique often used in climate studies to identify spatial modes, or patterns, of variability and how they change over time. The EOF analysis has been largely used to define various climate modes, such as the North Atlantic Oscillation and Arctic Oscillation (Zhang and Moore, 2015). Anomaly data was processed to exclude seasonal variations.

Role of the Mentor

During the research process, the student took a leading role in both the development of the project and carrying out the research itself. Weekly meetings were held on Saturdays, over Google Meets, between the student and the mentor, where the student would report findings and progress made and the mentor would provide feedback, suggestions, and sources of information for further research. While the mentor aided in guiding the student through the research process and different analysis techniques, the student conducted the project independently.

RESULTS

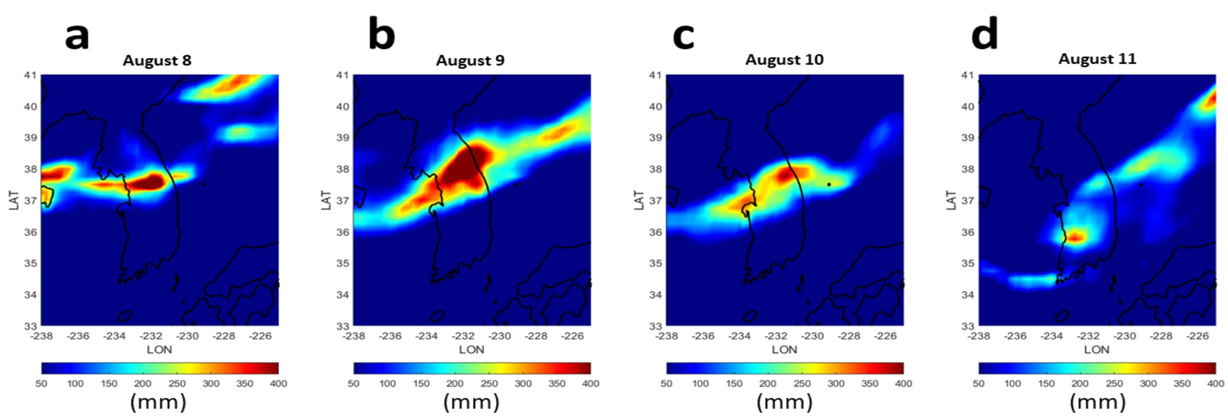

Figure 3. Spatial distribution of total precipitation over Korea during August 2022 flooding event. (a-d) distribution of daily total precipitation over Korea from August 8-11, 2022. Figure provided by the student.

Figure 3 plots the total precipitation, measured in millimeters, for four days in August 8-11. During this time there is a precipitation band across the middle of the Korean Peninsula. The precipitation band moves east and south over the period. This is in line with the westerly and southerly winds shown in figure 4b and 4c. Precipitation was greatest on

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August 9th and then decreased from there. The amount of precipitation daily can be seen by the light green line on figure 1a, and the total precipitation during this time period is circled on figure 1b.

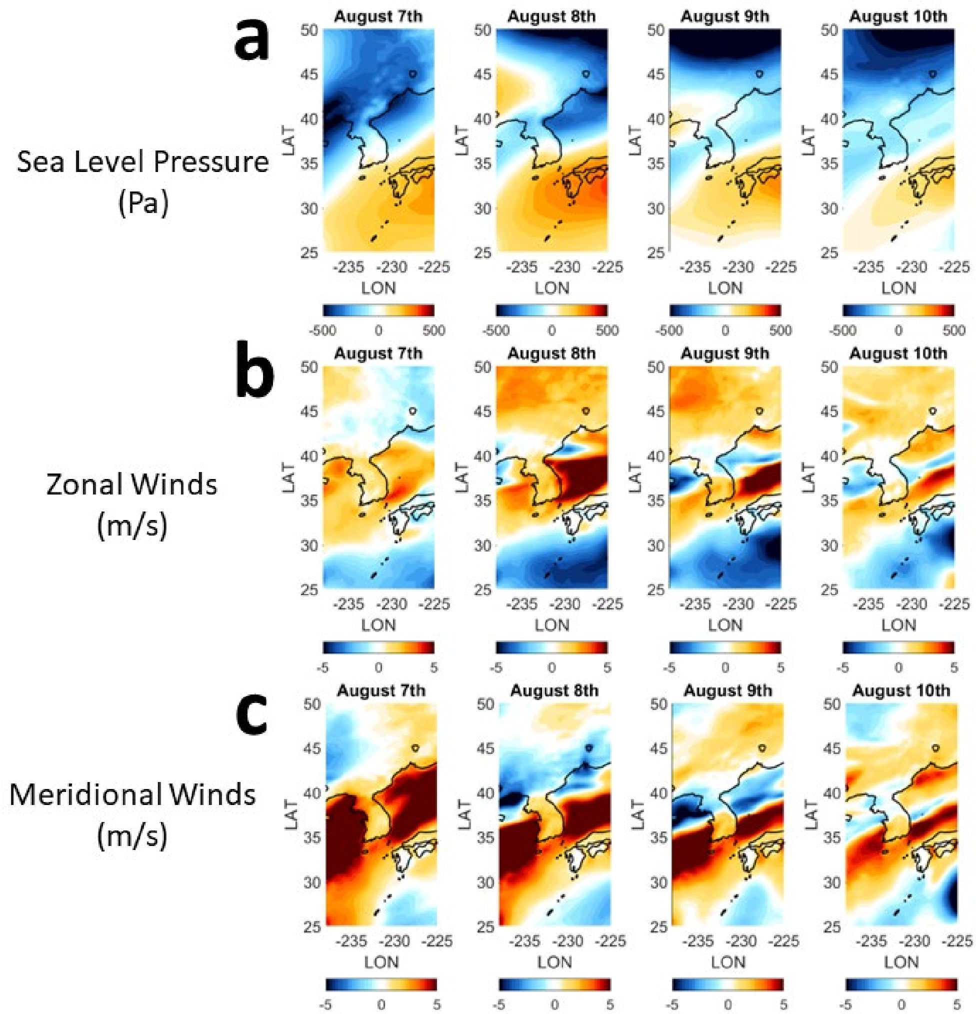

Figure 4: Spatial distribution of (a) Sea Level Pressure, (b) zonal winds, and (c) meridional winds around the Korean Peninsula during the August 2022 flooding event. Positive values of zonal winds in this figure indicate a westerly direction, and the positive values of meridional winds are southerly winds. **(c)** Figures created by the student.

Figure 4 is a map showing SLP, zonal winds (westerly), and meridional winds (southerly) for four days from August 7th to August 10th, 2022. 4a shows opposing anomalous low SLP in the north and anomalous high SLP in the south, where the low pressure locates over North Korea and China, and high pressure stays off of South Korea's southern coast and Japan. The high-pressure pattern south of Korea in this figure is a part of the North Pacific High, which is unable to expand northward, trapped by the low pressure, leading to a stationary front and blocking.

Zonal winds are predominantly westerly across the Korean Peninsula and China, and meridional winds are predominantly southerly across the Korean Peninsula. Westerly zonal winds carry the heat and moisture of the air in the Yellow Sea to Korea, while southerly meridional winds transport air from the East China Sea to Korea.

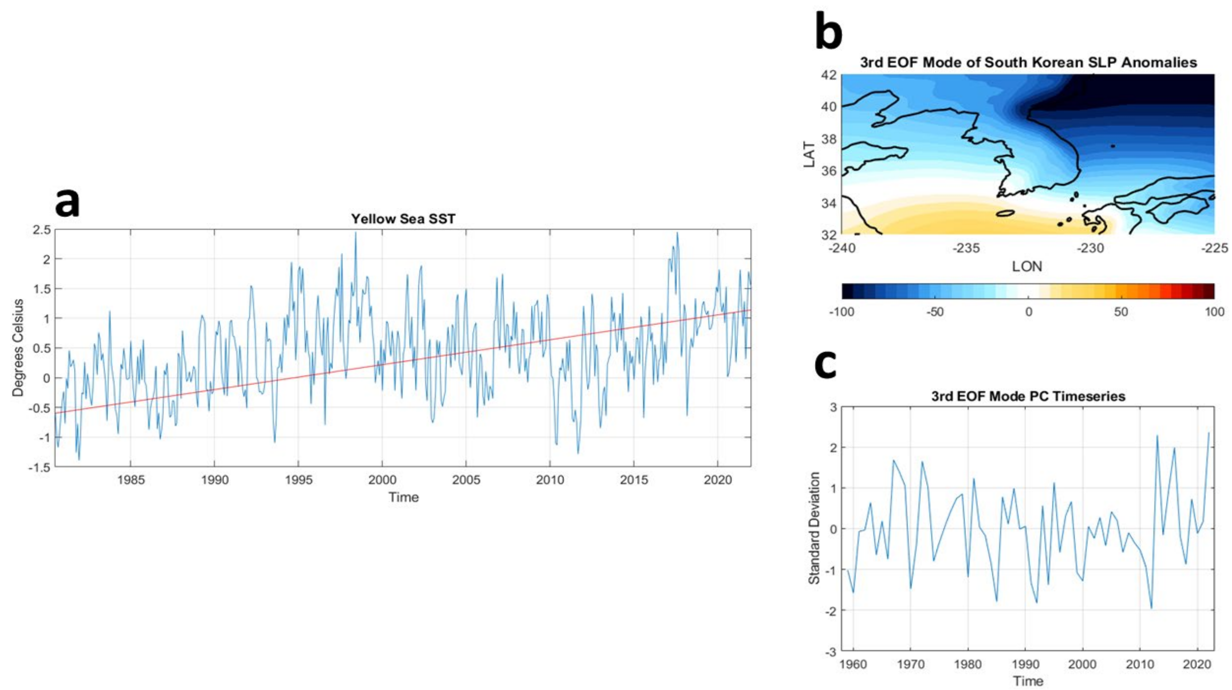

Figure 5: The Yellow Sea SST from 1980-2022. The 3rd dominant mode and principal component of South Korean SLP anomalies during August. (a) Time series (blue) of Yellow Sea SST from 1980-2022 with the slope of the trendline (red) (0.4185℃ per decade). **(b)** The third dominant mode of South Korean SLP anomalies from Empirical Orthogonal Function (EOF) analysis. **(c)** The time series associated with the third mode of South Korea SLP, showing standard deviation (amplitude) over time. Figures generated by the student.

Figure 5a shows temporal evolution of the SST in the Yellow Sea from 1980-2022. It has shown a steady increase with the trendline demonstrating a 0.4185℃ increase every 10 years. 5b and 5c use empirical orthogonal function analysis, along with monthly August data from 1959-2022, to show the 3rd dominant mode of SLP anomalies and principal component of this mode, respectively. 5b shows that there is a significant dipole pattern between the north and south of the peninsula, wherein the north is low pressure, and the south is high, similar to the results shown in figure 4a. Moreover, figure 5c shows the standard deviation of SLP anomalies is increasing, with the graph's amplitude lying at August 2022.

DISCUSSION

Atmospheric Blocking

In a close examination of South Korea's August 2022 extreme rainfall using various climatic variables like monthly and hourly observational data from 1959-2022, the persistent precipitation conditions concentrated around the middle of the peninsula and the Seoul area throughout all four days (Figure 3) appear to cause the unusual high-rate rainfall leading to devastating heavy floods (Figure 1). The rainfall anomalies are found to be maintained by the prolonged dipole atmospheric system (Figure 4a) with the low in the north and high pressure in the south, which also forms a persistent and strong stationary front causing succeeding rain concentrated in Seoul and Gyeonggi Province. Specifically, the low pressure caused cyclonic winds moving counterclockwise, while the high pressure caused anticyclonic winds moving clockwise. The result was a channel of westerly winds over Korea (figure 4b). Additionally, southerly meridional winds carried more warm moist air to Korea as well (figure 4c). According to EOF analysis from 1959-

2022, this dipole pattern has been increasing in commonality in recent years, and it was highest in August 2022 (figure 5c).

The present study notes that the anomalous positive SLP over the East China sea, characterized by the large-scale atmospheric anomalies known as the North Pacific high, resemble the atmospheric blocking signature which is a seemingly stationary circulation anomaly disrupting westerly flow of normal weather patterns (Steinfeld et al. 2022). The common characteristics of "blocking" are quasi-stationary and persistence atmospheric condition, exhibiting a large anticyclonic anomalies (high SLP anomalies) that closely affect the wind flow and regional extreme weather (e.g., heavy rainfall or heat waves) (Woollings et al. 2018). Typically, the Northern hemisphere mid-latitudes have weather fronts that move from west to east, carried by the westerly jet streams (McSweeney, 2021). These jet streams keep weather systems moving across Earth's surface, so generally certain conditions will only remain for a few days before moving to another location. However, due to the warming of the atmosphere and the melting of Arctic Sea ice, the meridional temperature gradient is decreasing, reducing the speed of the jet stream and increasing local blocking events (Kautz et al. 2022; McSweeney, 2021; Choi, 2020). Recent papers have demonstrated that the future projection climate models indicate significant increase in frequency and/or intensity of high-latitude atmospheric blocking events, especially under increasing greenhouse gas concentrations (Woollings et al. 2018, Davini et al. 2014). Given the changes in atmospheric blocking dynamics in a warming climate, the regions adjacent to the block may experience more frequent extreme weather conditions, including extreme rainfall and temperature anomalies due to the persistent deflection of atmospheric circulations.

Yellow Sea

The westerly winds over Korea blew directly from the Yellow Sea to the East Sea (Sea of Japan) (map illustrated on figure 1c). As such, the August floods were largely impacted by the condition of the Yellow Sea, which has seen an increase in SST during the recent decades (figure 5a) due to climate change. The sea has a major role in regulating the Earth's temperature, as the majority of solar radiation is absorbed by the ocean and it acts as a massive heat sink. This causes ocean water to be constantly evaporating and increasing the humidity and air temperature to form clouds and precipitation (Seneviratine et al. 2012). An increase in the SST would increase the air temperature and evaporation rate, creating conditions that would favor heavier precipitation.

CONCLUSION

Research Summary & Findings

To investigate the historic extreme precipitation in South Korea during August 2022 and the background situation and factors that limited forecast accuracy, this present study diagnoses the oceanic and atmospheric variables associated with the high rainfall rate and precipitation anomalies. The results first suggest that the consecutive high-rate rainfall between the 8th to 11th of August 2022 was mainly driven by a stationary front formed by the low (northern lobe) and high (southern lobe) sea level pressure anomalies over middle Korea. The presence of atmospheric blocking over the southern part of South Korea and East China sea induced strong zonal flow of the westerly winds over Seoul, resulting in the significant inflow of heat and moisture to the continent. Due to the anomalously warm ocean temperature of the Yellow sea, the warmer air that holds substantial heat and moisture led to torrential downpours causing significant rainfall accumulations that far exceeded that of the typical monsoon season in South Korea. The two hypotheses evaluated in this study were that climate change is a major factor in changing monthly trends and increasing precipitation rates in the month of August, and that Korea's forecasting system failed due to global warming exacerbating changes in Korea's precipitation cycle and South Korea's strong regional variability for its weather.

My first hypothesis was supported by my results in that global warming is increasing variations of August precipitation, demonstrated by its increasing standard deviation in factors such as precipitation and SLP.

The second hypothesis was partially supported by my results. Global warming did in fact exacerbate changes in Korean precipitation. The phenomenon of dipole pressure on the peninsula, caused by the atmospheric blocking from reduced jet stream speed, kept consistent precipitation over middle Korea and was fueled by warm water from the Yellow Sea. In addition, the Yellow Sea's SST has increased over the past decades due to global warming. Forecasting can no longer rely solely on past experiences with climate patterns or known statistics to confidently predict weather since a warmer climate is changing the norms of our climate system. Though South Korea's local weather variability did not seem to have a significant effect on causing the flooding, it is a factor that may have made it harder to predict as one would have to make forecasts for several different regions.

Limitations & Future Research

In the future I would like to look at more data regarding other floods in South Korea. This flood event was unique in that it was not caused by a severe typhoon, but due to a prolonged stationary front related to atmospheric blocking events. Looking at the data of typhoon-based flood data would give me a greater insight into the greater picture of all floods in South Korea and would help create the best solution for South Korean extreme weather preparedness. In addition, I also want to look at other recent flooding events, such as Summer 2022 floods in Pakistan and the Southwestern United States, to see if they were caused by similar conditions as the recent ones in Korea (dipole pressure, atmospheric blocking, etc.). If their causes did overlap then I want to know how much of what is happening in Korea carries over to different parts of the globe.

Research Applications

This study analyzed the spatial and temporal evolutions of recent flooding in South Korea and found that there were certain physical conditions that contributed to the unusual consecutive heavy rain. This work could enhance our understanding of certain climate uncertainties and how current thinking needs to change in order to confidently forecast future weather events. Moreover, by identifying certain uncertainties in extreme weather predictions, this information could help inform public policy and help the people and government of South Korea to be better prepared for such events in the future. Well-informed and science-based action can help save property and lives.

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