Understanding the Characteristics of the Heatwaves using Temperature as the Only Variable – A Case Study on the Heatwaves in 1994 in South Korea

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ABSTRACT

Acutely warm weather coupled with extreme weather variables or latent cooling due to a deficit of soil moisture could generate heatwaves. South Korea is highly susceptible to heatwaves that occur annually in different intensities and cause devastating impacts. This study aimed to identify the characteristics of the heatwaves, especially focusing on one of the most severe heatwaves observed in 1994 in South Korea using only temperature as a variable. The summer season, June to September (JJAS), was selected for the study because heatwaves were prominent during the summer in South Korea. The maximum and minimum daily temperatures were collected from the 67 meteorological stations located in South Korea. The mean daily 95th percentiles of the temperatures were assessed to identify the heatwave durations and the intensities. In 1994, the 15 stations recorded their highest heatwave durations, and durations varied between 48 to 66 days in the JJAS season. *Busan* station recorded the highest heatwave duration in 1994, which persisted for 66 days or throughout half of the season. Further, it was interesting to identify that coastal meteorological stations were most vulnerable to heatwaves in South Korea. However, the relationship between temperature intensities and heatwave duration for coastal cities showed statistically low significance. Furthermore, it is identified that the daily maximum temperature was most influential in the occurrence of heatwaves in both the coastal and mainland meteorological stations, except for *Pohang* and *Ulleungdo*. Therefore, the characteristics of heatwaves observed in 1994 in South Korea were identified using temperature as the only variable. Furthermore, a study on the dynamic atmospheric oscillations due to heated waves in coastal regions of South Korea over characteristics of heatwaves observed in South Korea is suggested.

KEYWORDS: *Heatwaves, South Korea, Temperature, 95th percentile.*

1 INTRODUCTION

A heatwave is one of the extreme events observed as a result of excessively hot weather, which is coupled with high temperature, high humidity, and low rainfall (Mueller and Seneviratne, 2013; Quesada et al., 2012). Furthermore, latent cooling due to high temperature-influenced soil moisture depletion could also cause heatwaves in some instances. In addition, the blocking highs in the Northern hemisphere due to moisture deficit cause heatwaves in mid-latitudes (Quesada et al., 2012; Pfahl and Wernli, 2012; Hirschi et al., 2011). The recurrent high-amplitude Rossby wave for the hemisphere (Kornhuber et al., 2020) and the oceanic oscillations such as El-Nino Southern Oscillation (ENSO) and North Atlantic Oscillation could cause heatwaves too. (Hsu et al., 2017; Loughran et al., 2017; Grotjahn et al., 2015). Unfortunately, anthropogenic activities leading to the emission of urban heat in the cities and the emission of greenhouse gasses aggravate heatwaves as well. (Ramamurthy et al., 2017; Jaeger et al., 2008).

The definitions for heatwaves vary globally due to the temperature threshold levels used to define heatwaves. The globally applicable generalized definition for a heatwave is provided by the World Meteorological Organization (WMO) as the presence of warming air, in which the daily maximum temperature (T_{Max}) is higher than the mean temperature (i.e., between 1961 and 1990) by 5°C or more for 5 or more consecutive days and destroy routine human activities (Frich et al., 2002). Nonetheless, WMO noted that a heatwave differs from warm spells, since a warm spell is defined based on 90th or 95th percentiles of daily T_{Max}.

Furthermore, a warm spell can be observed at any time of the year, whereas heatwaves can only be observed during the warm season. Some countries have their criteria to identify heatwaves as shown in Table 1.

Table 1. The criteria to declare heatwaves in different countries

Country	**Criterion**	**Source**
Netherlands, Belgium, and Luxemburg	T_{Max} in De Bilt, Utrecht, Netherlands exceeds 25°C or 30°C for consecutive five days or consecutive three days, respectively	Seveno, 2020.
Denmark	average T_{Max} exceeds 28° C for at least three days over 50% of the country	Scanpix, 2018.
Australia	both the T_{Max} and minimum temperatures (T_{Min}) unusually hot over 3 consecutive days	Commonwealth of Australia, 2021.
South Korea	daily T_{Max} exceeds 33°C for consecutive two days	Lim et al., 2019; Yoon et al., 2018

2 SOUTH KOREA AND ITS SUSCEPTIBILITY TO HEATWAVES

The expansion of the Western North Pacific subtropical high (WNPSH) and anticyclone circulation over the East Asian–northwestern pacific region are the main origins of a heatwave in South Korea (Park and Schubert, 1997; Garcia-Herrera et al., 2010). Furthermore, the Foehn effect acts as a cause of heatwaves in the southeastern parts of South Korea (Kim and Lee, 2007; Lee, 2003), and the impact of the Foehn effect over the western hills of South Korea was identified by Byun et al. (2006) and Lee (2003).

According to the statistics, the duration of the heatwave has increased from 10.1 days to a maximum of 31.5 days from 1981 to 2010, and the mentioned maximum value was observed in 2018 (Kim et al., 2020). Even though the highest daily T_{Max} was recorded as 41°C in *Hongcheon* in 2018 and was identified as the highest recorded T_{Max} after 111 years, the heatwave that occurred between July and August in 1994 over South Korea had a devastating impact on South Korea, causing more than 3000 deaths (Kysely and Kim, 2009). Nonetheless, due to the high susceptibility to heatwaves in South Korea, a surveillance system was developed by The Korea Center for Disease Control and Prevention (KCDC) in 2011 to monitor the deaths and hospitalizations related to the diseases caused by annual heatwaves (Na et al., 2013). Later in 2018, the South Korean Government declared heatwaves a natural disaster, and the government is liable to compensate the victims (Lee, 2018). Furthermore, Kim et al. (2006) identified that the daily mortality rate would increase from 6.7% to 16.3% if the daily temperature increases by 1°C from the threshold level.

Temperature changes could intensify the occurrence of heatwaves in a country. Kwon (2005) identified that the emission of greenhouse gasses and urbanization increased the mean temperature of South Korea by 1.5°C and continuous anthropogenic activities altered the climate in South Korea drastically (Im et al., 2008). Furthermore, Boo et al. (2004 and 2006) stated that the projected daily temperature of Korea would increase by 6°C during 2071–2100 compared to the observed daily temperature during 1971–2000.

The intensified and prolonged duration of heatwaves could couple with other natural disasters such as droughts and could cause a massive impact on a nation such as inadequate water in the reservoirs leading to losses in agriculture, inefficacy in domestic and industrial water supply, damages to the economy and wellbeing of the society.

Therefore, it is a timely need to understand the duration and intensity of the heatwaves observed in South Korea. In this context, the study primarily aims to identify the temporal and spatial distributions of T_{Max} and T_{Min} in South Korea and, to understand the heatwaves observed in 1994 in South Korea.

3 METHODOLOGY

3.1 The Temperature in South Korea – The Study Area

South Korea is a temperate country located between 34°N–38°N and 126°E–130°E. The climate of South Korea depends on the land–air–oceanic impacts of the nearby large landmass in the Northeastern Asia and the Pacific Ocean (Ghafouri-Azar and Bae, 2020). The temperature of South Korea is governed by two mechanisms: a) Pacific high pressure governs the summer season temperature, and the average temperature varies from 22–25°C, b) Elevation difference governs the winter temperature, and the average temperature ranges from -5°C to -3°C. Figure 1a illustrates the distribution of the mean monthly T_{Max} and T_{Min} in South Korea, and both the T_{Max} and T_{Min} are at their highest in August, which decreases during the summer season.

Nonetheless, 70% of the annual rainfall occurs during the summer season, which is commonly called the rainy season (i.e., Changma in the Korean language) (Figure 1b). There are two foremost mechanisms that govern the rainfall during the summer season: a) The local convention govern the Changma season b) Tropical cyclones (typhoons) govern the Post–Changma season (Lee et al., 2016; Choi et al., 2017). A part of the Changma season delivers heavy rainfall to the southern parts of South Korea starting from the end of June and moving northward across the country, continuing for nearly one month. Despite that, June to September (JJAS) was selected as a reference season for the study because many heatwaves are observed in the mentioned season, and it is beneficial to understand the behaviors of T_{Max} and T_{Min} during the summer season in South Korea.

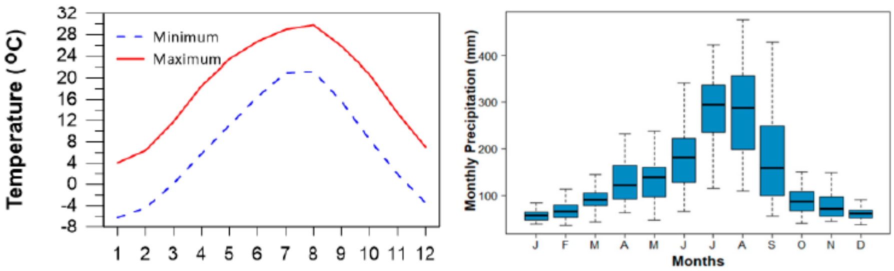

Figure 1. The distributions of a) mean monthly maximum and minimum temperatures (Left), and mean monthly precipitation (Right) in South Korea*

Source: a) Ghafouri-Azar and Bae, 2020. and b) Alcantara and Ahn, 2020.

* The X axis represents the months of the year in both figures.

3.2 Data

Two main data types – daily T_{Max} and T_{Min} data from 67 ASOS (Automated Surface or Synoptic Observing System) were used for the study (Figure 2). The 14 stations consist of data from 1960 to 2019 (i.e., 60 years), and the rest of the stations have data series between 32 years and 59 years.

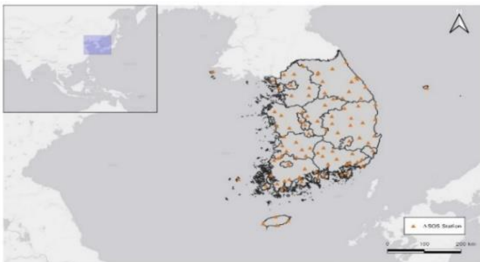

Figure 2. The location of KMA-managed ASOS stations used for the study

3.3 Use of 95th percentiles to identify the heatwaves

The heatwave episodes were identified using the methodology developed by Kuglitsch et al. (2010) with slight modifications. The daily time series of T_{Max} and T_{Min} for the JJAS season was plotted for each year and for each station. The long-term daily 95^{th} percentiles were calculated using the daily T_{Max} and T_{Min} from May to October, which was the calculation procedure developed by Della-Marta et al. (2007). Firstly, the mean daily T_{Max} and T_{Min} series for the period of May to October for each station was calculated. In this process, the mean temperature of a specific day was calculated by averaging the temperature of a given day for the total of selected years. Secondly, the 95^{th} percentile of a specific day was calculated based on the sample of 15 days (i.e., seven days on either side of the particular day). The 95^{th} percentiles for each day between May to October were calculated for both the T_{Max} and T_{Min} time series. Finally, the heatwave is identified where both the daily T_{Max} and T_{Min} exceed their 95^{th} percentiles by plotting the daily climatologies of T_{Max}, T_{Min}, and 95^{th} percentiles of T_{Max} and T_{Min}. Based on the methodology adopted by Della-Marta et al. (2007), a heatwave is identified as a period of three or more consecutive hot days and nights not interrupted by more than a non-hot day or night. Specifically, in this study, the duration is not specified to identify the heatwave, but the consecutive days of temperature which exceed both the 95^{th} percentiles of T_{Max} and T_{Min} are identified as the presence of a heatwave phenomenon or a heatwave duration.

The intensities of daily T_{Max} and T_{Min} were developed using temperatures and their respective heat wave durations. Thereafter, the intensities were plotted against the number of days identified as the presence of heatwaves within a year to identify the correlation between the intensities and the days which had heatwaves annually.

4 RESULTS AND DISCUSSION

4.1 The heatwave in 1994 – the longest heatwave duration observed in South Korea

As discussed in the previous paragraphs, intensified or long-duration heatwaves can lead to the occurrence of droughts. South Korea observed severe droughts in 1994 and 2018 due to the severe heatwaves during the mentioned years. Nevertheless, in 1994 it was recorded that there were 29 consecutive days in which daily T_{Max} exceeded 33°C which was a remarkable record for the longest duration heatwave observed in South Korea (Lee and Lee, 2016). Ahn (2019) presented that the droughts observed between 1994 and 1995 depleted the reservoir levels and impacted agriculture, drinking water, and industrial water in South Korea.

Out of 67 stations, 15 stations (i.e., the third-highest number of stations) recorded their highest heatwave duration (days) in 1994. The heat wave durations for those 15 stations varied between 48 – 66 days for the JJAS season. The highest heatwave duration in 1994 is observed in *Busan* station, and it is 66 days out of 122 days in the JJAS season (Figure 3a). The *Ulleungdo* station on *Ulleungdo* Island, which is located in the east of the mainland, had the second longest heatwave duration (i.e., 65 days) in 1994 (Figure 3b). Therefore, both regions experienced heatwaves during almost half of the JJAS season in 1994.

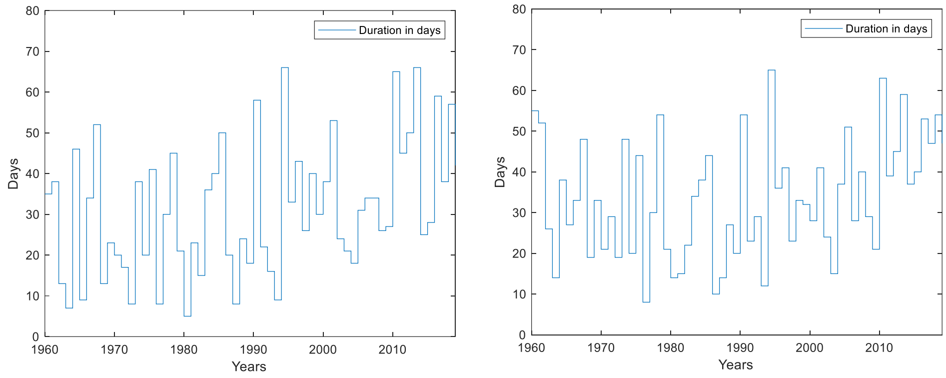

Figure 3. The distribution of heatwave durations* for a) *Busan* station (Left) and b) *Ulleungdo* station (Right)
*The blue line represents the duration in days

It is interesting to observe that heatwaves in *Busan* and *Ulleungdo* stations continued from the beginning of July to the beginning of August, where the daily T_{Max} and T_{Min} exceeded both their respective 95th percentiles (Figure 4a and 4b). However, the persisting heatwaves stopped for a few days and resumed and lasted till the beginning of September (Figure 4a and 4b). Choi et al. (2012) showed that the end of the Changma season in mid-July could trigger the occurrence of a heatwave in South Korea.

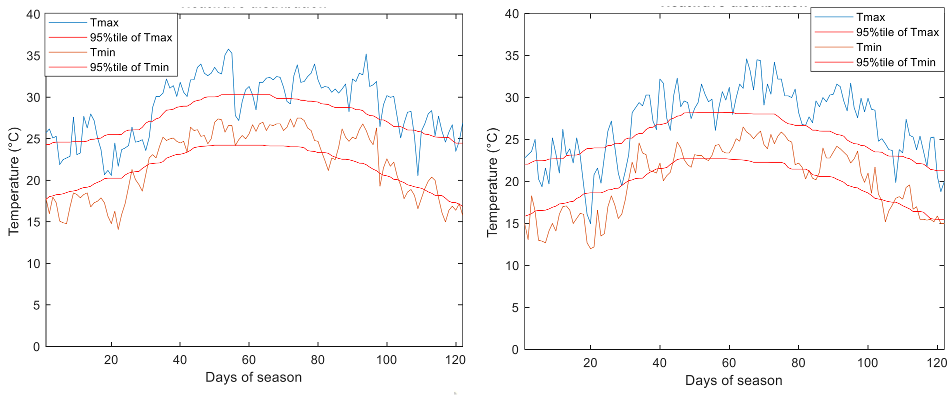

Figure 4. Time series distribution of daily T_{Max} and T_{Min} and respective 95th percentiles* for a) *Busan* station (Left) and b) *Ulleungdo* station (Right)
*The blue and brown lines represent the T_{Max} and T_{Min}, respectively. The red line represents the 95th percentiles for each temperature distribution.

4.2 Changes in temperature intensities during the heatwaves

During JJAS in 1994, the diurnal difference in daily T_{Max} and T_{Min} intensities for *Busan* station is insignificant, where T_{Max} was 2.7078°C/day, and T_{Min} was 2.0488°C. However, it is noteworthy that in 1992 and 1993, the daily T_{Min} intensity was higher compared to the T_{Max} intensity for the *Busan* station (Figure 5a). Therefore, it could be due to the increase in the daily mean T_{Min}, i.e., the temperature at night during the summer season is significantly higher than the variation in T_{Max} during daytime. This scenario may have occurred due to the increased humidity levels in the nighttime and, it could be because there was no time lapse to reduce the increased humidity levels in the daytime due to the heatwaves, and increased humidity levels continued for the night, causing disastrous heat impact in the night. Further, this phenomenon could be intensified in the coming days. Even though *Ulleungdo* station had the second-longest heatwave duration in 1994, T_{Min} intensity did not exceed the T_{Max} intensity (Figure 5b). Therefore, the main reason could be that the breezes may have reduced the heat generated during the daytime and decreased the temperature in the nighttime for *Ulleungdo* Island compared to the *Busan* station.

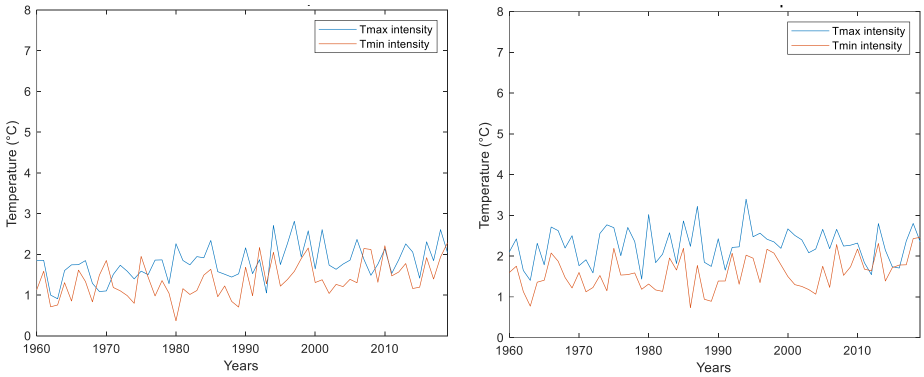

Figure 5. Time series distribution of intensities of daily T_{Max} and T_{Min}* a) *Busan* station (Left) and b) *Ulleungdo* station (Right)

*The blue line represents the T_{Max} intensity and the red line represents the T_{Min} intensity.

A higher correlation between both the temperature intensities and the durations of heatwaves was observed for *Busan* station compared to *Ulleungdo* station (Table 1). The correlation resulted in most of the coastal cities, including *Busan*, *Ulleungdo*, *Seosan*, *Pohang*, *Mokpo*, *Tongyeong*, and *Jinju that were* impacted by the deadly heatwaves in 1994. However, the relationship between heatwave duration and the temperature intensities for stations located in coastal cities showed statistically low significance. This could be due to the dynamic changes in surface temperature in coastal cities because of the land-sea breezes. This could have caused vigorous changes in the behavior of the heated air in the atmosphere. Furthermore, Park and Schubert (1997) suggested that the orographic and zonal wind over the Tibetan Plateau could change the atmospheric oscillations over South Korea and result in extreme heat in 1994. Consequently, it is recommended to study the teleconnection between the oceanic and atmospheric oscillations over temperature variation or the generation of a heatwave in South Korea.

Furthermore, the inland stations such as *Icheon*, *Cheonan*, *Geumsan*, and *Yeongju* were also severely affected in 1994. For the Pohang station, the daily T_{Min} is highly influenced by heatwave intensity and duration (Table 1). Interestingly, correlation resulted in daily T_{Max} being statistically more influential for the duration of heatwave compared to daily T_{Min} for stations on the mainland.

Table 2. The correlation between the duration of a heatwave (days) and the temperature (T_{Max} and T_{Min}) intensities for relevant durations for selected stations.

Location of the station	**Station Name**	**Correlation**	
		T_{Max}	**T_{Min}**
Near to coast or coastal cities	Busan	0.596	0.581
	Ulleungdo	0.327	0.577
	Seosan	0.523	0.211
	Pohang	0.180	0.699
	Mokpo	0.563	0.473
	Jinju	0.635	0.447
Mainland	Icheon	0.618	0.411
	Geumsan	0.544	0.388
	Yeongju	0.512	0.342

4.3 Evidence of absence of heatwave impacts in 1994

As mentioned previously, the longest duration of heatwave observed at *Busan* station in 1994 was 66 days. In addition, the study identified some stations which had longer heatwave durations in different years where there was no evidence for declared occurrences of heatwaves. The *Jeju* and *Seogwipo* stations on *Jeju* Island, South Korea, had the longest heatwave duration in 2017 and 2014, about 74 days and 72 days, respectively, for the period 1960 to 2019. South Korea is geographically and temporally highly diverse within the country. Therefore, it is helpful to identify the teleconnections between temperature and other weather variables which would lead to heatwaves in South Korea.

5 CONCLUSION

South Korea is prone to heatwave-induced devastations which have an impact on the economic, social, and environmental status of South Korea. Therefore, identification of the occurrence of heatwaves would be advantageous. Therefore, this study attempted to identify heatwaves in South Korea using only temperature as a variable such as daily maximum and minimum temperatures and their 95th percentiles and focused on the occurrence of severe heatwave incidents observed in 1994.

The study identified that *Busan* and *Ulleungdo* stations showed the longest durations of a heatwave during 1994. Further, the heatwaves were identified from the beginning of July to the beginning of August for both stations. Nonetheless, there was an intermittent break in between August, and the heatwave lasted until September. Some researchers argued that the end of the Changma season in mid-July could prompt the occurrence of a heatwave in South Korea.

Further, the correlation between temperature intensities and the heatwave durations showed that mainland stations had a higher correlation with the T_{Max} compared to the coastal stations. The coastal stations may have been influenced by land-sea breezes over temperature changes. For some instances, T_{Min} intensities exceeded the T_{Max} intensities because the heated air persisted until night and caused the heatwave impacts in the nighttime.

Some stations were not impacted by the heatwaves observed in 1994, but they had the longest heatwave durations in different years based on the method used in this study. It may be due to the presence of geographically wide variations in South Korea.

The study suggests further studies on the teleconnections between land-atmospheric circulations with regard to the occurrence of heatwaves in South Korea.

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