Climate change impacts on reference evapotranspiration in South Korea over the recent 100 years

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Abstract

The damage owing to climate change is increasing worldwide. In South Korea, the increase in temperature has exceeded the average global temperature increase. These temperature changes have increased the frequency and damage of droughts. To reduce drought damage, the importance of efficient water management policies and evapotranspiration (an index used for water management policies) is increasing. Generally, the potential evapotranspiration ($ET_0$) is estimated by using the FAO-56 Penman–Monteith (PM) equation on meteorological datasets. In this study, long-term meteorological data with a maximum of 100 years were collected from 12 sites to estimate evapotranspiration. The objectives of this study were to (1) estimate the evapotranspiration based on the PM equation, (2) analyze the trends in the temperature and evapotranspiration, and (3) evaluate the relationship between the temperature and evapotranspiration through a correlational analysis. The results improve our understanding of climate change and provide a valuable reference for regional water resource management. It is found that there are generally increasing trends in spring, summer, and autumn, and generally decreasing trends in winter. The results from a seasonal Mann–Kendall test between the temperature and $ET_0$ show that the maximum temperature exhibits a distinct increase in spring and winter in certain areas. We determined the strengths of the relationships between temperature metrics and $ET_0$ using Pearson’s correlation coefficient, and the results show that the maximum temperature metric has the strongest relationship.

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1 Introduction

Climate change is one of the most significant global issues and is predicted to alter climate patterns and increase the frequency of extreme weather events (Hayes et al. 2004; Intergovernmental Panel on Climate Change (IPCC) 2012). According to the IPCC, land and ocean temperatures increased by an average of between 0.3 and 0.6 °C from 1900 to 1995, and have increased by approximately 0.2 to 0.3 °C over the past 40 years. For centuries, the global climate has been gradually warming; the average temperature has increased by 0.74 °C (Douville et al. 2013). The magnitude of the surface warming in South Korea is much larger than the global average over the same period, as it is affected by various climate events over the northeastern coast of the Asian continent (Jung et al. 2002; Chung et al. 2004; Nam et al. 2018). The Korea Meteorological Administration (KMA) published a report on future climate change, combining several research papers aimed at diagnosing signs of global warming on the Korean Peninsula and examining the associated climate change (KMA 2012). According to the KMA report, the annual average temperature in South Korea increased by 1.2 °C between 1981 and 2010, representing a mean warming rate of 0.4 °C per decade (Choi et al. 2018).

According to several previous studies, the intensity and frequency of dangerous weather events, such as tropical cyclones, heavy rains, cold surges, droughts, and heat waves on the Korean Peninsula have increased over the past decades (Jeong et al. 2011; Park et al. 2011; Lee et al. 2012; Min et al. 2015; Nam et al. 2015b; Nam et al. 2016). In recent years, the frequency and severity of droughts owing to climate change have also increased (Dai et al. 2004; Sheffield et al. 2012; IPCC 2013; Spinoni et al. 2017; Zhang et al. 2017). South Korea is classified as a water-deficient country by the United Nations and has experienced serious drought and water scarcity problems in recent years (Kim et al. 2014). Historical weather records confirm that South Korea has recently experienced a massive drought at the national level (Min et al. 2003; Kim et al. 2011). Drought is expected to become more frequent and severe. Moreover, the water demand is expected to further increase owing to population growth, limited or uncertain water supplies in the context of increasing temperatures, and increasingly extreme precipitation regimes (Smith and Katz 2013; Trenberth et al. 2014). Faced with these challenges, water resource decision-makers in South Korea require clear information to help develop preparatory plans and establish policies to reduce the effects of drought under changing climatic conditions (Nam and Choi 2014; Hong et al. 2016; Zhang et al. 2019).

The reference evapotranspiration ($ET_0$) is an important component of the hydrological cycle and plays a key role in estimating crop growth and water demand for irrigation water management (Vicente-Serrano et al. 2014; Milly and Dunne 2016; Lian et al. 2018; Yassen et al. 2020). Changes in the $ET_0$ are critical indicators for water resource planning, irrigation requirement systems, and agricultural production (Peterson and Keller 1990; Hatch et al. 1999; Czикowsky and Fitzjarald 2004; Onyutga 2016; Guo et al. 2017; Zhao et al. 2020). Understanding the $ET_0$ as the climate and crops change can be useful for improving crop growth and irrigation water management. The first critical step in understanding the impacts of climate change on hydrological processes involves a trend analysis of the changes in the $ET_0$. Many studies have analyzed $ET_0$ trends in the context of climate variability, aiming to determine the importance of this factor (Vanderlinden et al. 2008; Tabari et al. 2011; Kousari and Ahani 2012; Croitoru et al. 2013; Casa and Ovando 2014; Xiang et al. 2020). Analyzing the observed trends in the $ET_0$ can provide considerable insights into current climate change and the influences that such change may have on agricultural and water resources (Peterson et al. 1995; Xu et al. 2006; Irmak et al. 2012; Xu et al. 2018). Various studies have confirmed increases in the $ET_0$ under different climate change scenarios (Chattopadhyay and Hulme 1997; Mo et al. 2013; Garcia-Garizabal et al. 2014; Vicente-Serrano; Peng et al. 2017; Berg and Sheffield 2019; Bian et al. 2020). Thomas (2000) analyzed trends using Penman–Monteith (PM) $ET_0$ estimates from 1954 to 1993 at 65 stations in mainland China and Tibet. Their results showed that in China, the $ET_0$ decreased during all four seasons. Espadafor et al. (2011) used the PM equation to show the $ET_0$ trends in southern Spain from 1960 to 2005. Their results indicated a positive trend over the last 45 years (i.e., the annual $ET_0$ has been increasing). Although several studies have used historical $ET_0$ values to analyze climate change in South Korea, these studies have been limited in that they analyzed statistical indicators, such as the annual mean and variance. In spring and winter, the spatial distribution of the $ET_0$ is important for crop production, as it is closely related to spring drought (Nam et al. 2012a; Nam et al. 2012b). Although previous studies have suggested significant trends in the $ET_0$ for South Korea, there has not yet been a study examining the spatial and temporal changes over the entire country. To accurately detect the long-term changes in the $ET_0$ owing to climate change, it is necessary to understand the regional scale of the spatiotemporal pattern changes. Although there remain limitations to using the observation point data to analyze spatial changes, it is considered that the data from the 12 meteorological stations used in this study can be used as basic data for analyzing the variability according to a spatial distribution through subsequent studies. In this sense, it is meaningful to analyze the changing characteristics of the $ET_0$ at the 12 meteorological stations across South Korea (Nam et al. 2015a).

In this study, we analyzed the effects of climate change on the $ET_0$ using long-term historical meteorological data. The objectives were as follows: (1) to calculate the long-term...
$ET_0$ based on the FAO-56 PM formula using long-term historical meteorological weather data from 12 stations in South Korea; (2) to quantify changes in temperature and evapotranspiration using the seasonal Mann–Kendall test and Sen’s slope estimator; and (3) to analyze the effects of temperature change on evapotranspiration changes using

Fig. 1 Location of 12 meteorological stations in South Korea. The global land cover information map is used as a background image (refer to Table 1 for information on ground meteorological stations)

| Station number | Station     | Latitude  | Longitude  | Data period   | Maximum annual $ET_0$ (mm) | Minimum annual $ET_0$ (mm) | Average $ET_0$ for recent 10 years (mm) | Average $ET_0$ for past 10 years (mm) |
|----------------|-------------|-----------|------------|---------------|-----------------------------|-----------------------------|----------------------------------------|----------------------------------------|
| 47105          | Gangneung   | 37° 45’   | 128° 53’   | 1912–2018     | 1132.1                      | 846.7                       | 1030.8                                 | 1029.9                                 |
| 47108          | Seoul       | 37° 34’   | 126° 57’   | 1908–2018     | 1214.4                      | 930.1                       | 1115.2                                 | 1007.0                                 |
| 47112          | Incheon     | 37° 28’   | 126° 37’   | 1904–2018     | 1143.3                      | 937.7                       | 1040.7                                 | 1004.0                                 |
| 47135          | Chupungnyeong | 36° 13’   | 127° 59’   | 1953–2018     | 1126.3                      | 920.2                       | 1042.8                                 | 1034.9                                 |
| 47138          | Pohang      | 36° 34’   | 128° 42’   | 1949–2018     | 1345.0                      | 967.7                       | 1156.4                                 | 1112.9                                 |
| 47143          | Daegu       | 35° 49’   | 128° 39’   | 1909–2018     | 1326.6                      | 1026.6                      | 1165.2                                 | 1086.8                                 |
| 47146          | Jeonju      | 35° 50’   | 127° 07’   | 1919–2018     | 1090.8                      | 903.9                       | 1026.6                                 | 1000.9                                 |
| 47152          | Ulsan       | 35° 34’   | 129° 20’   | 1946–2018     | 1211.9                      | 981.8                       | 1108.8                                 | 1064.1                                 |
| 47156          | Gwangju     | 35° 10’   | 126° 53’   | 1939–2018     | 1155.9                      | 922.6                       | 1052.1                                 | 999.0                                  |
| 47159          | Busan       | 35° 06’   | 129° 01’   | 1904–2018     | 1351.4                      | 1040.5                      | 1225.6                                 | 1181.1                                 |
| 47165          | Mokpo       | 34° 49’   | 126° 22’   | 1906–2018     | 1246.4                      | 908.4                       | 1071.3                                 | 1024.4                                 |
| 47168          | Yeosu       | 34° 44’   | 127° 44’   | 1942–2018     | 1337.0                      | 1040.8                      | 1215.1                                 | 1125.4                                 |
the Pearson correlation coefficient. This study is significant because it analyzes the long-term changes in reference evaporation, and provides information regarding the effects of temperature changes on such reference evaporation.

2 Data and methodology

2.1 Meteorological data

In this study, data were collected from 12 KMA stations in South Korea (Gangneung, Seoul, Incheon, Chupungnyeong, Pohang, Daegu, Jeonju, Ulsan, Gwangju, Busan, Mokpo, and Yeosu) for the temperature, relative humidity, wind speed, and sunshine hours; the data are shown in Figure 1 and Table 1. The KMA performed data quality management on the raw data, including quality assurance and quality control (KMA 2011). This KMA quality management process, a real-time quality management system for weather observation data, checked the physical ranges, frequency distributions, flat lines, center filters, and vertical consistency of the observed data. This data quality management ensured that all of the data were reliable for every observation station managed by the KMA.

All available datasets from the founding year for each station were analyzed aside from the period of the Korean War (1950–1953), for which the data from some stations were unavailable. Observations at the Seoul, Incheon, Daegu, Busan, and Mokpo stations began before 1910. Since 1910, additional observation stations have been established in Gangneung, Jeonju, Gwangju, Yeosu, Ulsan, Pohang, and Chupungnyeong. To identify the long-term variability in the seasonal temperature, the average temperature (T_mean), maximum temperature (T_max), minimum temperature (T_min), and daily mean temperature for each season were analyzed, i.e., winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). This study focused on the seasonal temperature, as the interannual variations in the annual mean temperature may not represent the detailed characteristics of long-term variations. Because the temperature records at these 12 stations began in different years, the temperature change characteristics could be mixed if the average temperature was measured at one time for all stations. Thus, the temperature records were analyzed for each station.

2.2 Food and Agriculture Organization (FAO)-56 Penman–Monteith

The PM equation was published by the Food and Agriculture Organization in Irrigation and Drainage Paper No. 56 (Allen et al. 1998; Allen 2000; Pereira et al. 2015). It has received acceptance and application throughout much of the world (including the USA) for establishing a reference evapotranspiration (ET_0) index as an official weather parameter (Allen et al. 2005; Blonquist et al. 2010). The PM equation is shown in Eq. 1. In this study, the daily ET_0 was estimated, and the daily ET_0 values were summed to compare the seasonal temperatures.

\[
ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C_p}{T_{\text{avg}}} u_2 (e_a - e_d)}{\Delta + \gamma (1 + C_d u_2)}
\]  

In the above, ET_0 is the reference evapotranspiration (mm • day^{-1}), R_n is the net radiation (MJ • m^{-2}), G is the sensible heat flux density from the surface to the soil (MJ • m^{-2} • day^{-1}), T_{avg} is the mean daily temperature (°C), U_2 is the wind speed at 2 m above sea level (m • s^{-1}), e_a is the saturation vapor pressure at the mean air temperature (kPa), e_d is the mean vapor pressure of air (kPa), Δ is the slope of e_a versus the T curve (kPa • °C^{-1}), and γ is a psychrometer constant (kPa • °C^{-1}). The net radiation (R_n) was computed as the sum of the net shortwave radiation and net long-wave radiation, and the solar radiation (R_s) was estimated from the measured sunshine hours, C_p=900, C_d=0.34 in reference grass (Lage et al. 2003; Allen et al. 2011).

\[
R_s = (0.25 + 0.5 \frac{n}{N}) R_n
\]  

\[
R_n = 0.77 R_s - 2.45 \times 10^{-9} \left( \frac{T_{\text{max}} - T_{\text{min}}}{2} \right)^4 \times (0.9 \frac{n}{N} + 0.1)(0.34 - 0.14 \sqrt{e_d})
\]  

Here, R_s is the extra-terrestrial radiation (MJ • m^{-2} • day^{-1}), n is the bright sunshine hours per day (h), and N is the total length of a day (hours). T_max is the maximum daily temperature (°C), and T_min is the minimum daily temperature (°C).

2.3 Statistical analysis

2.3.1 Seasonal Mann–Kendall test

The Mann–Kendall test is a non-parametric ranking test. It is useful for analyzing abrupt climate change (Goossens and Berger 1987). The seasonal Mann–Kendall test, a Mann–Kendall testing method, was originally proposed by Mann (1945) and improved through further studies (Kendall 1975; Hirsch et al. 1982; Hirsch and Slack 1984). In this study, the monthly temperature and ET_0 data for each season were analyzed using the seasonal Mann–Kendall test, and the significance was verified.

2.3.2 Sen’s slope

Sen (1968) developed a non-parametric procedure for estimating the slope of the trend in a sample of N pairs of data, as follows (Sen 1968):
\[ Q_i = \frac{x_j - x_k}{j - k} (i = 1, \ldots, N) \]  \hspace{1cm} (7)

In the above, \( x_j \) and \( x_k \) are the data values at times \( j \) and \( k \) \((j > k)\), respectively. If there is only one datum in each period, then \( N = \frac{n}{2} \), where \( n \) is the number of periods. If there are multiple observations in one or more periods, then \( N = \frac{m(n-1)}{2} \), where \( n \) is the total number of observations.

The \( N \) values of \( Q_i \) are ranked from smallest to largest, and the median of the slope, or Sen’s slope estimator, is computed as follows:

\[ Q_{\text{med}} = \begin{cases} \frac{Q_{[N+1]}/2}{Q_{[N]} + Q_{[N+2]/2}} & \text{if } N \text{ is odd} \\ \frac{Q_{[N+2]/2}}{Q_{[N]} + Q_{[N+1]/2}} & \text{if } N \text{ is even} \end{cases} \]  \hspace{1cm} (8)

Here, \( Q_{\text{med}} \) reflects the trend in the data, and its value indicates the steepness of the trend. The confidence interval of \( Q_{\text{med}} \) at a specific probability should be obtained to determine whether the median slope is statistically different from zero.

The confidence interval for the time slope (Hollander and Wolfe 1973; Gilbert 1987) is computed as follows:

\[ C_a = Z_{1-a/2} \sqrt{\text{Var}(S)} \]  \hspace{1cm} (9)

In the above, \( Z_{1-a/2} \) is obtained from a standard normal distribution table. In this study, the confidence interval was computed at the significance level of \( \alpha = 0.05 \). The slope \( Q_{\text{med}} \) is statistically different from zero if the two limits (\( Q_{\text{min}} \) and \( Q_{\text{max}} \)) have similar signs.

### 2.3.3 Pearson correlation coefficient

The Pearson correlation coefficient \( (r_{xy}) \) measures the linear correlation between two variables \( x \) and \( y \). The coefficient \( r_{xy} \) has a value between +1 and −1, where 1 represents a total positive linear correlation, 0 represents a linear correlation, and −1 represents a total negative linear correlation (Jeon et al. 2019). In this study, the relationship between the temperature (maximum, average, and minimum) and \( ET_0 \) was analyzed using \( r_{xy} \).

### 3 Result and discussion

#### 3.1 Long-term \( ET_0 \) estimate by region

In this study, the daily \( ET_0 \) was estimated from 1904 to 2018 by region using the PM equation. The calculated daily \( ET_0 \) values were categorized by year, as shown in Figure 2. In Figure 2, the black dotted lines represent the annual \( ET_0 \) values of the 12 stations, and the red lines represent the trend lines for all periods at each station. According to the trend lines, the annual \( ET_0 \) values for all stations show an increasing trend. The greatest increasing trend is found in Yeosu, whereas the least increasing trend is observed in Chupungnyeong. The maximum and minimum annual \( ET_0 \) values during the observation period were obtained at each meteorological station. Busan recorded the highest annual \( ET_0 \) at 1351.4 mm in 2013, and Gangneung had the lowest annual \( ET_0 \) during the entire period, at 846.7 mm in 1964. The seven stations (Gangneung, Seoul, Daegu, Jeonju, Gwangju, Busan, Mokpo) where the observations began before the 1940s showed lower average \( ET_0 \) values than the other five stations (Incheon, Chupungnyeong, Pohang, Ulsan, Yeosu), along with lower maximum and minimum \( ET_0 \) values.

Table 1 lists the maximum and minimum annual \( ET_0 \) values for each station. As shown by the differences between the recent \( ET_0 \) values and those from 10 years ago, the \( ET_0 \) is increasing; in particular, Seoul records the highest increase, at 108.1 mm. Gangneung and Chupungnyeong show less than a 10-mm difference between the recent and past 10 years \( ET_0 \) values; Gangneung recorded 0.9 mm, and Chupungnyeong recorded 7.9 mm. Gangneung and Chupungnyeong, among the eight stations, showed relatively lower increases, owing to less urbanization.

Figure 3 shows the annual time series of the seasonal \( ET_0 \) at the 12 stations. The brown line represents spring, the green line represents summer, and the blue line represents autumn. In spring, Gangneung recorded the highest \( ET_0 \) in 2015 at 366.2 mm, and the lowest \( ET_0 \) in 1963 at 212.2 mm. In summer, Daegu recorded 451.7 mm in 1994, and Mokpo recorded 234.0 mm in 1980, the highest and lowest \( ET_0 \) at each station, respectively. In autumn, Yeosu recorded 390.6 mm, the highest \( ET_0 \) in 2001, whereas Gangneung was 172.2 mm for the lowest \( ET_0 \) in 1958. In winter, Yeosu had the highest \( ET_0 \) in 2004 at 261.8 mm, and Jeonju had the lowest \( ET_0 \) in 2018, at 82.0 mm. In spring, summer, and autumn, the highest \( ET_0 \) values were observed in recent years, whereas the lowest \( ET_0 \) value was observed in the past year. In winter, the \( ET_0 \) was different from the other seasons, with the lowest \( ET_0 \) occurring in a recent year. Eleven stations (Seoul, Incheon, Chupungnyeong, Pohang, Daegu, Jeonju, Ulsan, Gwangju, Busan, Mokpo, and Yeosu) had the lowest \( ET_0 \) in 2018, excluding Gangneung. As shown in Figure 3, only summer shows an increasing trend, whereas
the other seasons show decreasing trends. These results are interpreted as a phenomenon caused by the decreasing annual $ET_0$ in 2018, as shown in Figure 2.

### 3.2 Analysis of trend by statistical index

#### 3.2.1 Trend analysis of seasonal temperature

In this study, the confidence interval was calculated as 5% for the seasonal Mann–Kendall test of the maximum, average, and minimum temperatures. The results are shown in Table 2. $T_{\text{max}}$ indicates the results of the Mann–Kendall test for the seasonal maximum temperature at the 12 stations.

In spring, the maximum temperature shows an increasing trend at all 12 stations, and the maximum temperature in winter also shows an increasing trend at all stations except for Incheon, Chupungnyeong, and Mokpo. In certain areas (Pohang, Jeonju, Gwangju, and Yeosu), the maximum temperature in autumn exhibits an increasing trend. The only decreasing trend is for the maximum temperature in autumn at Mokpo, and there is no trend in summer for any of the stations. In addition, the results from the Mann–Kendall test for the seasonal maximum temperature generally increase.

$T_{\text{avg}}$ indicates the results of the Mann–Kendall test for the seasonal average temperature at the 12 stations. The average temperature in spring shows an increasing trend at all stations, whereas the average temperature in summer...
also shows an increasing trend at all stations except Chupungnyeong. The average temperature in autumn shows an increasing trend at all stations except Pohang, Jeonju, Ulsan, Gwangju, and Yeosu. All 12 stations show no trend or an increasing trend. None shows a decreasing trend, unlike the case with the maximum temperature. In winter, the average temperature shows an increasing trend at all stations except Chupungnyeong, Busan, and Mokpo. These results show a more pronounced increasing trend than that of the maximum temperature. Thus, the average temperature trend generally increases.

\( T_{\text{mean}} \) displays the results of the Mann–Kendall test for the seasonal minimum temperature at the 12 stations. The minimum temperatures in spring and summer show an increasing trend at all stations except Chupungnyeong. In autumn, the minimum temperature shows an increasing trend at Pohang, Jeonju, Ulsan, Gwangju, and Yeosu. In winter, the minimum temperature shows an increasing trend, except for Chupungnyeong, Busan, and Mokpo. The minimum temperature at all stations shows either no trend or an increasing trend, similar to the average temperature. The minimum and average temperatures exhibit the same trend, except for the spring trend at Chupungnyeong. Thus, the minimum temperature trend generally increases.

These trend changes are represented in the graphs in Figures 4, 5, and 6. The gray lines represent the seasonal mean temperature anomalies. The black solid lines represent the moving average of 27 months to easily identify the long-term
Table 2. Result of Mann–Kendall and Sen’s slope for seasonal temperature

| Station   | Season | Temperature | $S$  | $Z$  | Trend     | Sen’s slope |
|-----------|--------|-------------|------|------|-----------|-------------|
| Gangneung | Spring | $T_{\text{max}}$ | 931  | 2.69 | Positive  | 0.024       |
|           |        | $T_{\text{avg}}$ | 1251 | 3.51 | Positive  | 0.035       |
|           |        | $T_{\text{min}}$ | 1249 | 3.51 | Positive  | 0.035       |
|           | Summer | $T_{\text{max}}$ | -35  | -0.1 | No trend  | 0           |
|           |        | $T_{\text{avg}}$ | 987  | 2.73 | Positive  | 0.014       |
|           |        | $T_{\text{min}}$ | 1313 | 3.65 | Positive  | 0.02        |
|           | Autumn | $T_{\text{max}}$ | -147 | -0.42| No trend  | -0.003      |
|           |        | $T_{\text{avg}}$ | 293  | 0.82 | No trend  | 0.011       |
|           |        | $T_{\text{min}}$ | 404  | 1.13 | No trend  | 0.018       |
|           | Winter | $T_{\text{max}}$ | 1031 | 2.96 | Positive  | 0.019       |
|           |        | $T_{\text{avg}}$ | 1132 | 3.15 | Positive  | 0.022       |
|           |        | $T_{\text{min}}$ | 1105 | 3.1  | Positive  | 0.028       |
| Seoul     | Spring | $T_{\text{max}}$ | 901  | 2.46 | Positive  | 0.031       |
|           |        | $T_{\text{avg}}$ | 1019 | 2.78 | Positive  | 0.041       |
|           |        | $T_{\text{min}}$ | 1054 | 2.88 | Positive  | 0.048       |
|           | Summer | $T_{\text{max}}$ | -43  | -0.11| No trend  | 0.001       |
|           |        | $T_{\text{avg}}$ | 978  | 2.65 | Positive  | 0.015       |
|           |        | $T_{\text{min}}$ | 1215 | 3.31 | Positive  | 0.024       |
|           | Autumn | $T_{\text{max}}$ | -244 | -0.67| No trend  | -0.002      |
|           |        | $T_{\text{avg}}$ | 176  | 0.48 | No trend  | 0.016       |
|           |        | $T_{\text{min}}$ | 294  | 0.08 | No trend  | 0.03        |
|           | Winter | $T_{\text{max}}$ | 885  | 2.4  | Positive  | 0.019       |
|           |        | $T_{\text{avg}}$ | 892  | 2.43 | Positive  | 0.025       |
|           |        | $T_{\text{min}}$ | 1012 | 2.76 | Positive  | 0.038       |
| Incheon   | Spring | $T_{\text{max}}$ | 941  | 2.4  | Positive  | 0.034       |
|           |        | $T_{\text{avg}}$ | 1076 | 2.74 | Positive  | 0.036       |
|           |        | $T_{\text{min}}$ | 1120 | 2.85 | Positive  | 0.036       |
|           | Summer | $T_{\text{max}}$ | 628  | 1.6  | No trend  | 0.014       |
|           |        | $T_{\text{avg}}$ | 1044 | 2.65 | Positive  | 0.018       |
|           |        | $T_{\text{min}}$ | 1094 | 2.79 | Positive  | 0.021       |
|           | Autumn | $T_{\text{max}}$ | -708 | -1.8 | No trend  | -0.011      |
|           |        | $T_{\text{avg}}$ | -403 | -1.02| No trend  | 0.001       |
|           |        | $T_{\text{min}}$ | -294 | -0.75| No trend  | 0.007       |
|           | Winter | $T_{\text{max}}$ | 714  | 1.8  | No trend  | 0.012       |
|           |        | $T_{\text{avg}}$ | 934  | 2.36 | Positive  | 0.018       |
|           |        | $T_{\text{min}}$ | 899  | 2.29 | Positive  | 0.02        |
| Chupungnyeong | Spring | $T_{\text{max}}$ | 491  | 2.72 | Positive  | 0.029       |
|            |       | $T_{\text{avg}}$ | 368  | 2.05 | Positive  | 0.017       |
|            |       | $T_{\text{min}}$ | -64  | -0.36| No trend  | -0.002      |
|            | Summer | $T_{\text{max}}$ | 144  | 0.79 | No trend  | 0.006       |
|            |       | $T_{\text{avg}}$ | 81   | 0.45 | No trend  | 0.001       |
|            |       | $T_{\text{min}}$ | 72   | -0.39| No trend  | -0.004      |
|            | Autumn | $T_{\text{max}}$ | 166  | 0.92 | No trend  | 0.008       |
|            |       | $T_{\text{avg}}$ | 27   | 0.15 | No trend  | 0.001       |
|            |       | $T_{\text{min}}$ | -151 | -0.78| No trend  | -0.009      |
|            | Winter | $T_{\text{max}}$ | 271  | 1.5  | No trend  | 0.019       |
|            |       | $T_{\text{avg}}$ | 194  | 1.07 | No trend  | 0.012       |
|            |       | $T_{\text{min}}$ | 46   | 0.26 | No trend  | 0.003       |
| Station | Season | Temperature | $S$ | $Z$ | Trend | Sen’s slope |
|---------|--------|-------------|-----|-----|-------|-------------|
|        |        | $T_{\text{max}}$ |     |     |       |             |
| Pohang | Spring | 565         | 2.99| Positive | 0.039 |
|        |        | $T_{\text{avg}}$ | 583 | 3.08 | Positive | 0.041 |
|        |        | $T_{\text{min}}$ | 575 | 3.04 | Positive | 0.046 |
|        | Summer | 300         | 1.55| No trend | 0.017 |
|        |        | $T_{\text{avg}}$ | 531 | 2.77 | Positive | 0.028 |
|        |        | $T_{\text{min}}$ | 651 | 3.4  | Positive | 0.039 |
|        | Autumn | 522         | 2.7 | Positive | 0.016 |
|        |        | $T_{\text{avg}}$ | 591 | 3.11 | Positive | 0.027 |
|        |        | $T_{\text{min}}$ | 574 | 3.01 | Positive | 0.039 |
|        | Winter | 514         | 2.66| Positive | 0.026 |
|        |        | $T_{\text{avg}}$ | 507 | 2.62 | Positive | 0.026 |
|        |        | $T_{\text{min}}$ | 522 | 2.72 | Positive | 0.035 |
| Daegu  | Spring | 1339        | 3.5 | Positive | 0.04  |
|        |        | $T_{\text{avg}}$ | 1306 | 3.42 | Positive | 0.043 |
|        |        | $T_{\text{min}}$ | 1293 | 3.38 | Positive | 0.043 |
|        | Summer | 708         | 1.83| No trend | 0.008 |
|        |        | $T_{\text{avg}}$ | 1118 | 2.91 | Positive | 0.015 |
|        |        | $T_{\text{min}}$ | 1025 | 2.68 | Positive | 0.021 |
|        | Autumn | $-91$       | $-0.24$ | No trend | 0.004 |
|        |        | $T_{\text{avg}}$ | $-75$ | $-0.2$ | No trend | 0.014 |
|        |        | $T_{\text{min}}$ | $-128.67$ | $-0.33$ | No trend | 0.017 |
|        | Winter | 1030        | 2.7 | Positive | 0.024 |
|        |        | $T_{\text{avg}}$ | 995.33 | 2.6  | Positive | 0.025 |
|        |        | $T_{\text{min}}$ | 1006 | 2.63 | Positive | 0.027 |
| Jeonju | Spring | 1438        | 4.32| Positive | 0.027 |
|        |        | $T_{\text{avg}}$ | 1293 | 3.91 | Positive | 0.028 |
|        |        | $T_{\text{min}}$ | 1232 | 3.72 | Positive | 0.023 |
|        | Summer | 499         | 1.48| No trend | 0.006 |
|        |        | $T_{\text{avg}}$ | 976  | 2.92 | Positive | 0.013 |
|        |        | $T_{\text{min}}$ | 1043 | 3.13 | Positive | 0.015 |
|        | Autumn | 1041        | 3.12| Positive | 0.014 |
|        |        | $T_{\text{avg}}$ | 1196 | 3.59 | Positive | 0.018 |
|        |        | $T_{\text{min}}$ | 1206 | 3.62 | Positive | 0.023 |
|        | Winter | 1186        | 3.55| Positive | 0.025 |
|        |        | $T_{\text{avg}}$ | 1071 | 3.2  | Positive | 0.021 |
|        |        | $T_{\text{min}}$ | 1017 | 3.04 | Positive | 0.02 |
| Ulsan  | Spring | 620         | 2.99| Positive | 0.027 |
|        |        | $T_{\text{avg}}$ | 619  | 3    | Positive | 0.038 |
|        |        | $T_{\text{min}}$ | 655  | 3.18 | Positive | 0.038 |
|        | Summer | 202         | 0.96| No trend | 0.007 |
|        |        | $T_{\text{avg}}$ | 565  | 2.71 | Positive | 0.02 |
|        |        | $T_{\text{min}}$ | 658  | 3.16 | Positive | 0.022 |
|        | Autumn | 274         | 1.3 | No trend | 0.008 |
|        |        | $T_{\text{avg}}$ | 653  | 3.13 | Positive | 0.021 |
|        |        | $T_{\text{min}}$ | 661  | 3.17 | Positive | 0.028 |
|        | Winter | 418         | 1.99| Positive | 0.019 |
|        |        | $T_{\text{avg}}$ | 559  | 2.66 | Positive | 0.024 |
|        |        | $T_{\text{min}}$ | 660  | 3.14 | Positive | 0.034 |
Table 2 (continued)

| Station  | Season | Temperature | $S$ | $Z$ | Trend | Sen’s slope |
|----------|--------|-------------|-----|-----|-------|-------------|
| Gwangju  | Spring | $T_{\text{max}}$ | 889 | 3.8 | Positive | 0.033 |
|          |        | $T_{\text{avg}}$ | 773 | 3.33 | Positive | 0.037 |
|          |        | $T_{\text{min}}$ | 755 | 3.25 | Positive | 0.04 |
|          | Summer | $T_{\text{max}}$ | 321 | 1.36 | No trend | 0.009 |
|          |        | $T_{\text{avg}}$ | 514 | 2.2 | Positive | 0.014 |
|          |        | $T_{\text{min}}$ | 547 | 2.33 | Positive | 0.016 |
|          | Autumn | $T_{\text{max}}$ | 578 | 2.44 | Positive | 0.014 |
|          |        | $T_{\text{avg}}$ | 749 | 3.21 | Positive | 0.026 |
|          |        | $T_{\text{min}}$ | 884 | 3.76 | Positive | 0.037 |
|          | Winter | $T_{\text{max}}$ | 601 | 2.56 | Positive | 0.028 |
|          |        | $T_{\text{avg}}$ | 632 | 2.69 | Positive | 0.027 |
|          |        | $T_{\text{min}}$ | 580 | 2.48 | Positive | 0.028 |
| Busan    | Spring | $T_{\text{max}}$ | 1207 | 2.99 | Positive | 0.029 |
|          |        | $T_{\text{avg}}$ | 1169 | 2.9 | Positive | 0.031 |
|          |        | $T_{\text{min}}$ | 1119 | 2.78 | Positive | 0.034 |
|          | Summer | $T_{\text{max}}$ | 1058 | 2.62 | Positive | 0.014 |
|          |        | $T_{\text{avg}}$ | 1359 | 3.37 | Positive | 0.02 |
|          |        | $T_{\text{min}}$ | 1287 | 3.19 | Positive | 0.021 |
|          | Autumn | $T_{\text{max}}$ | −464 | −1.15 | No trend | −0.005 |
|          |        | $T_{\text{avg}}$ | −374 | −0.93 | No trend | 0.001 |
|          |        | $T_{\text{min}}$ | −365 | −0.9 | No trend | 0.004 |
|          | Winter | $T_{\text{max}}$ | 842 | 2.07 | Positive | 0.012 |
|          |        | $T_{\text{avg}}$ | 627 | 1.54 | No trend | 0.008 |
|          |        | $T_{\text{min}}$ | 573 | 1.42 | No trend | 0.008 |
| Mokpo    | Spring | $T_{\text{max}}$ | 828 | 2.08 | Positive | 0.025 |
|          |        | $T_{\text{avg}}$ | 883 | 2.22 | Positive | 0.025 |
|          |        | $T_{\text{min}}$ | 872 | 2.19 | Positive | 0.023 |
|          | Summer | $T_{\text{max}}$ | 655 | 1.64 | No trend | 0.01 |
|          |        | $T_{\text{avg}}$ | 1035 | 2.59 | Positive | 0.015 |
|          |        | $T_{\text{min}}$ | 946 | 2.37 | Positive | 0.016 |
|          | Autumn | $T_{\text{max}}$ | −783 | −1.97 | Negative | −0.016 |
|          |        | $T_{\text{avg}}$ | −507 | −1.27 | No trend | −0.008 |
|          |        | $T_{\text{min}}$ | −550 | −1.38 | No trend | −0.008 |
|          | Winter | $T_{\text{max}}$ | 366 | 0.91 | No trend | 0.002 |
|          |        | $T_{\text{avg}}$ | 386 | 0.95 | No trend | 0 |
|          |        | $T_{\text{min}}$ | 390 | 0.96 | No trend | 0 |
| Yeosu    | Spring | $T_{\text{max}}$ | 696 | 3.22 | Positive | 0.023 |
|          |        | $T_{\text{avg}}$ | 684 | 3.19 | Positive | 0.024 |
|          |        | $T_{\text{min}}$ | 729 | 3.37 | Positive | 0.024 |
|          | Summer | $T_{\text{max}}$ | 294 | 1.34 | No trend | 0.007 |
|          |        | $T_{\text{avg}}$ | 519 | 2.37 | Positive | 0.011 |
|          |        | $T_{\text{min}}$ | 535 | 2.47 | Positive | 0.014 |
|          | Autumn | $T_{\text{max}}$ | 437 | 1.99 | Positive | 0.01 |
|          |        | $T_{\text{avg}}$ | 498 | 2.27 | Positive | 0.012 |
|          |        | $T_{\text{min}}$ | 541 | 2.47 | Positive | 0.016 |
|          | Winter | $T_{\text{max}}$ | 620 | 2.83 | Positive | 0.024 |
|          |        | $T_{\text{avg}}$ | 551 | 2.52 | Positive | 0.023 |
|          |        | $T_{\text{min}}$ | 554 | 2.53 | Positive | 0.024 |
variations. The red lines represent the average of the most recent 30 years and the past 30 years. The average value was calculated by grouping monthly data by season. Figure 4 is representative of the changing seasonal maximum temperatures at the 12 stations. All stations show an increasing trend in the red line (a moving average of 27 months of the maximum temperature). The two stations in Seoul and Incheon show a dramatic increase in the 1950s but soon decrease. Figure 5 shows the changing seasonal average temperatures at the 12 stations. All stations show an increasing trend (red line), as shown in Figure 4. However, unlike Figure 4, the values for all stations generally increase during the entire observation period. Figure 6 shows the changing seasonal minimum temperatures at the 12 stations. All stations show an increasing trend except Chupungnyeong, although Chupungnyeong has a slight difference of 0.05 mm between the recent and past red lines. As a result, from Figures 4, 5, and 6, it can be seen that the three temperature metrics (maximum, average, and minimum) generally increase at the 12 stations by season. Yoon et al. (2018) analyzed the increases in temperature in urban areas compared with those in non-urban areas by comparing the average annual temperature (maximum and minimum) by region over a period of 60 years. The results from these two studies indicate that there is a difference in the change in the temperature rise owing to urbanization.

3.2.2 Trend analysis of $ET_0$

For the seasonal Mann–Kendall test and Sen slope analysis of the $ET_0$, the confidence interval was calculated.
as 5%. The results from the Mann–Kendall test and Sen slope of $ET_0$ are shown in Table 3. In spring, the $ET_0$ shows an increasing trend at ten stations (Gangneung, Seoul, Incheon, Pohang, Daegu, Jeonju, Ulsan, Gwangju, Busan, and Yeosu), but not Chupungnyeong and Mokpo. There is a negative trend in summer at Jeonju and Mokpo, whereas the other stations show no trend. In autumn, only Gwangju shows a positive (increasing) trend, whereas the other stations show no trend. In winter, eight stations (Seoul, Incheon, Pohang, Daegu, Jeonju, Ulsan, Gwangju, and Yeosu) exhibit an increasing trend.

A greater number of stations show an increasing trend in summer and autumn, although the values are outside the confidence interval. The analysis of the seasonal $ET_0$ trends at Jeonju in summer and Mokpo in autumn shows a negative (decreasing) trend. These two stations show the lowest increasing trend in the annual $ET_0$, as shown in Figure 2. Owing to these negative trends, the annual $ET_0$ values at Jeonju and Mokpo show the smallest increases. As shown in the trend analysis, the $ET_0$ values in the spring and winter show an increasing trend, whereas summer and autumn show no trend. As shown in Figure 2, the annual $ET_0$ values show an increasing trend. Overall, these results show an increasing trend in spring and winter and an increasing trend in the annual $ET_0$.

### 3.3 Pearson correlation coefficient

By analyzing the Pearson correlation coefficient ($r_{xy}$), we determined the strength of the relationship between
the temperature and $ET_0$. Monthly $r_{xy}$ values were calculated and combined by season to compare the seasonal relationships. In this study, we analyzed $r_{xy}$ such that $\pm 1$ to $\pm 0.8$ indicated a very strong correlation between the temperature and $ET_0$, $\pm 0.8$ to $\pm 0.5$ indicated a strong correlation, $\pm 0.5$ to $\pm 0.3$ somewhat higher, $\pm 0.3$ to $\pm 0.1$ lower, and less than 0.1 showed almost no correlation. Table 4 shows the results of the Pearson correlation coefficient for each temperature metric (maximum, average, and minimum) for the $ET_0$.

From comparing the Pearson correlation coefficients between each temperature metric and the $ET_0$, it can be seen that the maximum temperature shows a higher $r_{xy}$ than the average and minimum temperatures at all stations. In addition, the average temperature exhibits a higher $r_{xy}$ than the minimum temperature. Comparing $r_{xy}$ by season, in summer, $r_{xy}$ is greater than in the other seasons. In spring and summer, the maximum temperature shows a very strong or strong correlation with the $ET_0$. In autumn and winter, the maximum temperature exhibits a somewhat higher correlation. The average temperature exhibits a larger $r_{xy}$ than the minimum temperature at the 12 stations. In spring and summer, the average temperature shows a strong correlation, but is less than that of the maximum temperature $r_{xy}$. The average temperature exhibits a lower correlation in autumn and winter. The minimum temperature exhibits the lowest $r_{xy}$ at the 12 stations. In spring and summer, the minimum temperature shows varying results, from strong correlation to low correlation. In autumn and winter, the minimum
temperature also shows varying results, from a somewhat high correlation to almost no correlation.

### 4 Conclusions

In this study, we analyzed the variations in the $ET_0$ and temperature and evaluated the relationship between them. The $ET_0$ was calculated using a PM equation by collecting up
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and Sen slope and found that in spring, the $ET_0$ shows an increasing tendency at all 12 stations. The five stations (Incheon, Chupungnyeong, Pohang, Ulsan, and Yeosu) which started measurements after the 1940s show greater annual $ET_0$ values than the other seven stations (Gangneung, Seoul, Daegu, Jeonju, Gwangju, Busan, and Mokpo). This result represents the past $ET_0$ less than the recent $ET_0$, indicating an increasing tendency in the $ET_0$. The difference between the recent and past 10 years $ET_0$ values is shown to increase at all twelve stations, especially in Seoul, whereas at Gangneung and Chupungnyeong, it is decreasing. Therefore, it is judged that the rate of increase has changed according to urbanization. The analysis of the seasonal $ET_0$ at all stations generally shows increasing trends in spring, summer, and autumn, with generally decreasing trends in winter.

The results from the seasonal Mann–Kendall test between the temperature metrics (maximum, average, and minimum) and $ET_0$ show that the maximum temperature exhibits a distinct increase in spring and winter in certain areas. Using the Mann–Kendall test, we found that the seasonal maximum temperatures generally increase. The average temperature increases in spring, summer, and winter, and at five stations (Pohang, Jeonju, Ulsan, Gwangju, and Yeosu), it also increases in autumn. In contrast to the maximum temperature, no decreasing trend is observed. These results show that the average temperature generally increases. In the case of the minimum temperature, there is a generally increasing trend but no decreasing trend. Based on these results, an increasing trend is observed at all temperatures. For the $ET_0$, an increase in the spring and winter is observed. The times when the maximum temperature and amount of evapotranspiration increase are similar. It is interpreted that the maximum temperature significantly affects the amount of evapotranspiration.

According to the trend analysis of the seasonal temperature, all 12 stations show an increasing trend. We found that the three temperature metrics (maximum, average, and minimum) generally increase at the 12 stations by season. We analyzed the $ET_0$ using the seasonal Mann–Kendall test and Sen slope and found that in spring, the $ET_0$ shows an increasing trend at ten stations (Gangneung, Seoul, Incheon, Pohang, Daegu, Jeonju, Ulsan, Gwangju, Busan, and Yeosu). Only two stations (Jeonju and Mokpo) show a negative trend during the summer. In autumn, only Gwangju shows an increasing trend; in winter, eight stations (Seoul, Incheon, Pohang, Daegu, Jeonju, Ulsan, Gwangju, and Yeosu) show an increasing trend. This means that both the temperature and the amount of evapotranspiration have increased over time owing to global warming.

In this study, we determined the strength of the relationship between the temperature and $ET_0$ using Pearson’s correlation coefficient. The maximum temperature exhibits a greater $r_{xy}$ than the other temperature metrics at all stations. The average temperature shows greater $r_{xy}$ values than the minimum temperature at all stations. Comparing $r_{xy}$ by season, $r_{xy}$ is greater in summer than in the other seasons. Therefore, to determine a water balance policy, it is necessary to continuously monitor changes in the maximum temperature. Twelve small stations had limitations that did not allow for the analysis of trends according to regional characteristics, such as mountains or coastal regions. For example, in high-altitude regions such as Chupungnyeong, no significant change in $ET_0$ was detected. In the future, if the amount of weather observation data by region is sufficient, we expect that an analysis of regional characteristics will be possible.

Author contribution WH Nam devised the study and analysis approach. MG Jeon and YS Mun conducted the analyses, produced the figures, and wrote the first draft of the manuscript. HJ Lee, JJ Shin, and EM Hong helped with data processing. WH Nam, EM Hong, and X Zhang discussed the results and participated in writing the text. All authors contributed to the writing of the manuscript.

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Data availability Not applicable.

Declarations

Ethics approval The authors declare that they have approval.

Consent to participate The authors declare that they have approval to participate.

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