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Trend Analysis of Long-Term Reference Evapotranspiration and Its Components over the Korean Peninsula

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Abstract: In this study, the spatial and temporal trends of reference evapotranspiration (ET_o) and its components consisting of the energy term (EN_o) and the aerodynamic term (AE_o) were considered over the Korean Peninsula. The T-test and Mann–Kendall (MK) test were used to detect parameter trends after removing the effect of serial correlation from annual and seasonal time series between 1980 and 2017. Due to the lack of solar-radiation data for North Korea (NK), a regionally calibrated model based on South Korea (SK) weather data was developed to estimate daily solar radiation in NK. The results showed that spatial distribution of the ET_o increased southward in the range from 705 mm/year in the northeast to 1195 mm/year in the southeast of the Korean Peninsula. The spatial patterns of the EN_o and AE_o varied from the minimum in the north and increased southward, reaching their maximum values in the southern parts of the Korean Peninsula. The mean annual ET_o values of SK and NK were also compared. Over the 37-year period, mean annual evapotranspiration in SK was approximately 18% higher than that in NK. Moreover, mean areal EN_o and AE_o in SK were higher than in NK. The trend of the EN_o on annual and seasonal scales was also upward. In contrast, the trend of the AE_o decreased over the Korean Peninsula through all seasons and annual scales. These opposite trends in the EN_o and AE_o parameters mitigated the significant trends of the ET_o . Finally, the stronger significant upward trend of the energy term led to significant increasing trends of ET_o on the Korean Peninsula, with EN_o being the dominant component in the increase of the ET_o .

Keywords: reference evapotranspiration; energy component; aerodynamic component; trend analysis; South Korea; North Korea; Korean Peninsula

1. Introduction

Aside from precipitation, evapotranspiration (ET) is the most important component of the hydrological cycle. ET determines crop-water requirements and can play an important role in groundwater recharge, water distribution, seasonal water management, long-term estimates of water supply, and the design and management of hydraulic structures. A common procedure to estimate ET is to calculate reference evapotranspiration (ET_o) and multiply it by an appropriate crop coefficient [1]. Careful attention to ET_o is necessary for the determination of water budget, efficient irrigation scheduling, and water-resource management [2]. Since the variability of ET_o directly affects the availability of water resources, detecting the trends of ET_o is necessary [3]. Additionally, this parameter can reflect the effects of climate change [4].

Many empirical methods have been suggested and utilized by researchers to estimate ET [5]. The Food and Agriculture Organization (FAO) of the United Nations recommends the FAO Penman–Monteith (FAO PM) method as a unique standard method for estimating ET_o [6], which consists of energy and aerodynamic terms.

In recent decades, several studies have detected global or regional ET trends. On the global scale, both increasing and decreasing trends worldwide have been reported for ET [7–9]. Previous studies have demonstrated that the ET_o trend varies regionally. Some studies reported increasing trends in ET_o (e.g., Wang et al. (2014) in China [10], Tabari et al. (2012) in Iran [11], and Silva (2004) in Brazil [12]). Downward trends in ET have also been found in several countries worldwide, including China [13], Japan [14], New Zealand [15], Thailand [16], and the United States [17]. Moreover, several researchers have reported both positive and negative ET_o trends in areas with different climate types. Gao et al. [18] found a decreasing trend in most areas of east China, while there was a positive trend in the west and the northern parts of northeast China. Moreover, Li et al. [19] indicated mixed trends of significantly increasing ET_o in the lower Huai River Basin (HRB) and decreasing ET_o in the upper-middle HRB and Yi-Shu-Si River Basin of China. In another study, Mosaedi et al. [20] reported mixed trends of significantly increasing and decreasing ET_o in different parts of Iran (i.e., in mountainous, semidesert, coastal wetland, and semimountainous areas).

The above studies provide useful information on ET trends; however, these studies have obtained more or less similar results in different parts of the world. Interestingly, as of now, there is no study investigating which ET_o term (energy term or aerodynamic term) has the main impact on the change in ET_o trends and how these terms change over the seasons in an area characterized by heterogeneous weather and geographic conditions. The Korean Peninsula, which is exposed to subtropical monsoons, is covered by nearly 70% mountainous areas and, being a peninsula, is surrounded by water on three sides, resulting in complex spatial and temporal weather conditions. In this study, we focus on the analysis of ET_o trends, as well as the aerodynamic and energy terms of ET_o , to understand how it varies annually and seasonally over the Korean Peninsula. To this end, the spatial and temporal variation of ET_o and the energy and aerodynamic terms of the FAO PM method were explored using the T-test and MK test over seasonal and annual time scales.

2. Methods

2.1. Estimation of ET_o

The FAO PM method is recommended as a standard method for estimating ET_o . The reference surface is defined as a hypothetical crop that has evaporation similar to an extension surface of green grass with a height of 0.12 m, an albedo of 0.23, and a constant surface resistance of 70 s m^{-1} , and that is actively growing and well-watered. The FAO PM method can be expressed as follows [6]:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), Δ is the slope vapor pressure curve ($\text{KPa } ^\circ\text{C}^{-1}$), R_n is the net radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), G is the soil heat flux density ($\text{MJ m}^{-2} \text{ day}^{-1}$), γ is the psychrometric constant ($\text{KPa } ^\circ\text{C}^{-1}$), T is the average daily air temperature ($^\circ\text{C}$), u_2 is the wind speed at 2 m above ground level (m s^{-1}), e_s is the saturation vapor pressure (KPa), and e_a is the actual vapor pressure (KPa). Other relevant equations used in computing ET_o via the FAO PM method are explained in FAO 56 [6] and summarized in Table S1.

Because the FAO PM method is a combination of energy and aerodynamic components, it can be written as follows:

$$ET_o = \frac{0.408\Delta(R_n - G)}{\Delta + \gamma(1 + 0.34u_2)} + \frac{\gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} = EN_o + AE_o \quad (2)$$

where EN_o is the energy component (mm day^{-1}) and AE_o is the aerodynamic component (mm day^{-1}) of the FAO PM equation. The energy term represents the ET_o when the heat-exchange budget of the surface is obtained based on solar radiation and temperature under the condition in which

short and well-watered reference vegetation is exposed to bright sunshine and light wind speed. The aerodynamic term reveals the ET_o when short and well-watered reference vegetation is exposed to high wind speed and a large vapor-pressure deficit.

In this study, the daily ET_o was calculated for each station. Then, the mean seasonal and annual ET_o values for each year were derived by adding the daily values during each season and the annual ET_o was obtained by summing the seasonal values.

2.2. Estimation of Solar Radiation

Solar radiation, or total sunshine hours, is one of the inputs used in the FAO PM method to estimate ET_o . However, when solar-radiation or sunshine-duration data are unavailable, FAO 56 recommends using Hargreaves' radiation formula to estimate solar radiation. Hargreaves' radiation formula is calibrated and validated for various stations in different climate conditions. This formula, proposed by Reference [21], is expressed as follows:

$$R_s = K_{Rs} \sqrt{(TD)} R_a \quad (3)$$

where R_s is the solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$); TD is the diurnal temperature, which is the difference between the maximum temperature (T_{max}) and the minimum temperature (T_{min}) ($^{\circ}\text{C}$); K_{Rs} is the adjustment coefficient; and R_a is the extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), which varies throughout the day of the year and latitude.

Hargreaves (1994) [22] suggested values of $K_{Rs} = 0.16$ for inland areas and $K_{Rs} = 0.19$ for coastal regions. However, other studies have recommended calibrating K_{Rs} regionally to obtain an accurate estimation of solar radiation using long-term mean temperature (T_{mean}) and diurnal temperature (TD) [23–25]. In the regional calibration of K_{Rs} , K_{Rs} values are calculated using the ratio of the daily R_s to R_a and the square root of TD for each meteorological station. Then, the different relations for K_{Rs} are determined using multiple regression with the long-term mean T_{mean} and TD ($\frac{T_{mean}}{TD}$), station elevation (EL), and latitude (φ) as the independent variables. After statistical analysis, the selected relation for K_{Rs} was applied to estimate R_s using Equation (3).

2.3. Trend-Analysis Method

Parametric T-tests [26] and nonparametric Mann–Kendall trend tests [27–29] were used to determine the trends in the seasonal and annual ET_o and components of the FAO PM method (i.e., EN_o and AE_o).

2.3.1. Parametric T-Test

The T-test is a parametric test considering the assumption that data are normally distributed and uses a statistical technique for detecting trends in a time series by fitting a linear equation to observations. The estimated equation uses a linear relationship between X as an independent variable and Y as a dependent variable, and is written as follows:

$$Y = A + B \times X \quad (4)$$

where A and B denote the intercept and the slope of the regression line, respectively. Positive slope A represents an upward trend and a negative slope indicates a downward trend in a time series. The T-tests apply the hypothesis test on the standard slope coefficient, and the result defines as T_o and is calculated with the following equation:

$$T_o = \frac{B_1}{SE} \quad (5)$$

where B_1 is the standard slope of the regression line and SE is the standard error of the slope. SE is calculated as follows:

$$SE = \frac{\sqrt{\sum_{i=1}^n (y_i - \bar{y})^2 / n - 2}}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2}} \quad (6)$$

where, x_i is an independent variable and y_i is an independent variable in the time series. $\bar{x}$ is the average of x_i and $\bar{y}$ is the average of y_i in the time series, and n is the number of observed data. T_0 has a t distribution with $n-2$ degrees of freedom, where n is the total number of observations. Null hypothesis has no significant trend for T_0 if

$$-t_{\frac{\alpha}{2}, n-2} < T_0 < t_{\frac{\alpha}{2}, n-2} \quad (7)$$

where $t_{\frac{\alpha}{2}, n-2}$ and $-t_{\frac{\alpha}{2}, n-2}$ represent the standard normal deviates and α determines the level of significance. In this test, 5% and 10% significance levels are considered.

2.3.2. Nonparametric Mann–Kendall test

The Mann–Kendall (MK) test is a nonparametric test used to analyze the null hypothesis of no change in the mean of a series (no trend) against the alternative hypothesis of an increase or decrease over time (existence of a trend) [30]. This method is frequently used to determine trends in hydrological variables. Kendall's statistic S is obtained using the following equations:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{Sgn}(X_j - X_i) \quad (8)$$

$$\text{Sgn}(X_j - X_i) = \begin{cases} +1 & \text{if } (X_j - X_i) > 0 \\ 0 & \text{if } (X_j - X_i) = 0 \\ -1 & \text{if } (X_j - X_i) < 0 \end{cases} \quad (9)$$

where n is the number of observations, X_j and X_i are sequential data ($j > i$), and $\text{Sgn}(X_j - X_i)$ is a sign function that extracts the sign of $X_j - X_i$. Statistic S has normal distribution with zero mean and variance and is computed as

$$\text{Var}(S) = \frac{[n(n-1)(2n+5) - \sum_{i=1}^m t(t-1)(2t+5)]}{18} \quad (10)$$

where m is the number of ties, t is the size of the i th tie, and Σ is the summation of all ties. MK statistic Z is estimated as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (11)$$

where Z is the standard normal variable, with positive values of Z indicating increasing trends, whereas negative values indicate decreasing trends. The null hypothesis H_0 that Z has no significant trend is accepted if $-Z_{1-\frac{\alpha}{2}} \leq Z \leq Z_{1-\frac{\alpha}{2}}$, where α is the significance level for the test (5% and 10% significance levels) and $+Z_{1-\frac{\alpha}{2}}$ and $-Z_{1-\frac{\alpha}{2}}$ are the critical values for the two-sided hypothesis. The slope of the trends in the nonparametric MK test can be calculated as follows:

$$\beta = \text{Median} \left[\frac{X_j - X_i}{j - i} \right] \text{ for all } i < j \quad (12)$$

where X_j and X_i are sequential data ($j > i$) and β is Theil–Sen’s estimator, which is a robust estimate of the trend magnitude in the MK test. A positive Theil–Sen slope indicates an increasing trend and a negative slope represents a decreasing trend in a time series.

2.4. Impact of Serial Correlation in a Time Series

The parametric T-test and MK test are designed for serially independent series. Therefore, the presence of incorrect rejection of the null hypothesis when there is no trend (Type I error) is correct only when the data are independent. As serial correlation increases, the variance of the test statistic and the rejection rate of the null hypothesis increase, specifically when there is a positive serial correlation [30,31]. In this study, the prewhitening approaches proposed by von Storch and Navarra [32] were used to eliminate the effect of serial correlation by removing the lag-one autoregressive component (r_1) of the series with serial correlation before applying trend tests. To this end, r_1 was computed and compared to the 95% confidence limits. If r_1 ranged between $\frac{-1-1.96\sqrt{n-2}}{n-1} \leq r_1 \leq \frac{-1+1.96\sqrt{n-2}}{n-1}$, r_1 was not significant; otherwise, r_1 is significant (n is the number of data). The trend tests are applied to the original time series ($x_1, x_2, \dots, x_n$) if r_1 is not significant. However, if r_1 is significant, then the time series should be prewhitened as $(x_2 - r_1x_1, x_3 - r_1x_2, \dots, x_n - r_1x_{n-1})$ to remove the effect of serial correlation prior to application of the trend tests [31,33].

3. Study Area and Data

The Korean Peninsula is in northeastern Asia and is divided into two parts: South Korea (SK) and North Korea (NK). Figure 1 shows the spatial distribution of stations (name and code) of topographic and land-cover characteristics of the study area. The Korean Peninsula is connected to the northeastern part of mainland China and is surrounded by oceans along the eastern, western, and southern coasts. The peninsula is mountainous in the northern and eastern parts and has well-developed plains in the western and southern parts. The climate of the peninsula is affected by the East Asian monsoon in summer and typhoons in autumn. Nearly two-thirds of the annual rainfall occurs during the flooding season in the summer months [34]. Winters are cold, with typical January temperatures below freezing and minimal precipitation and little snow accumulation outside of the mountainous areas. However, climate differs dramatically from North to South Korea. The northern regions have a colder climate in the more mountainous area (in the north and east), while the southern regions have a warm and wet climate in the flat plains of the southern and western peninsula. Monthly average rainfall is approximately 112.5 mm in SK and 74.5 mm in NK. Mean annual temperature is 13.1 °C in SK, from 1.2 °C in winter to 24.1 °C in summer, and 9.0 °C in NK, from −4.7 °C in winter to 21.5 °C in summer.

The detection of ET_0 trends requires the use of long-term meteorological data, including the daily observed R_s , T_{max} , T_{min} , dew-point temperature (T_{dew}), and wind speed (W_s). Daily meteorological data from 21 meteorological stations in SK and 27 stations in NK were collected from the Korea Meteorological Administration (<https://data.kma.go.kr>) within a sufficient meteorological time period (1980–2017). Statistics for the observed daily R_s are available for the 21 weather stations in SK but not for those in NK. The spatial distribution of the stations in SK and NK is shown in Figure 1.

The data quality and integrity assessments were performed using the procedures explained by Reference [6] prior to the analysis. The missing data were filled with averaged values from the neighboring sites using an inverse-distance weighting method [35]. The numbers of missing data for each parameter of stations in SK and NK are provided in Table S2. For the quality check for temperature, the observed T_{max} and T_{min} data were compared against the long-term temperature extremes for each year [24]. To evaluate the integrity of solar-radiation data, the observed solar-radiation data of each station were compared with the clear-sky solar-radiation envelope (R_{s0}) for each year. R_{s0} is a function of a day of the year, latitude, and elevation. The calculated R_{s0} can be plotted as an upper envelope of observed R_s . This method is especially useful for areas with high air pollution or airborne dust without clear skies. In these regions, there were differences between the measured R_s and calculated R_{s0} , and R_s was significantly below or above the computed R_{s0} . This issue was further investigated by using multiplicative

factor $((R_s)_{cor} = a \cdot R_s)$, additive factor $((R_s)_{cor} = a + R_s)$, or a combination of these variables to force the measured R_s to reach the computed R_{so} (where a is the corrective factor). Additional explanation about the integrity of solar-radiation data using clear-sky comparisons can be found in FAO 56 [6,24,36]. There were differences between R_s and R_{so} for some years at stations in SK. These mismatches were found and modified for all stations in SK. Figure 2 shows the time series of solar radiation before and after this prescreening for the Incheon station in 1980 and Seosan station in 1982.

Figure 1. Spatial distribution of (a) topographic characteristics and name of weather stations, and (b) land cover and code of stations on the Korean Peninsula.

Figure 2. Adjustment of daily solar radiation using the clear-sky envelope for the Incheon station in 1980 ((a) and (b)), and the Seosan station in 1982 ((c) and (d)); results for before and after adjustment are shown.

4. Results and Discussion.

4.1. Regional Calibration of K_{Rs} and Estimation of Solar Radiation

Due to the lack of solar-radiation data in NK, R_s was estimated based on Hargreaves' formula and the regionally calibrated formula for K_{Rs} . The different relationships were determined by multiregression of long-term mean values of $\frac{T_{mean}}{TD}$, EL, and φ as the independent variables and station values of K_{Rs} as the dependent variable. The following equation was selected as the best model after statistical analysis:

$$K_{Rs} = 0.032 \frac{T_{mean}}{TD} + (2.29 \times 10^{-5} EL) + 0.105 \quad (13)$$

Figure 3 depicts the actual K_{Rs} against the computed K_{Rs} using Equation (13) in SK. The estimated K_{Rs} values are well-correlated with the calculated values, with a high correlation coefficient ($R^2 = 0.89$) and small root-mean-square error (RMSE = 0.007). Using the K_{Rs} values for all stations in SK and NK, R_s was estimated using Hargreaves' formula (Equation (3)) for all stations in SK and NK.

Table 1 shows the statistical analysis for the comparison of observed and calculated daily solar-radiation data for 21 stations in SK. The results show good agreement between observed and estimated solar-radiation data in SK. However, because K_{Rs} was determined using regional calibration data in SK, there is uncertainty in the estimated R_s in NK.

Table 1. Statistical analysis for comparison of daily observed and calculated solar-radiation data for 21 stations of South Korea (SK).

Station Code	Station Name	R^2	Root-Mean-Square Error (RMSE)
100	Daegwalryeong	0.87	3.00
101	Chuncheon	0.85	3.07
105	Gangnung	0.86	3.10
108	Seoul	0.84	3.57
112	Incheon	0.82	3.73
114	Wonju	0.66	4.96
129	Seosan	0.85	4.11
131	Cheongju	0.83	3.49
133	Daejeon	0.86	2.68
135	Chupungyong	0.81	3.53
136	Andong	0.84	2.98
138	Pohang	0.85	3.18
143	Daegu	0.89	2.71
146	Jeonju	0.88	2.81
156	Gwangju	0.88	2.70
159	Busan	0.86	3.17
165	Mokpo	0.89	2.59
184	Jeju	0.92	2.67
185	Gosan	0.87	2.84
169	Heuksando	0.90	1.78
192	Jinju	0.88	2.56

Figure 3. Actual value of KR_s for each station compared with the results of Equation (13).

4.2. Estimation of ET_o Using the Penman–Monteith Method

The time series of the annual ET_o for 27 stations in NK and 21 stations in SK are illustrated as a box-and-whisker plot in Figure 4a and b, respectively. In NK, the maximum and minimum estimated ET_o values were at Huicheon station (1005.5 mm) and Seonbong station (660.3 mm), respectively. In SK, the maximum estimated ET_o was 1192.8 mm for Daegu station, whereas the minimum was 826 mm for Daegwalryeong station, indicating that the mean annual ET_o in SK is higher than that in NK.

Figure 4. Box-and-whisker plots of the variability of annual ET_o for stations in (a) North Korea and (b) South Korea from 1980 to 2017. (Note: The line inside the boxes represents the median, and the upper and lower lines indicate 75% and 25%, respectively. The upper and lower portions of the whiskers represent the maximum and minimum annual ET_o , respectively).

4.3. Spatial Distribution of Mean Annual and Seasonal ET_o , EN_o , and AE_o

The Kriging method was used to interpolate the mean annual and seasonal ET_o , EN_o , and AE_o over the Korean Peninsula by including the data of all stations in SK and NK. The Kriging method is widely used for spatial analysis by using geographic information systems (GIS). This method applies the distance-weighting approach to interpolating the data by including information from specific locations [37]. The spatial distribution pattern of the mean annual ET_o averaged from 1980 to 2017 is shown in Figure 5, which reflects the combined effect of meteorological variables and topographic characteristics across the Korean Peninsula. The annual ET_o variation exhibits a clear spatial pattern (southward increase), ranging from 705 mm/year to 1195 mm/year over the entire basin. A lower ET_o is present in the northeast, while higher values are found in the southeast of the Korean Peninsula.

Figure 5. Cont.

Figure 5. Spatial distribution of mean annual ET_0 , EN_0 , and AE_0 on annual and seasonal scales.

The spatial distribution of mean annual EN_0 and AE_0 show that there is a distinct pattern of minimum values in the northern area and maximum values in the southern area of the Korean Peninsula with different directions of variation. The spatial distribution of EN_0 decreases from the southwest to the northeast direction of the Korean Peninsula, while regarding the AE_0 , the maximum was established in the southeastward direction and the minimum in the northward. This pattern occurs because the energy term mainly affects the R_s and T . R_s is different based on the latitude due to the differences in the position of the sun [6], and it is higher near the equatorial region than the polar region. Thus, higher R_s were observed in the southern part (higher latitude) of the Korean Peninsula than the northern part (lower latitude). Additionally, T in North Korea mainly affects the propagation of Siberian cold weather, and the movement of this cold stream from Siberia to North Korea produces temperature drops in the region. However, T in South Korea is higher, which is mostly affected by the subtropical warm current. Therefore, the higher magnitude of R_s and T in South Korea causes a higher value of EN_0 in SK than NK. AE_0 primarily affects the relative humidity and wind speed. The intense value of relative humidity and wind speed in the southern part causes higher AE_0 in SK relative to NK. In general, the higher value of EN_0 and AE_0 in SK than NK results in higher ET_0 in SK.

Moreover, the seasonal spatial distribution of ET_0 shows that the highest amount of ET_0 occurs in the summer and then in spring, while winter has the lowest value of ET_0 . This pattern exists due to the high amount of EN_0 in the summer and the seasonal spatial distribution of EN_0 . Furthermore, the comparison of the spatial distribution of ET_0 with EN_0 and AE_0 in different seasons shows that ET_0 in spring and summer is mostly affected by EN_0 , whereas in autumn and winter it is mostly caused by AE_0 . This finding indicates that ET_0 in spring and summer has a stronger effect resulting from the superimposed effect of R_s and T in autumn and winter by the combined influence of RH and WS.

4.4. Differences in the Mean Annual and Seasonal ET_0 , EN_0 , and AE_0 between SK and NK

The time series of seasonal and annual ET_0 , EN_0 , and AE_0 from 1980 to 2017 averaged over the entire catchment in SK and NK are graphically presented in Figure 6, and the comparison of the results is reported in Table 2. The mean annual ET_0 in SK is 971.2 mm/year, whereas that for NK is 823.5 mm/year, which indicates that the mean annual ET_0 in SK is 18% higher than that in NK over the 37-year period. In addition, the annual EN_0 and AE_0 terms are 708.4 and 262.7 mm/year in SK

and 648.0 and 175.5 mm/year in NK, respectively. It follows that mean areal EN_o and AE_o are higher, at 9.3% and 49.7%, respectively, in SK than in NK.

Figure 6. Difference between the amount of mean annual and seasonal ET_o , EN_o , and AE_o in SK and North Korea (NK).

Table 2. Mean seasonal and annual ET_o , EN_o , and AE_o from 1980 to 2017 and ratios with ET_o .

Period	ET_o (mm/year)	Annual ET_o (%)	EN_o (mm/year)	AE_o (mm/year)	EN_o/ET_o (%)	AE_o/ET_o (%)
South Korea						
Spring	267.6	27.6	180.5	87.1	67.4	32.6
Summer	426.9	44.0	358.0	68.9	83.9	16.1
Autumn	196.0	20.2	133.3	62.8	68.0	32.0
Winter	80.6	8.3	36.6	43.9	45.5	54.5
Annual	971.2	100.0	708.4	262.7	72.9	27.1
North Korea						
Spring	224.9	27.3	164.4	60.5	73.1	26.9
Summer	391.1	47.5	346.3	44.8	88.6	11.4
Autumn	155.9	18.9	111.4	44.4	71.5	28.5
Winter	51.7	6.3	25.9	25.8	50.1	49.9
Annual	823.5	100.0	648.0	175.5	78.7	21.3

The most seasonal ET_o occurs in summer, which constitutes 44% and 47.5% of the total ET_o in SK and NK, respectively (Table 2). The lowest ET_o occurs in winter in both SK and NK (8.3% in SK and 6.3% in NK). However, the annual ET_o exhibits similar ratios in spring and autumn.

To understand which of the components of ET_o (i.e., EN_o and AE_o) result in higher ET_o in SK than NK, the percentages of mean EN_o and AE_o were compared to the mean ET_o for each season (see

Table 2). The results reveal that spring and autumn have similar percentages of EN_o and AE_o in SK and NK, while the energy term (EN_o) constitutes almost 70% and the aerodynamic term covers (AE_o) 30% of the total ET_o on the Korean Peninsula. The EN_o in summer has the greatest impact on the ET_o when compared to the other seasons and contains approximately 85% of the total ET_o in SK and NK. Furthermore, in winter, EN_o and AE_o have almost the same portion of ET_o (approximately 50%). These results indicate that the EN_o term plays an important role in ET_o during the spring, summer, and autumn, while in the winter, both terms contribute equally to the amount of ET_o .

4.5. Spatial Variation of Annual and Seasonal ET_o , EN_o , and AE_o Trends

The results of prewhitening for ET_o , EN_o , and AE_o on an annual scale are reported in Tables S3–S5 as supplementary documents. The spatial distributions of stations in SK and NK from 1980 to 2017 with significant increasing or decreasing trends according to the MK test are presented in Figure 7. As shown, 43% of stations in SK reveal significant increasing trends, and 14% show significant decreasing trends in annual ET_o . The significant decreasing trend in SK is located in the southeastern area of the Korean Peninsula. However, 22% of stations in NK detected significant increasing trends, mainly located in the coastal areas, while 4% of the stations revealed significant decreasing trends. The annual spatial distribution of EN_o showed that 66% of stations in SK, as well as NK, detected significant increasing trends, while no station showed significant decreasing trends for annual energy trends. In contrast, for AE_o , significant decreasing trends were detected at 19% of stations in SK and 33% stations in NK; however, there were no significant increasing trends for this variable. These results indicated that significant increasing trends on the Korean Peninsula are caused by the significant increasing trends in the energy term. As described above, the EN_o is primarily related to solar radiation and temperature. It follows that the trends of R_s and T were increased on the Korean Peninsula. Similar results were also found using the T-test, and the results are shown in Figure 8.

The results showed that ET_o increased more significantly on the plains than in the mountainous areas. EN_o increased in both areas, while AE_o decreased more significantly in the plains than in the mountainous areas.

In addition, the spatial distributions of the seasonal trends in ET_o and its components were investigated. The spatial trends of ET_o in spring revealed significant increasing trends for 29% and 44% of stations in SK and NK, respectively. Additionally, in summer, 33% of stations in SK and 59% of stations in NK detected significant increasing trends. This finding indicates that there is a more intense significant trend during spring and summer in NK. Moreover, the spatial distribution of ET_o during autumn and winter revealed both significant upward and downward trends on the Korean Peninsula. Regarding the EN_o , only significant increasing trends were detected for stations, and no station detected a significant downward trend. In contrast, almost all significant detected trends for AE_o are decreasing for all seasons over the Korean Peninsula. These opposite trends in EN_o and AE_o caused the mitigation of the significant trends of ET_o . Furthermore, the stronger significant upward trends of energy terms led to significant increasing trends of ET_o on the Korean Peninsula.

Figure 7. Spatial distribution of stations with increasing and decreasing trends according to the Mann-Kendall (MK) test on annual and seasonal ET_0 , EN_0 , and AE_0 during the period 1980 to 2017. Upward- and downward-pointing triangles indicate increasing and decreasing trends, respectively. Blue and red colors show the 90% and 95% confidence levels, respectively. The white color shows no significant trends.

Figure 8. Spatial distribution of stations with increasing and decreasing trends according to the T-test on annual and seasonal ET_0 , EN_0 , and AE_0 during the period 1980 to 2017. Upward- and downward-pointing triangles indicate increasing and decreasing trends, respectively. Blue and red colors show the 90% and 95% confidence levels, respectively. The white color shows no significant trends.

4.6. Difference in Trends of Mean Annual and Seasonal ET_0 , EN_0 , and AE_0 in SK and NK

The time series of ET_0 , EN_0 , and AE_0 from 1980 to 2017 were averaged over the entire SK and NK using the kriging method. Then, the parametric T-test and nonparametric MK test were performed to detect the trends of ET_0 and its components in the seasonal and annual scales, and the results are reported in Table 3. The positive values of T and Z indicate increasing trends, whereas negative values indicate decreasing trends. B and β show the standard slope of the linear regression and Theil–Sen slope of the MK test, respectively, which reflect the rate of increase or decrease on seasonal and annual timescales. The results of the trends test for ET_0 showed that spring and summer trends in SK and NK exhibited significant increasing patterns, with stronger trends in summer. Furthermore, NK had more significant increasing trends for both seasons than those in SK. However, autumn showed increasing trends and winter decreasing trends, which were not significant on the Korean Peninsula. In addition, the annual trends of ET_0 indicated that although there are increasing trends in both SK and NK, significant trends were detected only in SK. A study conducted by Kim et al. [38] focused on the precipitation trends over the Korean Peninsula, and their results indicated that there was an increasing trend in precipitation in SK and a decreasing trend in NK during the summer months. The results of the present study showed that a significant increasing trend for ET_0 was observed in summers in NK. Lower precipitation and higher ET_0 in the summer months in NK could cause a reduction in soil moisture and vegetation cover and induce severe drought in NK.

Table 3. Statistical trends in the seasonal and annual ET_0 , EN_0 , and AE_0 from 1980 to 2017.

Period	South Korea				North Korea			
	Parametric T-Test		Nonparametric MK Test		Parametric T-Test		Nonparametric MK Test	
	T	B	Z	β	T	B	Z	β
ET_0								
Spring	<u>1.67</u>	0.26	<u>2.03</u>	0.28	<u>1.94</u>	0.31	<u>2.09</u>	0.35
Summer	<u>2.18</u>	0.34	<u>2.26</u>	0.45	<u>2.51</u>	0.39	<u>2.63</u>	0.40
Autumn	0.59	0.09	0.04	−0.03	0.66	0.10	<u>0.16</u>	−0.03
Winter	−0.53	−0.08	−0.46	−0.06	−0.32	−0.05	−0.21	−0.07
Annual	<u>2.42</u>	0.38	<u>2.69</u>	0.60	1.30	0.21	0.98	0.08
EN_0								
Spring	<u>2.23</u>	0.35	<u>2.33</u>	0.23	<u>2.42</u>	0.38	<u>2.77</u>	0.33
Summer	<u>3.47</u>	0.55	<u>3.39</u>	0.65	<u>2.90</u>	0.46	<u>2.64</u>	0.54
Autumn	<u>2.44</u>	0.38	<u>2.03</u>	0.15	<u>2.54</u>	0.40	<u>2.08</u>	0.16
Winter	<u>1.97</u>	0.31	<u>2.15</u>	0.07	<u>1.66</u>	0.26	<u>1.96</u>	0.05
Annual	<u>2.63</u>	0.42	<u>2.86</u>	0.64	<u>2.15</u>	0.34	<u>2.15</u>	0.43
AE_0								
Spring	−2.73	−0.43	−2.34	−0.18	−0.82	−0.14	−0.64	−0.17
Summer	−2.61	−0.41	−2.54	−0.22	−1.60	−0.27	−1.62	−0.18
Autumn	−2.19	−0.35	−2.07	−0.21	−1.26	−0.21	−1.31	−0.16
Winter	−1.56	−0.25	−1.54	−0.10	−0.70	−0.12	−0.90	−0.09
Annual	−2.55	−0.40	−2.46	−0.52	−1.01	−0.17	−1.30	−0.49

– Underline indicates that the trend is statistically significant at the 95% confidence level. = Double underline indicates that the trend is statistically significant at the 90% confidence level.

The results of the trend tests in EN_0 SK indicate that all trends are significantly positive in SK and NK on the seasonal and annual scales, and the trends are stronger in SK except for autumn. In contrast, AE_0 exhibited decreasing trends during all seasons and the annual time series in SK and NK. However, significant decreasing trends were shown in spring, summer, autumn, and the annual time scale in SK, while the other trends were not significant. The results of the trends test of EN_0 and AE_0 indicate that there are opposite trends for the energy term and aerodynamic term on the Korean Peninsula. Although the energy term exhibited significant increasing trends, the aerodynamic terms showed decreasing trends on seasonal and annual time scales. These trends are primarily affected by meteorological effects on the energy and aerodynamic terms.

Additionally, the comparison between the results of the two tests indicates that similar results were obtained by the parametric T-test and nonparametric MK test on the Korean Peninsula on both seasonal and annual scales, which is related to the degree of normality of the distribution [39,40].

5. Conclusions

This study investigated ET_o , EN_o , and AE_o trends in seasonal and annual time series for the Korean Peninsula from 1980 to 2017 by considering the lack of solar-radiation data in NK. First, a regionally calibrated model was constructed based on SK weather data to estimate the daily solar radiation in NK. Meteorological data were collected from 21 stations in SK and 27 stations in NK. Then, ET_o was estimated using the FAO PM method. Next, the effects of serial correlation in the time series with significant r_1 were removed using prewhitening, and trend analysis was performed to understand the temporal variations in ET_o over the 37-year period in SK and NK using parametric linear regression and nonparametric MK tests on both seasonal and annual time series. The following results may be drawn from the present study:

- The spatial distribution of the mean annual ET_o exhibited increasing spatial variation in annual ET_o from NK to SK. A lower ET_o was evident for the northeastern Korean Peninsula, and higher values were found over the southeastern Korean Peninsula.
- The spatial distribution of the EN_o and AE_o revealed a clear distribution from the minimum in NK and reached the peak in SK for both energy and aerodynamic terms. The energy term is influenced by R_s and T , and the aerodynamic term is affected by RH and WS . The lower latitude in NK causes a lower amount of R_s than that in SK, and mean annual T in NK is lower than in SK because T in the northern area of the Korean Peninsula is mostly affected by the influx of cold air from the Siberian high. These superimposed effects cause the higher energy term in SK.
- A comparison of the mean annual ET_o showed that the average annual ET_o in SK was 18% higher than that in NK from 1980 to 2017. Additionally, the mean areal EN_o and AE_o is higher, at 9.3% and 49.7%, respectively, in SK than in NK.
- The results of the trends test indicate that the significant increasing trend of ET_o is mainly caused by significant increasing trends in the EN_o term in SK and NK. This finding indicates that EN_o is the dominant component affecting the ET_o over the Korean Peninsula. In addition, opposite trends exist for EN_o and AE_o on the Korean Peninsula (significant increasing trends for EN_o and significant decreasing trends for AE_o on seasonal and annual time scales). The different trends in the mentioned parameter mainly arise from the effect of meteorological variables on the energy and aerodynamic terms (R_s and T for EN_o and WS and RH for AE_o).

In general, the findings of the present study showed an increasing trend in ET_o over the Korean Peninsula. However, this increasing trend is an undesirable outcome from water-resource perspective because it represents the increasing demand for water in the Korean Peninsula. Therefore, the results obtained from this research, which is the first study to determine ET_o trends for the Korean Peninsula, could be helpful for the future planning of agriculture and water demands. Moreover, understanding how the trends of these terms change during seasons could provide insight into the possible impact of climate change on future water resources of the Korean Peninsula. Although this study is limited to the Korean Peninsula, these results might be applicable to East Asia as well. Moreover, further research on the impacts of meteorological parameters on ET_o over the Korean Peninsula could be of interest.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4441/10/10/1373/s1>: Table S1: required equations for computing ET_o using the FAO PM method; Table S2: numbers of missing data for each parameter for each station; Table S3: MK test results before and after the prewhitening test for ET_o on an annual scale; Table S4: MK test results before and after the prewhitening test for EN_o on an annual scale; Table S5: MK test results before and after the prewhitening test for AE_o on an annual scale.

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