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Estimation of the Reference Evapotranspiration using Daily Sunshine Hour

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일조시간을 이용한 기준 증발산량 추정

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Abstract

이 논문에서는 일사량과 일조시간에 관한 통상적인 선형관계식보다 정확한 비선형 관계식에 대한 적용검토를 수행한다. 일조시간을 이용한 일사량 추정에 이어서 Penman-Monteith 방정식을 이용하여 기준 증발산량을 추정하였다. 우리나라 20개 지점의 1997년부터 2006년까지의 일사량 및 일조시간 자료를 포함한 기상자료를 이용하여 선형 그리고 수정 비선형 Angstrom 방정식을 보정하고 기준 증발산량을 추정하였다. 일조시간과 일사량 사이의 선형과 비선형 관계식을 이용한 기준 증발산량의 상대비교를 수행하였다. 선형 및 비선형 관계식을 이용한 방법 모두 RMS 오차는 5.96, NSC(Nash-Sutcliffe Coefficient)는 0.95로 추정되었고, 그 차이는 매우 미미하였다. 그러나 상대적으로 일사량이 기준 증발산량에 크게 기여하는 하계에는 그 차이가 증가하기 때문에 보다 개선된 비선형 관계식을 이용하는 방법에 대한 엄밀한 검토가 필요하다.

주요어 : Modified Angstrom equation, Reference evapotranspiration, Solar radiation, Bright sunshine duration, Penman-Monteith equation

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I. INTRODUCTION

In places where solar radiation (R_S) is not measured directly, it can be estimated by interpolation from nearby localities where radiation data are available, by using models and empirical correlations, starting with the more diffusely known meteorological data or by using a combination of methods (Allen,1995; Allen, 1997; Lee, 2009a). A typical example of the second method is the correlation found by Angstrom (1924) and others between global solar radiation (R_S) and bright sunshine duration (hours, n) and measured at many meteorological stations. This relationship to draw solar radiation estimates is used more often than those estimates determined by using only direct measured radiation data.

The Angstrom equation (Angstrom, 1924; Prescott, 1940) has long been a dominant tool to use as a basis approach to estimate the R_S. The Angstrom equation is a very convenient tool for a large number of locations (Annear and Wells, 2007; Gopinathan, 1988); however, many scientists have presented slightly different model parameters for different locations (Doorenbos and Pruitt, 1977). Atmospheric constituents, such as molecules, aerosols, and clouds, can affect solar radiation, and these atmospheric constituents should be included in building the relationship between R_S and bright sunshine hours (n). Consequently other attempts have been made to modify the Angstrom equation, including the use of more meteorological parameters, such as surface albedo, latitude, ambient temperature, total precipitation, humidity, elevation, amount of cloud cover, etc. (Dorvlo and Ampratwum, 2000; Hargreaves *et al*., 1985; Hay, 1979; Supit and van Kappel, 1988). However, the additional meteorological parameters needed to improve the original Angstrom equation could present a bottleneck for these previous approaches. Hence, Lee (2009b) recently suggested a simple nonlinear form of the modified Angstrom equation to improve both its accuracy and fitness. It showed successful performance. This study focused on the simple modified Angstrom equation.

Evapotranspiration (ET) as a major component of the hydrologic cycle will affect crop water requirement and future planning and management of water resources. Estimates of reference evapotranspiration (hereafter ET_0) are an important input to hydrologic models and the present models generally do not provide direct estimates of ET_0 from the land surface. Management of regional and local water resources and irrigation has required the use of an empirical equation to estimate ET_0. Either a relatively accurate equation or a simple equation usually requires solar radiation data as an essential input variable; yet in most cases the available network of meteorological stations does not allow direct measurement or even an estimation of incoming solar radiation.

In this study, the modified Angstrom equation was facilitated at 20 meteorological stations on the Korean Peninsula. Then ET_0 was calculated and tested against reference values to see how the modified Angstrom equation affects ET_0. This study is meaningful in the sense that temperature and solar radiation can explain at least 80% of ET_0 (Vanderlinden *et al*., 2004; Samani, 2000; Priestly and Taylor, 1972). The results show that both the original and the modified equation present a similar level of performance once they are locally calibrated, and the modified Angstrom equation is not able to provide superiority in terms of accuracy.

II. METEOROLOGICAL DATA

The meteorological data used for the study were provided by the Korea Meteorological Administration (KMA), corresponding to the period of 1997-2006 (total 120 months) and consisting of 3,652 carefully screened daily values. All the stations were close to the reference condition (Allen, 1996). A summary of site information, including daily manual observations, such as mean temperature, relative humidity, wind speed, and solar radiation (R_S) at the 20 stations (12 inland and 8 coastal, including island: Stations 16 and 17) appear in Table 1 (see Fig. 1).

Study sites were selected on the basis of data completeness and reliability. Those days when observations were not available were averaged and filled with neighboring values. The measured weather data was checked for integrity, quality, and reasonableness. Data quality and integrity checks were made and followed up on, using precedent-setting studies (Irmak *et al*., 2003a; Temegsen *et al*., 1999; Allen, 1996) for all locations. In the temperature data quality check, the measured maximum and minimum air temperature (T_{max} and T_{min}, respectively) data for each individual year were compared against the long- term temperature extremes. The deviation of dew point temperature (T_{dew}) from T_{min} was within 3-4 ˚C for the substantial portion of the records for all locations. To check the integrity of Rs, clear sky envelopes (Allen, 1995; Allen, 1997)

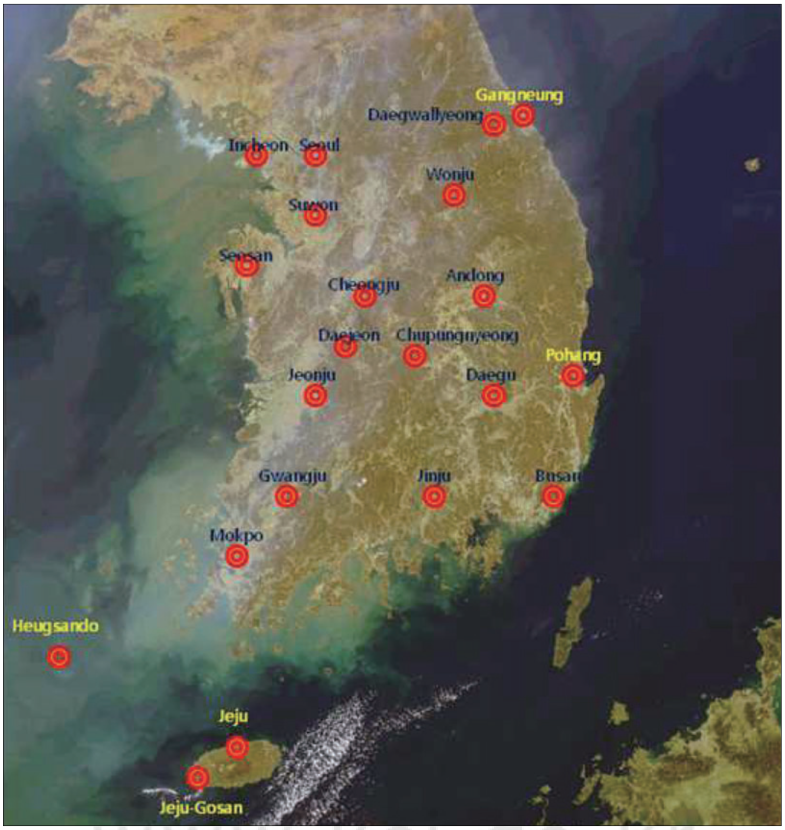

Figure 1. Study region and meteorological stations(The base map is the GOCI image provided by the Korea Ocean Satellite Center, KORDI)

Table 1. Summary of weather stations used for the study. Ele. = elevation (m), Lat. = latitude (degree), Lon. = longitude(degree), H_t = height of thermometer above the ground(m), H_w = height of anemometer above the ground(m), R_s = Incoming Solar Radiation ($MJm^{-2}d^{-1}$), Sunhr=bright sunshine duration(hours), WS = wind speed(m/sec), RH = relative humidity(%), Tmean = daily mean temperature(˚C). The mean and standard deviation values for all variables are for the period of the study (1997-2006).

	Station index.	Station name	Ele.	Lat.	Lon.	H_t	H_w	Mean					Std				
								Rs	Sunhr	WS	RH	T	Rs	Sunhr	WS	RH	T
Inland	1	Andong	140.7	36.57	128.70	1.5	15.5	13.65	5.90	1.57	65.44	12.42	6.12	3.69	0.82	15.48	9.74
	2	Cheongju	56.4	36.63	127.43	1.5	10.0	13.10	5.86	1.81	64.71	13.25	8.53	3.78	0.90	13.26	10.02
	3	Chupungnyeong	242.2	36.22	127.98	1.5	20.7	12.67	5.85	2.53	66.06	12.27	6.58	3.89	1.60	15.06	9.56
	4	Deagu	57.4	35.88	128.62	1.5	18.2	13.08	6.10	2.37	59.14	14.83	6.31	3.82	1.00	16.04	9.26
	5	Daejeon	62.6	36.37	127.37	1.6	22.8	13.48	5.86	1.92	67.22	13.47	6.71	3.73	1.03	14.02	9.78
	6	Daegwallyeong	790.0	37.67	128.72	1.8	10.0	12.73	5.79	4.29	74.22	7.39	7.10	4.05	2.53	17.33	9.84
	7	Gwangju	74.5	35.17	126.88	1.5	17.5	13.65	5.56	2.09	67.15	14.53	6.69	3.65	0.95	13.00	9.23
	8	Jeonju	61.1	35.82	127.15	1.5	18.4	12.82	5.50	1.79	68.04	14.24	6.34	3.71	0.76	12.55	9.67
	9	Jinju	27.1	35.15	128.03	1.5	10.0	13.65	6.09	1.61	67.67	13.99	6.52	3.76	0.88	14.59	9.34
	10	Seoul	85.5	37.57	126.95	1.5	10.0	11.68	5.10	2.17	62.64	13.27	6.37	3.59	0.88	14.24	10.18
	11	Suwon	34.5	37.27	126.98	1.5	20.0	13.31	5.80	1.89	65.33	12.83	6.55	3.79	0.86	13.81	10.23
	12	Wonju	150.7	37.33	127.93	1.6	10.0	12.88	5.32	1.08	67.94	12.26	6.57	3.59	0.64	13.28	10.48
Coast	13	Busan	69.2	35.10	129.02	1.7	17.8	13.27	6.08	3.47	63.73	15.41	6.70	3.84	1.36	18.84	7.97
	14	Gangneung	26.1	37.75	128.88	1.7	13.8	12.81	5.82	2.81	59.11	13.71	6.61	3.94	1.26	20.51	8.98
	15	Incheon	54.6	37.47	126.62	1.4	11.0	13.30	6.15	2.47	67.65	13.24	7.36	3.83	1.26	14.11	9.75
	16	Jeju	19.9	33.50	126.52	1.8	12.3	12.81	5.06	3.23	68.16	16.37	7.70	4.11	1.48	12.42	7.59
	17	Jejugosan	70.9	33.28	126.15	1.8	10.0	13.14	5.40	7.42	74.39	15.87	7.81	4.12	4.13	12.85	7.27
	18	Mokpo	37.4	34.82	122.37	1.5	15.5	14.08	5.92	3.82	71.20	14.45	7.08	3.91	1.98	12.09	8.85
	19	Pohang	1.3	36.02	129.37	1.6	13.2	13.27	6.12	2.72	61.85	14.95	6.64	3.97	0.92	18.95	8.69
	20	Seosan	25.2	36.77	126.48	1.4	20.2	13.40	5.81	2.60	72.71	12.39	6.67	3.84	1.35	10.48	9.87

were calculated. There was some mismatch between the measured and the clear sky radiation envelope because some points never reached a clear sky. These points needed further scrutiny; adjustment multipliers were applied to force the upper surface of measured R_S to reach computed clear-sky radiation envelopes. This adjustment was based on the assumption that there are commonly some clear-sky days at each location and that a single factor could produce suitable calibration correction for the measurement (Allen, 1996).

Solar radiation is measured using pyranometers of the CMP21 and sunshine duration with the MS-093. Expected daily accuracy of the pyranometers is 2%, and the integration error of the sunshine duration meters is less than 10min/day. The data used for the study were daily averages on a horizontal surface. Table 1 also presents a summary of weather stations, including geographical coordinates, elevation, and measurement height. Stations 6 and 12 were located in a mountainous area and influenced by the orographic effect. The logarithm wind profile equation (Brustaert, 1991) was used to adjust the measured wind speed at each height to a reference height of 2m. The Korean Peninsula has a moderate climate that is characterized by distinct wet and dry seasons. The dry season coincides with the Northwest wind, which is predominant from

November to March. The wet season results from the Southeast wind, which brings moisture-laden air from the Pacific Ocean. That season lasts from May to October and accounts for 70 % of the annual precipitation. July-August is usually the wettest season. All sites exhibit typical daily and seasonal variations in moderate temperature trends, ranging between a seasonal maximum from April to October to a minimum from November to March. Coastal sites show less variability in temperature, with a diurnal temperature range (DTR) of approximately 7 ˚C.

The net radiation was computed using the measured shortwave R_S and the outgoing longwave radiation equation (Irmak *et al.*, 2003c) as follows;

$$Rn = R_{ns} - R_{nl} \qquad (1)$$

in which, Rn=net radiation ($MJ/m^2/day$); R_{ns}=the rate of incoming net shortwave radiation ($MJ/m^2/day$); R_{nl} = the rate of outgoing net longwave radiation ($MJ/m^2/day$).

The incoming net shortwave radiation was calculated as follows;

$$R_{ns} = Rs(measured)\ (1\text{-}\alpha) \qquad (2)$$

in which, α = surface albedo and 0.23 was used for grass reference crop surface; Rs(measure) =total incoming (measured) solar radiation ($MJ/m^2/day$).

The rate of outgoing net longwave radiation was expressed quantitatively as

$$R_{nl} = \sigma\left[\frac{T_{max}^4 + T_{min}^4}{2}\right](0.34 - 0.14\ \ e_a)(1.35\frac{R_s}{R_{so}} - 0.35)(3)$$

where σ is the Stefan-Boltzmann constant ($4.903 \cdot 10^{-9}$ $MJ/K^4/m^2/day$); e_a is actual vapor pressure (kPa), and R_{so} is the clear-sky solar radiation ($MJ/m^2/day$).

III. THEORETICAL BACKGROUND

1. The Angstrom Equation

Angstrom (1924) and Prescott (1940) suggested a correlation in linear form as follows;

$$\frac{R_s}{R_a} = a + b\left(\frac{n}{N}\right) = 0.177 + 0.552\left(\frac{n}{N}\right) \qquad (4)$$

where R_s is the total incoming shortwave solar radiation ($MJ/m^2/day$); R_a is the extraterrestrial radiation ($MJ/m^2/day$); a and b are the model parameters; n is the bright sunshine duration (hour); and N is the total day length (hour). To compute the extraterrestrial radiation R_a and total day length N, the following equations are used.

$$R_a = 15.392 d_r\ (\omega_s \sin\phi \sin\delta + \cos\varphi \cos\delta \sin\omega_s) \qquad (5)$$

$$N = \frac{24}{\pi}\omega_s \qquad (6)$$

$$d_r = 1 + 0.033\cos(2\pi J/365) \qquad (7)$$

$$\omega_s = \arccos(-\tan\phi \tan\delta) \qquad (8)$$

$$\delta = 0.4093\sin(2\pi J/365 - 1.405) \qquad (9)$$

where Ra = extraterrestrial radiation (equivalent evaporation [mm/day] = 0.408 Radiation [$MJ/m^2/day$]); d_r = relative earth-sun distance (-); ω_s = sunset hour angle (radians); φ = latitude of site (+ for northern hemisphere, - for southern hemisphere) (radians); δ = solar declination (radians), and J = Julian days.

In equation (4), n/N denotes the cloudiness fraction, while Rs/Ra is affected by various atmospheric conditions, as stated earlier.

The input of extraterrestrial shortwave radiation Ra is absorbed by atmospheric gases, particularly water vapor and ozone, and is scattered by air molecules and aerosol particles in clear sky conditions and additionally by clouds when these clouds are present (Maidment, 1993). Equation (4) is generalized in an attempt to improve accuracy and performance as follows and so called the “modified Angstrom equation” (Lee, 2009b);

$$\frac{R_s}{R_a} = a + b\left(\frac{n}{N}\right)^{c} = 0.128 + 0.556\left(\frac{n}{N}\right)^{0.649} \qquad (10)$$

An additional parameter c, which describes the influence of the impeding factor and nonlinearity between Rs/Ra and n/N, is introduced in the equation (10). The original Angstrom equation (4) is a special form of the modified angstrom equation (10), giving c=1.0 (Lee, 2009b).

2. The FAO-56 Penman-Monteith Equation (FAO PM)

The limitation in availability of lysimeter measured ET_0 data in many locations required the scientists to use a standard method to develop a simplified equation with fewer input variables. Use of such a standard method has been, in practice, very beneficial; however, there can be certain/varied pros and cons as described in Irmak *et al*. (2003b). The concept of using one equation to calibrate or validate another equation is not new. Many studies have used the Penman-Monteith (PM) equation to calibrate and modify the coefficient for various empirical equations for different climate conditions (Trajkovic, 2007; Gavilan *et al*, 2006; Vanderlinden *et al*., 2004; Irmak *et al*., 2003a; Allen, 1998; Allen and Brockway, 1983; Gunston and Batchelor, 1983). The FAO PM has been used as a substitute for the measured ET_0 data, the standard procedure when there is no lysimeter data (Irmak *et al*., 2003b; Gavilan *et al*., 2006; Trajkovic, 2007). For the same reason, the FAO PM was selected here as a reference for the comparison with other methods as follows:

$$ET_{0PM} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T + 273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (11)$$

where ET_{0PM}= reference evapotranspiration estimated by the FAO PM equation (mm/day); Δ = slope of the saturated vapor pressure function (kPa/˚C), which can be calculated using mean air temperature; Rn = net radiation (MJ/m^2/day); G= soil heat flux density (MJ/m^2/day), which can be calculated using the air temperature difference for a specified time interval; γ = psychometric constant (kPa/˚C), which can be computed using atmospheric pressure; T = mean daily air temperature (˚C); U_2 =average 24-h wind speed at 2-m height (m/s); and (e_s-e_a) = vapor pressure deficit (kPa).

3. Evaluating the Efficiency of Fit for ET_0

To quantify the efficiency of fit for ET_0, the Nash-Sutcliffe coefficient of efficiency (NSC) (Nash and Sutcliffe, 1970) and Root Mean Squared Error (RMSE) were used as follows:

$$NSC = 1 - \frac{\sum_{i=1}^{m}([R_{s.est}]_i - [R_{s.obs}]_i)^2}{\sum_{i=1}^{m}([R_{s.obs}]_i - [\bar{R}_{s.obs}]_i)^2} \qquad (12)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{m}([R_{s.est}]_i - [R_{s.obs}]_i)^2}{m - 1}} \qquad (13)$$

where $R_{s \cdot est}$ and $R_{s \cdot obs}$ are the simulated and observed values of incoming shortwave solar radiation, respectively, and $\bar{R}_{s \cdot obs}$ is the mean observed, incoming shortwave solar radiation, m is the number of total data points. NSC has a maximum perfect score of 1.0 and no minimum with values greater than 0, indicating satisfactory results. Physically, NSC is 1 minus the ratio of the mean-squared error to the variance of the observed data (Nash & Sutcliff, 1970). The normal distribution of error structure is assumed to determine the confidence intervals (CI) of the model output.

IV. OUTCOMES

Both the original and modified Angstrom equation were locally calibrated to fit the meteorological data, using the Shuffled Complex Evolution algorithm (SCE; Duan *et al.*, 1993, 1994), a general-purpose global optimization method designed to handle many of the response problems encountered in the calibration of non-linear simulation models. The corresponding results are as follows;

$$\frac{R_s}{R_a} = 0.177 + 0.552\left(\frac{n}{N}\right)^{1.0} \tag{14}$$

for the original Angstrom equation

$$\frac{R_s}{R_a} = 0.128 + 0.556\left(\frac{n}{N}\right)^{0.649} \tag{15}$$

for the modified Angstrom equation

The readers are referred to Lee (2009b) for more details.

For the original equation, the corresponding absolute error (AE) of the RMSE is in the range of -0.126~0.158(3.40~8.45) (MJ/m^2/day) and the correlation coefficient (r) is in the range of 0.85~0.94. For the modified Angstrom equation, the corresponding AE(RMSE) is in the range of -0.089~0.154(2.52~7.54) (MJ/m^2/day) and the correlation coefficient is in the range of 0.86~0.95. Figure 2 presents a relative comparison of the basic statistics for both methods (RMSE in Figure 2a and absolute error (AE) in Figure 2b).

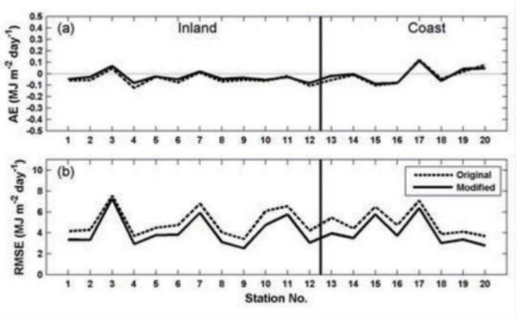

Figure 2. Relative comparison of basic statistics for two radiation methods: original and modified Angstrom equation

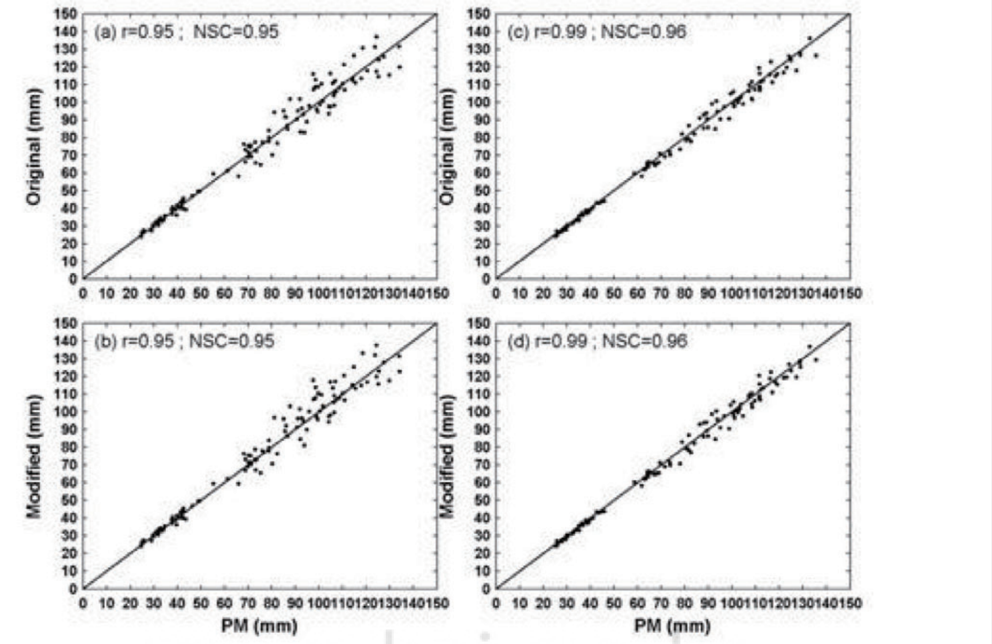

Figure 3. A scatter plot for the estimated vs. the reference values of monthly ET$_0$ at the representative stations: (a-b) for Seoul and (c-d) for Seosan station during the study period

Next, the solar radiations derived from both the original and the modified Angstrom equations were applied to compute ET_0 to see how significantly the modified Angstrom equation affects the irrigation schedule or water resources area. Other meteorological forcing parameters, such as air temperature, wind speed, and relative humidity, were set to be identical in computing ET_0; the only source that would differentiate the estimated ET_0 among the alternatives was the different solar radiation input derived from each method.

The PM equation has been selected for a reference here since the PM equation showed excellent performance under a variety of climatic conditions, and the FAO-56 PM (hereinafter called FAO PM) described the control condition against which the calibration methods were assessed as in many other studies (Trajkovic, 2007; Gavilan *et al*, 2006; Vanderlinden *et al*., 2004; Irmak *et al*., 2003a, b; Allen *et al*, 1998; Allen and Brockway, 1983; Gunston and Batchelor, 1983).

Figure 3 presents the scatter plots for the estimated versus the reference values of monthly ET_0 at the representative stations. It was found that there is no noticeable difference between two methods. Table 2-3 presents the monthly estimates for the ET_0 and its basic statistics. There is some suggestion that the difference is larger in some inland areas because it appears that inland areas are less windy as shown in table 1 and larger portion of ET_0 stems from solar radiation in inland areas. The RMSE (AE) is 5.96 (1.75) for the original equation, while it was 5.96 (2.02) for the modified equation. The NSC (r) is 0.95 (0.93) for the original equation, while it was 0.95 (0.93)

Table 2. The monthly estimates of the ET_0 and the corresponding basic statistics for the original Angstrom equation (in *mm*)

	Station index.	Station name	ET_{PM}	ET_0	*RMSE*	*NSC*	*r*	*AE*
Inland	1	Andong	76.03	75.49	6	0.97	0.94	-0.54
	2	Cheongju	77.34	79.91	5.19	0.98	0.95	2.57
	3	Chupungnyeong	75.17	78.06	7.29	0.95	0.92	2.88
	4	Deagu	85.45	87.02	3.19	0.99	0.96	1.57
	5	Daejeon	78.22	78.42	4.51	0.99	0.95	0.2
	6	Daegwallyeong	64.81	67.36	4.94	0.97	0.95	2.55
	7	Gwangju	79.39	82.16	8.81	0.93	0.91	2.78
	8	Jeonju	72.85	76.53	6.89	0.96	0.94	3.68
	9	Jinju	78.49	78.86	2.78	0.99	0.96	0.37
	10	Seoul	72.87	77.05	6.64	0.95	0.95	4.18
	11	Suwon	70.59	76.25	12.19	0.87	0.88	5.67
	12	Wonju	69.98	68.9	5.29	0.98	0.95	-1.08
Coast	13	Busan	87.28	90.55	5.96	0.94	0.93	3.28
	14	Gangneung	84.66	87.66	4.12	0.98	0.96	3.01
	15	Incheon	81.64	79.51	5.02	0.98	0.95	-2.13
	16	Jeju	86.53	87.55	4.17	0.98	0.95	1.02
	17	Jejugosan	86.57	90.06	16.66	0.62	0.63	3.5
	18	Mokpo	89.07	88.37	3.61	0.99	0.96	-0.71
	19	Pohang	86.92	87.99	2.92	0.99	0.96	1.07
	20	Seosan	74.06	75.12	2.99	0.99	0.96	1.05
avg			78.90	80.64	5.96	0.95	0.93	1.75

Table3. The monthly estimates of the ET_0 and the corresponding basic statistics for the modified Angstrom equation (in *mm*)

	Station index.	Station name	ET_{PM}	ET_0	*RMSE*	*NSC*	*r*	*AE*
Inland	1	Andong	76.03	76.05	6.04	0.97	0.94	0.02
	2	Cheongju	77.34	80.37	5.4	0.98	0.95	3.02
	3	Chupungnyeong	75.17	78.23	7.16	0.95	0.93	3.05
	4	Deagu	85.45	87.31	3.34	0.99	0.96	1.86
	5	Daejeon	78.22	78.84	4.3	0.99	0.95	0.62
	6	Daegwallyeong	64.81	67.17	4.43	0.98	0.95	2.36
	7	Gwangju	79.39	82.75	9.05	0.93	0.91	3.36
	8	Jeonju	72.85	77.04	7.02	0.96	0.94	4.19
	9	Jinju	78.49	79.22	3.03	0.99	0.96	0.73
	10	Seoul	72.87	77.81	7.24	0.95	0.95	4.94
	11	Suwon	70.59	76.74	12.54	0.86	0.88	6.16
	12	Wonju	69.98	69.67	4.75	0.98	0.95	-0.31
Coast	13	Busan	87.28	90.63	5.68	0.94	0.94	3.36
	14	Gangneung	84.66	87.53	4	0.98	0.96	2.88
	15	Incheon	81.64	79.83	4.84	0.98	0.95	-1.81
	16	Jeju	86.53	87.55	4.09	0.98	0.95	1.02
	17	Jejugosan	86.57	89.87	16.7	0.62	0.62	3.3
	18	Mokpo	89.07	88.35	3.7	0.99	0.96	-0.72
	19	Pohang	86.92	87.98	2.81	0.99	0.96	1.06
	20	Seosan	74.06	75.46	3.09	0.99	0.96	1.4
avg			78.90	80.92	5.96	0.95	0.93	2.02

for the modified equation. The corresponding results are shown in Table 2-3 and Figure 3. It was generally found that both methods show a similar level of performance and that agreement varied with different stations.

Figure 4 shows the monthly performance for both the reference and the estimated ET_0 at the

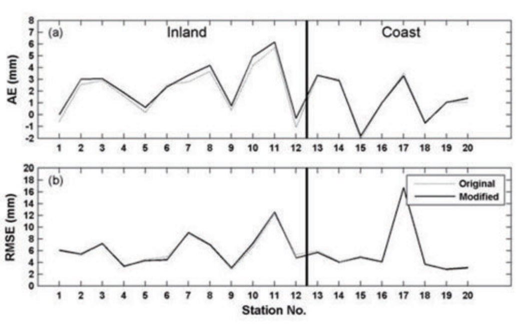

Figure 4. Relative comparison of basic statistics for the ET_0 derived from two radiation methods: original and modified Angstrom equation

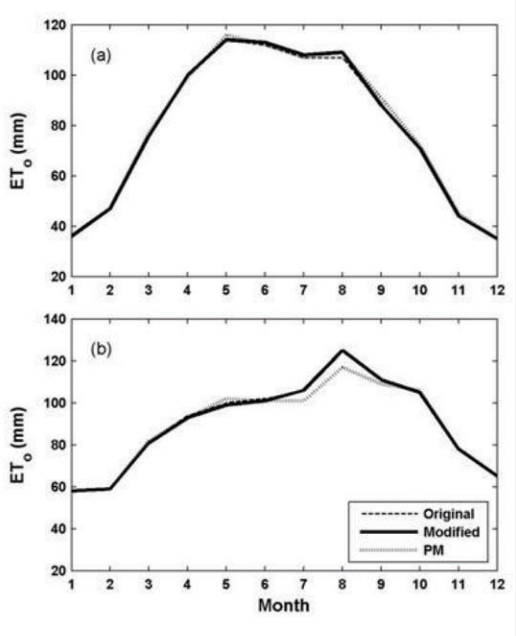

Figure 5. Monthly performance for the estimated ET_0 at the representative stations; (a) for Seoul and (b) for Seosan station during the study period.

representative station. The estimates from both alternatives were similar in their seasonal patterns. It appeared that the largest difference occurred during summer months for both alternatives. Previous research (Bois *et al.*, 2008; McVicar *et al.*, 2007; Gong *et al.*, 2006) has shown that the sensitivity of the climatic variables to ET_0 varies with season and region, and ET_0 is mainly governed by solar radiation during summer and by wind speed during winter. In accordance with

Table 4. The monthly average values of theat each station (in)

		Station index																			
	Mon	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PM	1	31	29	35	41	29	26	33	29	36	30	28	24	53	47	31	45	58	39	48	28
	2	40	40	44	52	41	35	45	39	47	40	37	34	61	55	42	51	59	47	56	37
	3	71	73	78	86	73	64	76	69	77	71	66	65	87	86	74	78	82	75	86	66
	4	96	104	101	113	105	94	103	99	99	99	93	96	103	113	101	100	93	100	111	93
	5	112	124	114	131	123	108	121	115	116	117	114	114	116	123	115	115	102	116	124	113
	6	114	121	109	128	121	102	119	114	112	115	114	116	112	120	116	117	101	120	121	112
	7	101	112	97	117	112	87	111	106	107	96	106	106	103	109	106	132	101	119	114	106
	8	96	110	94	111	110	79	111	107	109	102	111	105	116	105	111	128	117	127	110	111
	9	78	92	80	92	92	62	96	90	91	89	91	84	99	85	93	100	109	103	88	93
	10	60	68	69	77	69	60	76	70	72	71	68	61	90	83	74	89	106	90	81	68
	11	38	41	45	50	41	41	47	43	45	43	40	34	64	61	47	61	78	58	59	40
	12	30	28	36	41	29	30	34	30	35	31	28	23	55	53	34	49	65	42	50	29
Original	1	32	29	35	42	29	27	33	30	36	30	28	24	53	47	32	46	58	39	48	28
	2	41	40	45	53	40	35	43	40	47	40	38	33	61	55	42	52	59	46	56	37
	3	72	73	79	87	72	64	73	70	76	70	67	64	87	87	72	78	81	73	85	64
	4	102	106	109	116	105	96	103	102	100	101	97	95	105	116	101	102	94	100	113	94
	5	115	123	120	131	120	107	117	116	114	116	116	109	115	123	116	112	100	113	124	112
	6	116	120	113	128	119	102	115	114	112	115	115	110	113	119	116	114	102	115	124	111
	7	104	111	101	117	109	88	110	106	107	99	106	100	106	111	107	129	106	113	116	104
	8	101	110	97	113	106	81	110	107	107	104	111	99	118	105	111	126	125	122	114	109
	9	79	91	83	92	90	64	94	90	88	90	93	80	101	86	93	100	111	100	90	91
	10	63	69	69	78	68	60	76	71	71	72	69	59	91	83	74	88	105	88	82	68
	11	39	41	46	52	41	42	46	44	44	44	40	34	65	61	47	61	78	58	59	40
	12	30	29	36	42	29	30	34	30	35	32	29	23	56	53	34	49	65	42	50	29
Modified	1	32	29	35	42	29	26	33	30	36	30	28	24	53	47	32	46	58	39	48	28
	2	41	40	45	53	40	34	44	40	47	40	37	33	61	55	41	52	59	46	56	37
	3	72	73	79	86	72	63	73	70	76	71	67	64	87	87	72	78	81	73	85	64
	4	102	106	108	116	106	96	103	102	100	101	97	96	105	116	101	102	93	100	113	94
	5	115	123	119	131	120	107	117	116	114	117	115	110	115	124	116	112	99	112	124	112
	6	118	121	114	129	120	102	116	116	113	116	116	112	113	120	117	114	101	116	124	112
	7	105	113	102	118	110	87	111	108	108	100	107	101	106	110	108	129	106	114	116	104
	8	102	112	98	114	108	80	112	109	109	106	113	101	119	105	112	127	125	123	114	110
	9	80	91	83	92	90	63	95	91	88	91	94	81	101	86	93	99	111	100	89	92
	10	63	69	69	78	68	60	76	71	71	72	69	59	91	83	74	88	105	88	81	68
	11	39	41	46	52	41	41	47	44	44	44	40	34	65	61	47	61	78	58	59	40
	12	30	29	36	42	29	30	34	31	35	32	29	23	56	53	34	49	65	42	50	29

that work, Figure 5 presents the seasonal variation in ET_0 estimates with the largest difference occurs during summer season. Table 4 presents the monthly average of ET_0 estimated from two alternatives. It was shown that the difference for the two methods was up to ~2% during the summer season.

Figure 6 shows a relative comparison of the annual evolution of the cumulative ET_0 according to both alternatives at the representative stations. There was no prominent difference between the alternatives. The difference for the cumulative ET_0 was not remarkable for either the inland areas or the coastal areas.

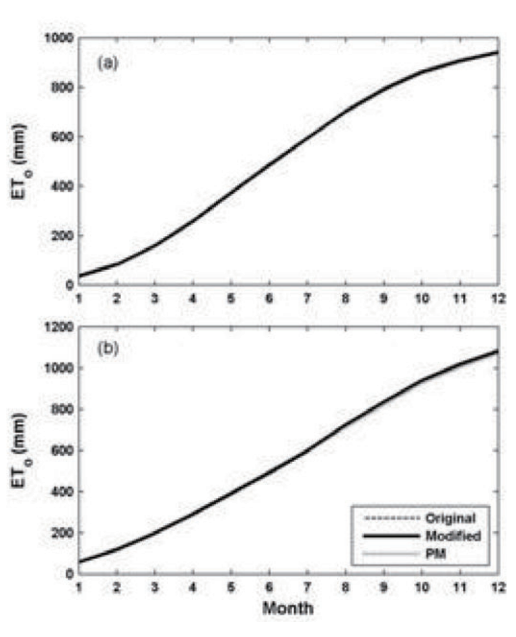

Figure 6. Relative comparison of the annual evolution of cumulative ET_0 according to both alternatives at the representative stations: (a) for Seoul and (b) for Seosan station during the study period

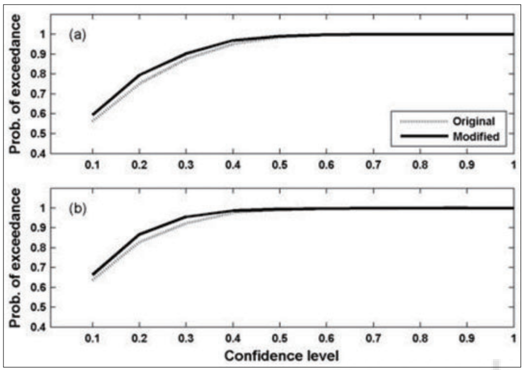

Figure 7. A statistical evaluation of the estimated ET_0 against the reference ET_0.

The figure shows the exceedance probability (EP) of upper/lower quantiles of the estimated ET_0 for a range of confidence level probability.

A statistical evaluation of the estimated ET_0 against the reference values is presented in Figure 7. Figure 7 shows the exceedance probability (EP) of upper/lower quantiles for the estimated ET_0 for a range of confidence level probability. Both stations showed a similar level of statistical accuracies for the suggested method, modified Angstrom equation. Both sites were associated with high EP values that ranged from near 100% at a high value of CI (0.5) to 60% at 0.1 of CI. It is obvious based on these findings that the modified Angstrom equation provided better performance than the original Angstrom equation at each station.

On the basis of the results above, it appears that the two alternatives present a similar level of performance and the modified Angstrom equation is not able to provide any superiority to the original equation in computing ET_0. The modified equation shows better accuracy at some stations, while the original equation shows better accuracy at other stations. These findings may imply that performance varies with region.

V. SUMMARY AND CONCLUSIONS

This paper is based on the previously accepted fact that the nonlinear relationship is more accurate than the conventional linear relationship between solar radiation and bright sunshine duration. The estimation method of solar radiation applies to the ET_0. The probable impact of the nonlinear relationships between the solar radiation and bright sunshine duration on the ET_0 in irrigation and water resources was thus examined for relative comparison using the conventional linear method. The relative accuracies of the different methods are assessed by a comparison to the reference values. It appears that the two alternatives discussed here present a similar level of performance, and the difference between the original Angstrom equation and the modified Angstrom equation does not provide the benchmark control that would be desirable to demonstrate a significant difference for the methods. This study suggests that the selection of method used for estimating solar radiation from bright sunshine duration may have a minor influence on estimating ET_0 regardless of linearity once the method is locally calibrated, but much attention does need to be paid during summer season because solar radiation dominates ET_0 during the summer season in relative terms.

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