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Determining the Effective Distance Spatially for Sharing the Climatic Data Relating to Reference Evapotranspiration

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Abstract The estimation of reference evapotranspiration (ET_0) with the FAO-Penman-Monteith method faces challenges in some places due to its high data demand. To overcome this challenge some methodologies recommended by FAO. However, sharing the nearby station's data is another way to estimate ET_0 more accurate in some cases than that of using the FAO's recommendation. In this paper, the important matter is the determination of an effective distance (Xc) which is the upper limit of distance for data sharing between the stations. $\Delta ET_{0(st)}$ which is the average errors between the two stations given by the measured data is theoretically very small if the distance is zero. $\Delta ET_{0(Alt)}$ which is the error produced from the alternative data given by FAO's recommendation is equal to $\Delta ET_{0(st)}$ at Xc. By using the data form 48 metrological stations in Japan, we examined this concept in the case of three kinds of data. The results confirmed, there was Xc exited along the investigated distance at which $\Delta ET_{0(st)}$ was smaller than $\Delta ET_{0(Alt)}$. This was the case corresponding to the solar radiation and actual vapor pressure. Xc was found smaller than the minimum distance in the case of wind data. It is, therefore, possible to use the FAO's alternative wind data.

Keywords: *effective distance, climatic variables, reference evapotranspiration, geostatistical technique, error theory*

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1. Introduction

When we discuss the climate condition for plants growth, not only soil characters but also climate conditions are essential, especially when we calculate crop water requirement. The FAO Penman-Monteith method, abbreviated as FAO-56PM in this study, is one of the well-known models for estimating ET_0 requires minimum air temperature (T_{min}), maximum air temperature (T_{max}), wind velocity (u_2), solar radiation (R_s) and relative humidity (RH) [1]. However, the availability of the complete set of measured data is a big challenge for estimating ET_0 in some locations worldwide [2,3]. This is an extreme restriction to the application of the Penman-Monteith method [4].

To overcome the problem of the data lucking, especially in the case when R_s, RH and u_2 are missing, there are some procedures proposed by FAO, allowing the alternative's data to be estimated. The validity of some alternative data in the ET_0 estimation was confirmed in variety of locations worldwide by many researchers [4,5,6,7]. However, some of the alternative data were not valid in some locations, depends upon the climatic regime of a place. Ganji and Kajisa [8] reported that the ET_0 estimation yielded with relatively higher errors when alternative R_s and e_a were used in the calculation compared to the alternative u_2, in the case of humid climate of Japan. This may be the case for many locations over the globe.

To estimate ET_0 more accurate than that of using the FAO's alternative data there is a possibility to use the nearby station's measured data when the data of a given station is missing. However, the important matter is the determination of a effective distance (Xc) which is the upper limit of distance for data sharing between the stations. This is the distance inside of that range sharing data leads smaller error than that of using the FAO's alternative data as we are thinking. Xc might be different of the range Xh which can be determined by using different kind of models. One of the successful technique is using optimal approximation, which is applied in a geostatistical technique termed kriging [9]. Xh is the upper limit that longer that point data are no longer correlated. In this paper, from this approximation model equation and $\Delta ET_{0(Alt)}$, we attempted to determine the Xc spatially for sharing the data of R_s, u_2 and e_a when they are missing. The existence of Xc was not clear before analyzing.

In this paper, $\Delta ET_{0(st)}$ is the average errors between the two places produced from the actual measured data. $\Delta ET_{0(st)}$ is theoretically very small in a case if the distance between two places is zero, and it may increase for the increasing of the distance. While $\Delta ET_{0(Alt)}$ is the error produced using the alternative data those given by FAO's methodology in a given station. $\Delta ET_{0(Alt)}$ might be equal to $\Delta ET_{0(st)}$ at the Xc based on our prediction. At the distance larger than Xc, $\Delta ET_{0(st)}$ could become larger than $\Delta ET_{0(Alt)}$.

The typical concept proposed in this study is illustrated in Figure 1. In Figure 1, the X-axis shows the distance between the stations in (km), Y-axis shows $\Delta ET_{0(st)}$, $y(x)$ shows the model equation, Xh shows the proper range in which data are no longer correlated, and Xc shows the effective distance at which $\Delta ET_{0(Alt)}$ crosses the theoretical model equation's graph which is given by $\Delta ET_{0(st)}$. Considering

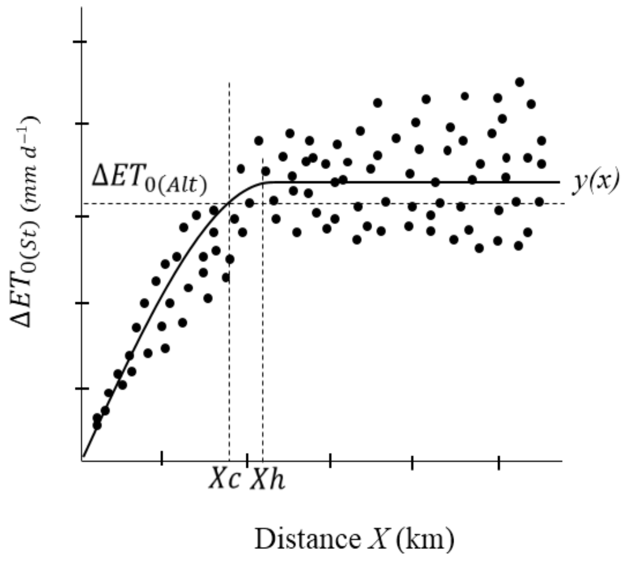

Figure 1. $\Delta ET_{0(St)}$, $\Delta ET_{0(Alt)}$, the model $y(h)$, Xc and the range Xh.

2. Methodology

2.1. Study Area and Metrological Data

The average meteorological data for a 30-year period used in this study were collected from the Japan metrological agency recorded in 48 places those are almost located in different prefectures over Japan, shown in Figure 2. The numbers in Figure 2 are in line with the numbers giving for each locations in Table 1. Details on elevation, coordinates and climate conditions of the locations are shown in Table 1.

Structural analysis of $\Delta ET_{0(St)}$ estimates was initially used in order to identify the spatial variability features of $\Delta ET_{0(St)}$ over Japan. As of the first step, we began with getting $\Delta ET_{0(St)}$, computed with the values obtained from Eq. 1 for all pairs of locations separated by distance. The right side of Eq. 1 consists of two components, one is the variables' differentiation (Δz) produced from the average difference between the measured data of two stations, given as Eq. 2 in which x is R_s, e_a or u_2. The second component is the slope of the functions obtained from the average values of station 1 and 2 given as Eq. 3.

Figure 2. Map of Japan with the study's locations marked from 1 to 48

The value of the partial differential is the derivation of ET_0 with respect to the variables. The second step was fitting of model equation. According to the Delhomme (1978), the well-known models are the monomial, spherical, exponential and Gaussian. In this paper, the spherical model was experimentally selected (see Eq. 4).

$$\Delta ET_{0(St)} = \Delta z \times \left(\frac{\Delta ET_0}{\Delta z_{1,2}} \right) \tag{1}$$

$$\Delta Z = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (z_{1i} - z_{2i})^2} \tag{2}$$

$$\frac{\Delta ET_0}{\Delta z_{1,2}} = \frac{1}{2} \left(\sqrt{\frac{1}{m} \sum_{i=1}^{m} \left(\frac{\partial ET_0}{\partial z_1} \right)_i^2} + \sqrt{\frac{1}{m} \sum_{i=1}^{m} \left(\frac{\partial ET_0}{\partial z_2} \right)_i^2} \right) \tag{3}$$

$$y(x) = \begin{cases} c_0 + c\left(\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a} \right)^3 \right) & (0 < x \le a) \\ c_0 + c & (a < x) \end{cases} \tag{4}$$

where, $\Delta ET_{0(St)}$ is the average error between the two places produced from the actual measured data (mm d^{-1}), z_1 and z_2 are the measured values in the first and second locations, respectively, 1 and 2 are the suffixes of each place first and second, c_0 is nugget effect which we considered very small in this study, x is the distance between the two locations (km), a means range Xh in this paper, and $c_0 + c$ means sill.

Table 1. Average record of the meteorological variables and estimated variables needed for calculating of the correct evapotranspiration

Station number	Station location	Coordinate		Measured variables				Estimated variables	
		Elevation (m)	Latitude (Degree)	n (hour)	T_{Ave} (°C)	u_2 (m s^{-1})	RH (%)	R_s (MJ m^{-2} d^{-1})	e_a (kpa)
1	Wakkanai	3	45.41	4.0	7.1	3.0	75.3	11.1	0.29
2	Sapporo	17	43.06	4.7	9.4	1.8	68.8	12.2	0.33
3	Kushiro	5	42.98	5.3	6.6	2.5	76.8	12.3	0.28
4	Aomori	3	40.82	4.3	10.9	2.3	74.6	12.2	0.45
5	Akita	6	39.71	4.2	12.1	2.6	72.8	12.2	0.48
6	Morioka	155	39.69	4.6	10.8	2.0	73.7	12.4	0.42
7	Sendai	39	38.26	5.0	13.0	1.9	70.9	13.0	0.50
8	Yamagata	290	38.25	4.4	12.4	1.3	73.8	12.6	0.55
9	Niigata	0	37.89	4.5	14.3	2.4	71.3	12.9	0.58
10	Fukushima	67	37.75	4.8	13.7	1.5	68.8	12.9	0.53
11	Toyama	9	36.70	4.4	14.6	2.0	76.3	12.9	0.68
12	Kanazawa	6	36.58	4.6	15.1	2.2	71.0	13.2	0.67
13	Utsunomiya	119	36.54	5.3	14.6	1.7	69.4	13.5	0.55
14	Maebashi	112	36.40	5.9	15.3	2.0	62.3	14.2	0.51
15	Matsumoto	610	36.24	5.8	12.6	1.6	67.8	14.4	0.46
16	Kumagai	30	36.15	5.7	15.7	1.7	64.7	14.1	0.55
17	Fukui	9	36.05	4.5	15.1	1.8	74.8	13.1	0.70
18	Tokyo	20	35.69	5.3	16.7	2.0	61.8	13.7	0.56
19	Kofu	273	35.66	6.1	15.6	1.4	63.8	14.7	0.53
20	Chiba	3	35.06	5.3	16.4	2.4	67.9	13.8	0.60
21	Tottori	7	35.48	4.5	15.5	1.9	73.5	13.2	0.67
22	Matsue	17	35.45	4.6	15.5	2.2	75.5	13.3	0.69
23	Yokohama	39	35.43	5.5	16.5	2.4	66.7	14.1	0.58
24	Gifu	13	35.40	5.7	16.4	1.7	66.3	14.5	0.63
25	Hikone	87	35.27	5.0	15.2	1.9	73.8	13.8	0.66
26	Nagoya	51	35.16	5.8	16.5	2.1	65.8	14.6	0.60
27	Kyoto	36	35.01	4.8	16.5	1.3	65.6	13.4	0.63
28	Tsu	2	34.73	5.7	16.5	2.8	67.8	14.5	0.60
29	Kobe	3	34.69	5.5	17.0	2.4	65.8	14.4	0.59
30	Okayama	3	34.68	5.5	16.5	1.9	66.6	14.3	0.63
31	Osaka	1	34.68	5.5	17.4	1.9	63.4	14.4	0.62
32	Nara	90	34.67	4.9	15.5	1.0	72.5	13.7	0.62
33	Hiroshima	4	34.39	5.5	16.8	2.0	67.4	14.4	0.67
34	Takamatsu	34	34.31	5.6	16.8	1.8	67.1	14.5	0.66
35	Wakayama	14	34.22	5.7	17.1	2.2	65.5	14.7	0.64
36	Yamaguchi	5	34.16	5.1	16.1	1.3	72.5	14.0	0.72
37	Tokushima	2	34.06	5.7	17.0	2.2	66.8	14.7	0.63
38	Shizuoka	14	34.05	5.9	16.9	1.5	68.0	14.7	0.61
39	Matsuyama	41	33.84	5.5	16.9	1.4	66.8	14.5	0.69
40	Fukuoka	3	33.58	5.1	17.5	1.8	67.6	14.1	0.71
41	Kochi	1	33.56	5.9	17.5	1.3	68.5	14.9	0.69
42	Oita	5	33.23	5.4	16.9	1.8	69.0	14.5	0.70
43	Saga	3	33.07	5.4	17.1	2.4	69.9	14.4	0.73
44	Kumamoto	15	32.81	5.4	17.4	1.5	70.1	14.6	0.76
45	Nagasaki	7	32.73	5.1	17.6	1.6	70.3	14.2	0.77
46	Miyazaki	9	31.93	5.8	18.0	2.0	73.0	15.0	0.86
47	Kagoshima	4	31.55	5.3	19.0	1.9	69.8	14.6	0.86
48	Naha	51	26.21	4.7	23.5	3.2	73.1	14.6	1.62
	Average	48.6		5.2	15.4	1.9	69.5	13.8	0.6

n, measured sunshine hours; T_{Ave}, average air temperature; u_2, measured wind speed; RH measured relative humidity; R_s, solar radiation estimated with sunshine hours; e_a, actual vapor pressure estimated with relative humidity.

To determine the Xc point, we computed $\Delta ET_{0(Alt)}$ using the error propagation approach. This approach was confirmed to approximate the root mean square error ($RMSE$) of ET_0 in Japan [8]. $\Delta ET_{0(Alt)}$ was calculated using Eq. 5. This consist of, the variable's differential ($\Delta z'$) yielded from the difference between measured data and alternative data at the same station (Eq. 6), and the partial differential of the function (Eq. 7). In Eq. 1 and 5, the FAO-56PM equation (Eq. 8) was transferred as Eq. 9. In Eq. 9 the components such as R_s, e_a and u_2 are independent, while those of c_1 to c_8 and e_s are constant. The variables such as R_s and e_a were calculated with measured climatic data, given as Eqs. 10-11.

$$\Delta ET_{0(Alt)} = (\Delta z') \times \left(\frac{\Delta ET_0}{\Delta z'} \right) \tag{5}$$

$$\Delta z' = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(z_i - xz_{(Alt)i} \right)^2} \tag{6}$$

$$\frac{\Delta ET_0}{\Delta z'} = \sqrt{\frac{1}{m} \sum_{i=1}^{m} \left(\frac{\partial ET_0}{\partial z} \right)_i^2} \tag{7}$$

$$ET_0 = \frac{0.408\Delta(R_n - G) + \frac{900}{T_{Ave}+273} u_2 (e_s - e_a)}{\Delta + (1 + 0.34 u_2)} \quad (8)$$

$$ET_0 = \frac{c_1 R_s - (c_2 - c_3 \sqrt{e_a})(c_4 R_s - c_5) + c_6 u_2 (e_s - e_a)}{c_7 + c_8 u_2} \quad (9)$$

$$R_s = \left(0.23 + 0.50 \frac{n}{N}\right) R_a \quad (10)$$

$$e_a = \frac{RH_{mean}}{100} e_s \quad (11)$$

where, $\Delta ET_{0(Alt)}$ is the error produced from the application of the alternative data in a given station (mm d^{-1}), $\Delta x'$ is the differentials between the measured data and alternative data in the same station, x and $x_{(Alt)}$ are the measured and alternative variables in a given station, R_n is the net radiation estimated with solar radiation data (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa°C^{-1}), T_{Ave} is the daily average air temperature (°C), u_2 is the daily average wind speed (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), c_1 is given by $0.408\Delta(1-\alpha)$, c_2 is given by $0.34 \times 0.408\,\Delta\sigma(T_{max} + T_{min}) \div 2$, c_3 is given by $0.14 \times 0.408\Delta\sigma(T_{max} + T_{min}) \div 2$, c_4 is given by $1.35 \div R_{so}$, c_5 is equivalent to 0.35, c_6 is given by $900\gamma \div (T_{Ave} + 273)$, c_7 is given by $\Delta + \gamma$ in which Δ means the slope of the vapor pressure curve, c_8 is given by 0.34γ, α is the albedo (0.23), σ is the Stefan-Boltzmann constant, R_{so} is the clear-sky solar radiation (MJ m^{-2} d^{-1}), RH_{mean} is the mean relative humidity (%).

The FAO's alternative methodologies are used in this paper to estimate the alternative data for the missing of R_s, e_a and u_2 are given as Eqs. 12-14.

$$R_{s(Alt)} = k_{Rs} \sqrt{T_{max} - T_{min}} \times R_a \quad (12)$$

$$e_{a(Alt)} = 0.611 \times e^{\left(\frac{17.27 \times T_{min}}{T_{min} + 273.3}\right)} \quad (13)$$

$$u_{2(Alt)} = 2ms^{-1} \quad (14)$$

where, $R_{s(Alt)}$ is the solar radiation based on temperature (MJ m^{-2} d^{-1}), T_{max} is the maximum air temperature (°C), T_{min} is the minimum air temperature (°C), R_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}). k_{rs} is the adjustment coefficient proposed by Allen et al. (1998) as 0.16 and 0.19 for interior and coastal areas, respectively (°C$^{-0.5}$). In this study, $k_{rs} = 0.19$ was used for all locations since the air masses that dominates in the all locations have their origin from the surrounding sea water around, $e_{a(Alt)}$ is the actual vapor pressure estimated using T_{min} (kPa), and $u_{2(Alt)}$ is the default world average value (ms^{-1}).

3. Results

Figure 3 from A to C shows the approximated $y(x)$ curve, plots of $\Delta ET_{0(St)}$ versus the distance X, and $\Delta ET_{0(Alt)}$ as horizontal line. Table 2 listed the values for Xh, Xc, X_{min}, X_{max}, $\Delta ET_{0(Alt)}$, c_0 and c.

Xc was confirmed within the investigated distance in the case of R_s and e_a only, shown in Figures 3A-B. While no Xc exited within the investigated distance in the case of u_2, shown in Figure 3C.

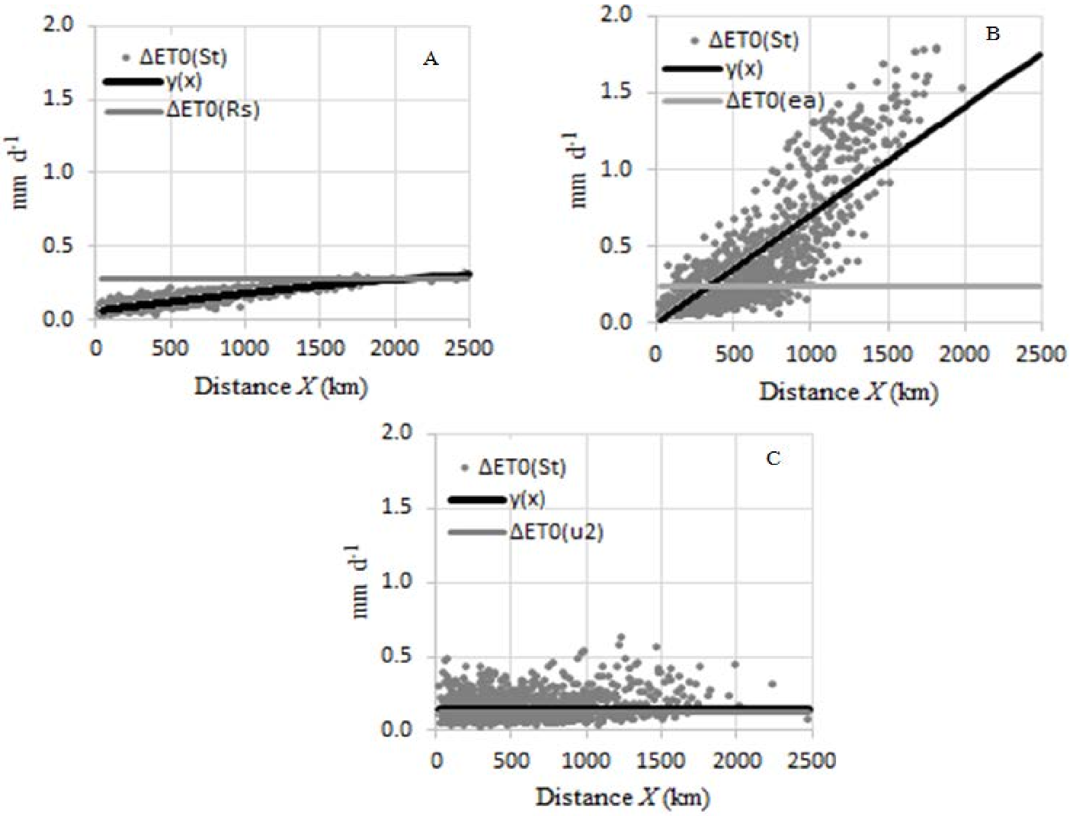

Figure 3. $\Delta ET_{0(St)}$, $\Delta ET_{0(Alt)}$ and the model $y(h)$; (A) is the case of R_s, (B) is the case of e_a, and (C) is the case of u_2

Table 2. Details of different distances for the three cases

	Xc (km)	Xh (km)	X_{min} (km)	X_{max} (km)	c_0	c	$\Delta ET_{0(Alt)}$
						(mm d^{-1})	
R_s	2,363.0	3,191.1	26.1	2,500.0	0.1	0.3	0.3
e_a	341.1	230,071.7	26.1	2,500.0	0.1	0.1	0.2
u_2	20.9	26.1	26.1	2,500.0	0.0	107.8	0.1

4. Discussion

As we expected before the analysis that $Xc < Xh$, the results from the analysis met our expectation, however, Xh was found out of the investigated distance. The results of the analysis found two different cases corresponding to the Figures 3A to C.

A and B) $X_{min} < Xc < X_{max}$, this is the case corresponding to the R_s and e_a shown in Figures 3A-B, respectively. In the case, any X smaller than Xc will mean the range inside of which sharing data will be effective, while any X larger than Xc will not mean so. Because, the approximated $\Delta ET_{0(St)}$ on the line, i.e. $y(x)$ yielded below $\Delta ET_{0(Alt)}$ for $X < Xc$, while it was yielded above $\Delta ET_{0(Alt)}$ for $Xc < X$. This is implying that sharing the data among the stations within the rage of X smaller than Xc will be useful than that of using the FAO's alternative data of R_s and e_a.

C) $Xc < X_{min}$, this case was found out of our expectation. Xc was found very short and not effective. Therefore, applying the FAO's recommended methodology for alternative u_2 was found useful. On the other hand, the average measured u_2 yielded 1.9 ms^{-1} in the study area, given in Table 1 which is almost close to the FAO's recommendation. In the case of missing u_2 we suggest to get the average u_2 in a given place if possible. Applying the average value should be very important which is free from the distance matter.

The fact that Xc very smaller than Xh means the alternative data recommended by FAO was much better than what we were thinking by seeing Figure 1.

5. Conclusion

Availability of the complete set of data is an extreme restriction to the application of the Penman-Monteith method in some places. Although, some producers have been recommended by FAO to estimate missing data using air temperature only, however, there is a possibility to use the nearby station's measured data when the data of a given station is missing. The important matter is the determination of an effective distance (Xc) for data sharing. In this paper, by using the error propagation theory and experimental approximation equation we attempted to determine the Xc spatially for sharing the data of R_s, u_2, and e_a when they are missing. The existence of Xc was not clear before the analyzing. In a examined cases of Japan, the analysis leads to the following conclusions:

1) The existence of Xc was confirmed in the cases of R_s and e_a.
2) In our case, the Xc was in the range of the measured data for R_s and e_a. Therefore, the shared data can be recommended at a distance smaller than Xc, while the alternative data recommended by FAO can be selected at a distance larger than Xc. The Xcs were given as 2363 km and 341 km for R_s and e_a, respectively.
3) Xc was smaller than any X in the case of u_2. Therefore, the alternative data recommended by FAO can be selected for the investigated distance. Xc was given as 20.11 km which was smaller than X_{min} which was 26.13 km.

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