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ASSESSMENT OF THE ACCURACY OF METEOROLOGICAL DATA OBTAINED FROM A VIRTUAL WEATHER STATION FOR THE PURPOSE OF ESTIMATING ETO FOR THE CONDITIONS OF THE SOUTH OF UKRAINE

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Abstract. *The article presents an assessment of the accuracy of meteorological data obtained from the Visual Crossing Weather Data (VWS VCWD) virtual meteorological station and the calculated reference evapotranspiration (ETo) based on these data for the conditions of southern Ukraine. It has been established that the data on air temperature and relative humidity are obtained with high accuracy, with MAPE and RMSE errors of 4.5 % and 0.94 °C and 9.1 % and 7.53 %, respectively. Good accuracy is characteristic of dew point temperature and solar radiation, with MAPE and RMSE errors of 20.9 % and 1.44 °C and 17.4 % and 3.41 MJ/m²·day, respectively. Dew point temperature data can also be obtained with satisfactory accuracy depending on the observation period. The MAPE and RMSE errors for water vapor pressure deficit are 46.2 % and 0.21 kPa, respectively, which corresponds to satisfactory accuracy. Depending on the observation period, water vapor pressure deficit data can also be obtained with unsatisfactory accuracy. Wind speed data at a height of 2 m, obtained with unsatisfactory accuracy, have MAPE and RMSE errors of 104.3 % and 1.20 m/s, respectively. To improve the accuracy of the meteorological data obtained, correction factors were calculated, and when applied, the accuracy of all meteorological data obtained is improved. The possibility of calculating ET using data from the Visual Crossing Weather Data virtual meteorological station for the period April-September with good accuracy has been confirmed. The MAPE error was 13.7 %, and the RMSE was 0.62 mm. To improve the accuracy of ET calculations in southern Ukraine, a correction factor of 0.95 must be used. Taking this into account, the accuracy of ET calculations for the period May-August increases to 89 %, and the RMSE is 0.63 mm. The use of refined meteorological data reduces the accuracy of ET calculations by 4.8 % and increases the RMSE by 0.15 mm. Based on the results of the research, a web application will be developed to calculate ET and ETc using the FAO56-RM methodology with data from VWS Visual Crossing Weather Data.*

Keywords: *virtual weather station, meteorological data, reference evapotranspiration, accuracy, MAPE and RMSE errors*

Relevance of the research. Currently, data from virtual weather stations (VWS) [1, 2] are increasingly used in various hydrological, environmental, and agricultural modeling programs. There is a growing demand for spatial climate data in digital form [3]. VWS is the integration of algorithms for downloading meteorological data, processing it, and using it to obtain data in nearby locations where there are no meteorological stations [1, 2]. Historically, weather data for modeling has been collected from meteorological weather stations, but they may not be close enough to the specific area being modeled. For these reasons, weather data from virtual meteorological stations can potentially replace or supplement ground-based weather measurements. [4]. To use virtual meteorological stations, it is first necessary to compare the obtained meteorological indicators with the actual ones [5]. Studies conducted around the world confirm the reliability of meteorological data obtained from virtual meteorological stations [1, 6, 7]. The reasons for the differences between data from virtual meteorological stations and measurements at weather stations may be related to spatial and temporal representativeness [8]. Another source of differences between data sets is data obtained from weather stations located at airports and in cities. Air temperature may increase and humidity may decrease at airports due to the predominance of asphalt and other non-watered surfaces. There is virtually no moisture available for evaporation on the pavement, so more solar energy is available to heat the air. This is known as the urban heat island effect. Differences may also be due to the failure to account for water use for irrigation in the land surface water balance models used in data collection systems. In arid regions where irrigation is prevalent, the microclimate near irrigated areas is affected by additional water inflow. Evaporation, which is made possible by the additional water inflow, absorbs solar energy that would otherwise heat the air in adjacent non-irrigated areas. Thus, the microclimate near irrigated areas is cooler and more humid than around non-irrigated land. This effect is called "air conditioning" [8].

To establish the accuracy of meteorological data obtained from virtual weather stations, we chose Visual Crossing Weather Data (VCWD) [4]. It provides access to all climate data necessary for calculating reference evapotranspiration (ETo) worldwide, including forecast data for the next 15 days. All data from the site is available for download via the weather data request page. A comprehensive verification of meteorological data measured by virtual meteorological stations for the conditions of southern Ukraine has not yet been carried out. Therefore, this study was conducted to verify the accuracy and quality of the meteorological data obtained and the calculated ETo from a virtual climate station for the conditions of southern Ukraine.

Analysis of recent studies and publications. Reference evapotranspiration (ETo) is important for water consumption in agriculture. Synoptic data from meteorological stations can provide reliable data for estimating ETo using the Penman-Monteith equation (FAO56-PM). However, the five main variables required by this equation suffer significant losses due to force majeure events [9]. Data loss will directly lead to errors in calculations. To achieve high data quality for calculating daily ET over a long period of time, it is necessary to first analyze the input data for omissions and errors in the records. To do this, algorithms must be selected to take into account different types of data loss and fill them in. Measurements of incoming shortwave solar radiation, air temperature, air humidity, wind speed, and precipitation at weather stations are taken at a height of 2–3 m. Accurate, continuous, and consistent measurements of these variables over years or decades are often lacking due to sensor failure, drift, age, poor calibration, debris, limited station maintenance, communication errors, lack of a sufficiently humid environment, and remote access. As a result, low-quality agricultural weather station data is common, and if not flagged for removal or correction, it will affect the accuracy of reference evapotranspiration calculations [10]. The ability to easily read, visualize, review, flag, and potentially delete, fill in, or correct historical and real-time meteorological data is essential for calculating ET at the local and global levels. Python agweather-qaqc [11] provides the ability to provide fast, thorough, and efficient meteorological data review and quality control for daily meteorological data. Many station networks use different formats for storing and recording meteorological data, and agweather-qaqc is capable of flexibly processing common input data, units of measurement, and formats so that all input data and ETo calculations can be used programmatically.

Air temperature values obtained from virtual meteorological stations are attractive due to the absence of instrumentation costs and the availability of long-term reconstructions of historical records [12]. Air temperature maps for the city of Warsaw (Poland) [13] constructed using machine learning are characterized by lower complexity and higher calculation speed in the field of urban meteorological research. The root mean square error was −1.06 °C, and the coefficient of determination was −0.94, compared to ground-based observations. The average monthly solar radiation and average daily maximum and minimum air temperatures obtained from the network of virtual climate stations of the New Zealand National Institute of Water and Atmospheric Research (NIWA) allow these data to be estimated for landscape points with reasonable accuracy and low error [6]. Studies conducted in the northeastern region of Brazil (Paraíba state) [14] on the assessment of solar radiation indicate that the calculated data from satellite images slightly exceed those observed at ground-based meteorological stations. A comparison of solar radiation data in Albania [15] provided by NASA with ground-based meteorological stations shows that ground-based data are underestimated compared to data provided by the NASA database. The conversion factor is 1.149. An assessment of the accuracy of meteorological data obtained from virtual weather stations for the conditions of Polissya, Ukraine [16], showed that data on average and maximum air temperature, as well as dew point temperature, were obtained with high accuracy. Good accuracy is characteristic of the minimum air temperature and average relative air humidity. Data on solar radiation and water vapor pressure deficit were obtained with satisfactory accuracy. Data on wind speed at a height of 2 m, total monthly and daily precipitation were obtained with unsatisfactory accuracy.

Satellite remote sensing of evapotranspiration (ET) offers a powerful approach for mapping large areas and time scales. Remote sensing ET data have significant potential for sustainable water resource management. However, experts require a reliable and thorough assessment of the accuracy of such data. Comparisons of OpenET [17] results with data from 152 eddy covariance tower stations in the United States showed that the average absolute error over agricultural land for OpenET is 15.8 mm per month, with an average bias error of –5.3 mm per month. Medium-range forecasts of daily reference evapotranspiration (ETo) are very useful for irrigation management. An analysis of artificial neural networks conducted in China [18] for ETo forecasting (FAO56-PM) showed that the correlation coefficients between observed and predicted temperatures for all stations exceeded 0.91, and the accuracy of the minimum temperature forecast ranged from 68.34 to 91.61 %, and for the maximum temperature – from 51.78 to 57.44 %. The accuracy of the ETo forecast ranged from 75.53 to 78.14 %, the average absolute error ranged from 0.99 to 1.09 mm/day, and the root mean square error ranged from 0.87 to 1.36 mm/day. The average correlation coefficient ranged from 0.70 to 0.75. For the conditions of Polissya, Ukraine [19], the accuracy of ETo calculation is 86.1 %, and the RMSE and SEE errors are 0.76 and 0.49 mm, respectively.

The purpose of the study was to evaluate the accuracy of meteorological data obtained from the Visual Crossing Weather Data virtual meteorological station in order to assess the accuracy of ET calculated based on these data and compare them with actual data obtained from the iMetos automated Internet meteorological station from Pessl Instruments.

M**aterials and methods.** The meteorological data for this study were obtained from the Visual Crossing Weather Data (VCWD) [4] for the period from April to September from 2013 to 2021 and from nine iMetos automatic weather stations (AWS) from Pessl Instruments [20], which were located in the Kherson and Zaporizhzhia regions (Table 1).

To analyze and calculate reference evapotranspiration (ET_0), average daily meteorological data were used: average air temperature (Ta) and dew point (Tdew), wind speed (u_2), and total solar radiation (Rs). Reference evapotranspiration was calculated according to the Penman-Monette FAO56-PM method [21] based on VWS VCWD meteorological data:

$$ET_0 = \frac{0,408\Delta\left(R_n - G\right) + \gamma\frac{900}{T+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0,34u_2\right)}, \quad (1)$$

where ET_0 is reference evapotranspiration, mm/day; Rn is net radiation on the plant surface, MJ/m^2·day; G is soil heat flux density, MJ/m$_{(2)}$·day; Ta – average daily air temperature at a height of 2 m, (°) C; $u_{(2)}$ – wind speed at a height of 2 m, m/s; $e_{(s)}$ – saturated vapor pressure, kPa; $e_{(a)}$ – actual pressure, kPa; Δ – vapor pressure gradient, kPa/(°C$^)$; γ – psychrometric constant, kPa/°C.

To calculate e_s and $e_{(a)}$,the values of the average air temperature and dew point were used, respectively. The average wind speed was

1. Location of AWS iMetos from Pessl Instruments

No	Station	District	Region	Latitude	E
1	Antonivka	Skladovskyi	Kherson	46.145	32.956
2	Pryvitne	Kherson		46.374	33.101
3	Novokamyanka	Kakhovka		46.601	33.382
4	Tavrichanka	Kakhovka		46.557	33.828
5	Chervona Polyana	Kakhovka		46.801	33.841
6	Bratske	Henichesk		46.784	34.077
7	Voskresenka	Henichesk		46.595	34.554
8	Velyka Bilozerka	Vasylivskyi	Zaporizhzhia	47.165	34.605
9	Vysokyi	Melitopol		46.813	34.971

converted for a height of 2 m. Other parameters included in formula (1) were calculated according to the FAO56-RM methodology [21].

Meteorological data and calculated reference evapotranspiration were compared with actual data obtained from AWS iMetos.

To assess the accuracy of the meteorological data obtained from VWS VCWD and the calculated reference evapotranspiration, the mean absolute percentage error (MAPE), Root Mean Square Error (RMSE), Standard Error of Estimate (SEE), and accuracy [22–25]:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x-y}{x}\right|\cdot 100\%, \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x-y)^2}, \quad (3)$$

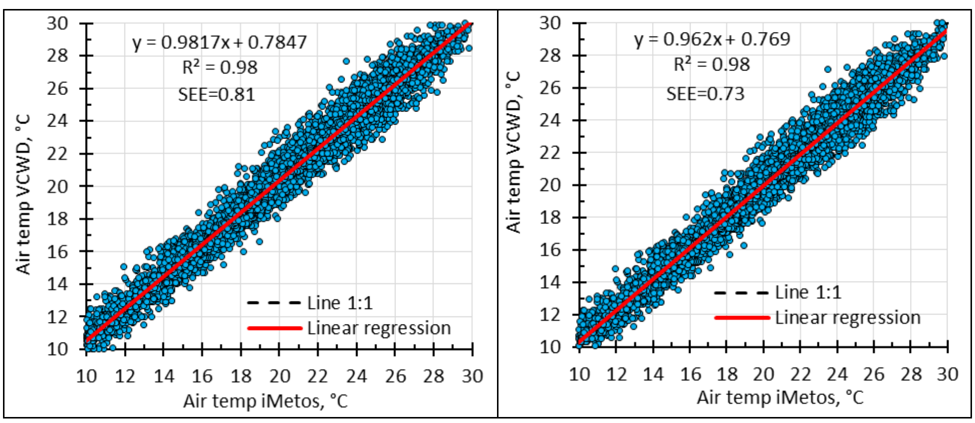
$$SEE = \sqrt{\frac{1}{(n-2)}\left[(y-\bar{y})^2 - \frac{\left[\sum(x-\bar{x})(y-\bar{y})\right]^2}{\sum(x-\bar{x})^2}\right]}, \quad (4)$$

$$Accuracy(\%) = 100\% - MAPE(\%), \quad (5)$$

where x is the meteorological indicator or ET_0according to AWS iMetos data; y is the meteorological indicator or ET_0(FAO56-PM) according to VWS VCWD data; n is the sample size.

Research results. Based on the results of air temperature assessment obtained from VWS Visual Crossing Weather Data and AWS iMetos for the period April-September, it was established that the data was obtained with high accuracy (Fig. 1). The mean absolute percentage error (MAPE) was only 4.5 % [23], and the root mean square error (RMSE) was 0.94 °C (Table 2).

To improve the accuracy of air temperature, a correction factor of 0.98 was calculated. When applied, the accuracy of the data obtained increases (Fig. 1b), and the MAPE and RMSE errors decrease by 0.7 % and 0.13 °C, respectively (Table 2). With the reduction of the observation period to May-August, the MAPE error decreased by 0.9 %, while the RMSE remained almost



a) actual b) refined

Fig. 1. Regression analysis for air temperature verification

2. MAPE and RMSE errors for air temperature, °C

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
1	2	3	4	5	6	7	8
By year							
2013	19.8	20.8	20.4	6.5	5.1	1.40	1.1
2014	19.5	20.4	20.0	6.4	5.3	1.23	1.0
2015	19.4	20.0	19.6	4.0	2.8	0.81	0.58
2016	19.8	20.3	19.9	3.6	2.8	0.87	0.68
2017	19.1	19.4	19.1	4.9	4.5	0.89	0.86
2018	20.7	21.2	20.7	3.6	3.1	0.88	0.77
2019	20.2	20.4	20.0	3.4	3.3	0.79	0.79
2020	19.2	19.6	19.2	4.4	3.9	0.93	0.88
2021	18.4	18.7	18.3	3.2	3.0	0.65	0.62

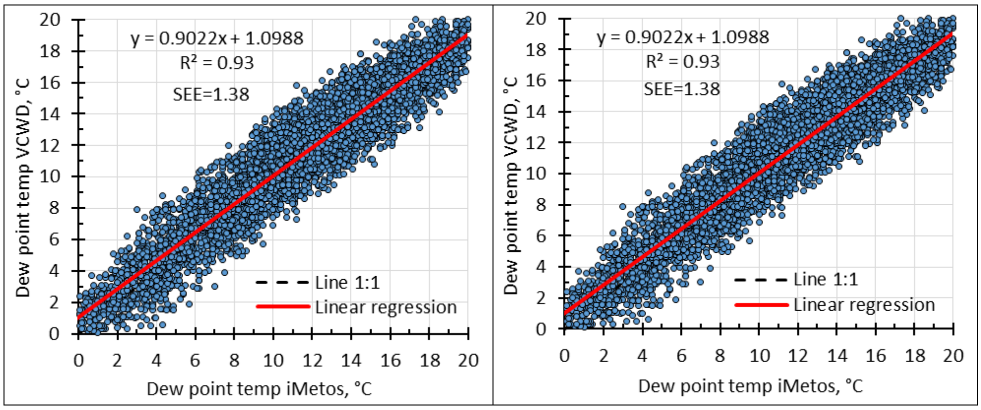
Continuation of Table 2

1	2	3	4	5	6	7	8
By month							
April	10.6	11.1	10.9	8.0	7.07	0.87	0.77
Vay	17.3	17.6	17.3	3.8	3.42	0.83	0.75
June	21.8	22.4	21.9	3.7	3.09	1.03	0.87
July	23.9	24.5	24.0	3.4	2.80	1.0	0.84
August	24.1	24.7	24.2	3.6	2.95	1.06	0.89
September	18.0	18.6	18.2	4.6	3.72	0.95	0.79
April – September	19.6	20.1	19.7	4.5	3.80	0.94	0.81
May – August	21.8	22.3	21.8	3.6	3.0	0.98	0.84
By station							
1	19.2	19.9	19.3	5.0	3.7	1.11	0.83
2	20.3	20.5	20.3	3.7	3.5	0.83	0.80
3	18.47	18.54	18.54	3.5	3.5	0.74	0.74
4	19.33	20.25	19.24	6.1	4.0	1.21	0.82
5	19.84	20.36	19.74	3.9	3.1	0.81	0.66
6	19.51	20.03	19.43	3.7	2.9	0.83	0.64
7	19.24	19.28	19.28	3.6	3.6	0.70	0.70
8	19.47	19.99	19.39	4.3	3.5	0.92	0.76
9	20.34	20.52	20.31	3.2	3.0	0.70	0.69

unchanged. Over the years of observation, the MAPE errors ranged from 3.2 % (2021) to 6.5 % (2013), and the RMSE errors ranged from 0.65 to 1.40 °C, respectively. The smallest MAPE errors were observed in the summer months, and the largest in April. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for air temperature are characteristic of station 9, and the largest – 4 (Table 1). However, despite all the fluctuations in MAPE errors by year, month, and station, they were all less than 10 %, which confirms the high accuracy of the data obtained.

Data for the dew point are obtained with good and satisfactory accuracy (Fig. 2). The MAPE error was 20.9 % [23], and the RMSE was 1.44 °C (Table 3). To improve the accuracy of the dew point temperature, a correction factor of 1.10 was calculated. When applied, the accuracy of the obtained data increases (Fig. 2b), and the MAPE and RMSE errors decrease by 1.4 % and 0.14 °C, respectively. With the reduction of the observation period to May-August, the MAPE error decreased by half, while the RMSE remained almost unchanged. Over the years of observation, the MAPE errors ranged from 8.3 % (2016) to 36 % (2020), and the RMSE errors ranged from 0.96 to 1.67 °C, respectively. The smallest MAPE errors were observed in June and July, and the largest in April. The accuracy of the data obtained also depended on the AWS iMetos and its location. Thus, the smallest errors for dew point temperature are characteristic of stations 2, 3, and 9, and the largest – 7. Dew point temperature data were obtained with good accuracy in 2014–2016, 2018, and 2021, from May to August, and for stations 2–4 and 8–9. For all other periods, the accuracy was satisfactory. It should be noted that the MAPE error for the period May-August, which accounts for almost all irrigation, is 10.8 % (and the refined 9.6 %), which almost corresponds to the high accuracy of the data obtained.

Data for relative air humidity are obtained with high accuracy (Fig. 3). The MAPE error was 9.1 % [23], and the RMSE was 7.53 % (Table 4). To improve the accuracy of relative air humidity, a correction factor of 1.06 was calculated. When the correction factor is applied, the accuracy of the data obtained increases (Fig. 3b), and the MAPE and RMSE errors decrease by 0.7 % and 1.11 %, respectively. With the reduction of the observation period to May-August, the MAPE and RMSE errors remained almost unchanged. Over the years of observation, the MAPE errors ranged from 7.4 % (2016) to 10.9 % (2014), and

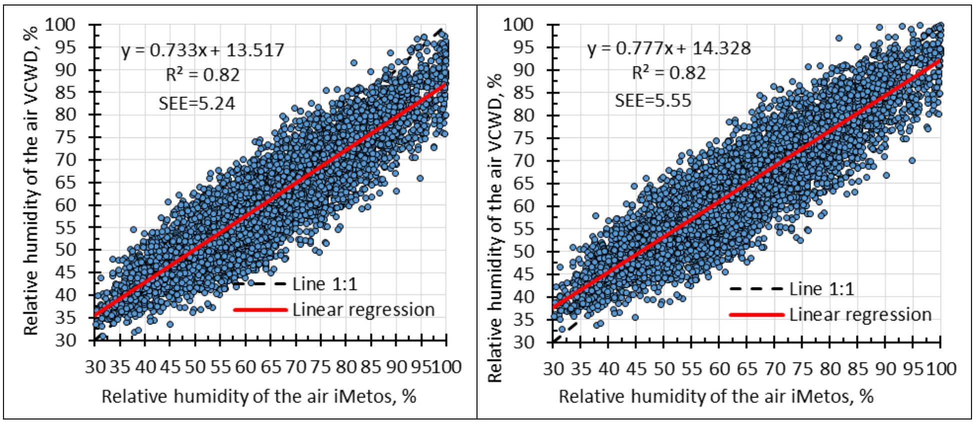


a) actual b) refined

Fig. 2. Regression analysis to verify dew point temperature

3. MAPE and RMSE errors for dew point temperature, °C

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	revised	actual	revised	actual	revised
By year							
2013	11.2	12.2	11.9	24.7	22.6	1.67	1.51
2014	11.1	11.7	11.3	20.8	19.7	1.67	1.57
2015	11.4	11.5	11.1	16.1	16.5	1.12	1.25
2016	12.4	12.3	11.8	8.3	9.4	0.96	1.16
2017	10.2	10.4	10.2	22.2	19.8	1.35	1.11
2018	10.9	11.2	11.1	20.7	17.8	1.61	1.35
2019	11.3	11.5	11.6	22.2	21.5	1.39	1.25
2020	10.2	9.9	9.9	36.0	33.3	1.59	1.30
2021	13.9	12.8	13.2	17.1	15.2	1.65	1.21
By month							
April	4.2	4.2	4.1	36.4	65.1	1.43	1.40
May	10.5	10.4	10.2	14	13.6	1.28	1.26
June	14.3	14.1	13.9	8.2	7.9	1.32	1.26
July	15	15	14.8	8.3	7	1.47	1.22
August	13.1	13.6	13.5	12.7	10.1	1.74	1.40
September	9.5	10.0	9.8	24.6	22.6	1.49	1.33
April – September	11.4	11.5	11.4	20.9	19.5	1.44	1.30
May – August	13.2	13.3	13.2	10.8	9.6	1.45	1.28
By station							
1	13.0	11.3	12.4	28.0	24.0	1.97	1.25
2	11.6	12	11.9	17.2	16.8	1.30	1.26
3	13.34	11.75	12.93	17.5	13	1.87	1.21
4	10.89	11.22	10.66	21.5	20.9	1.48	1.46
5	10.99	11.48	10.90	22.5	21.4	1.19	1.18
6	11.85	11.27	11.72	23.6	23	1.25	1.17
7	9.31	10.40	9.36	36.5	30.7	1.60	1.26
8	11.92	10.98	12.07	18.5	17.7	1.73	1.35
9	11.13	11.34	11.11	17.5	17	1.28	1.28



a) actual b) refined

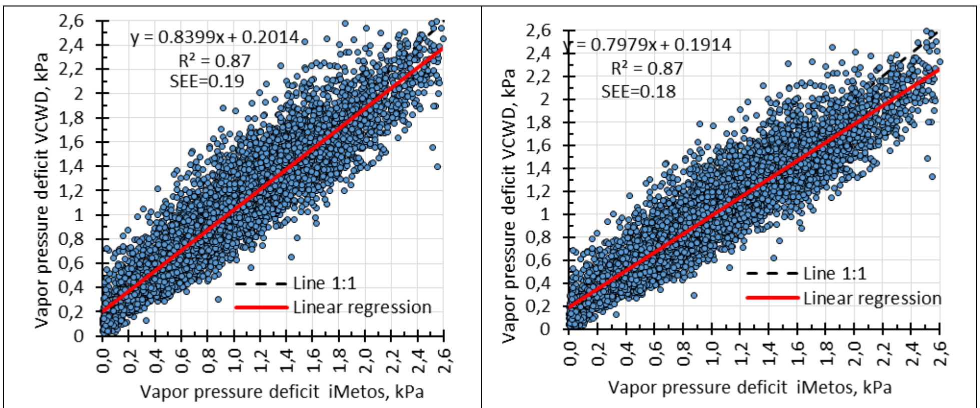
Fig. 3. Regression analysis to verify relative air humidity, %

4. MAPE and RMSE errors for relative air humidity, %

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
By year							
2013	63.0	60.9	64.6	8.8	9.1	6.96	6.71
2014	64.5	60.6	64.2	10.9	10	8.50	7.24
2015	66.9	62.4	66.1	7.6	6	7.07	5.28
2016	66.0	62.1	65.8	7.4	6	6.15	4.77
2017	62.7	60.1	63.7	8.5	8.5	6.64	6.04
2018	59	56.6	60	9.4	9.8	7.01	6.58
2019	63.1	61.0	64.6	8.2	8.8	6.54	6.30
2020	62	58.0	61.4	10.6	9.8	8.29	7.07
2021	76.4	68.7	72.8	10.4	7.2	9.87	7.17
By month							
April	70.6	66.2	70.1	9.4	8.3	8.28	6.82
May	69.7	65.8	69.8	8.2	7.5	7.39	6.18
June	68	62.5	66.3	9.5	7	8.31	6.41
July	63.2	59.2	62.7	9.2	8.3	7.58	6.43
August	56.3	53.9	57.2	9.7	10.2	7.03	6.50
September	63.1	60.8	64.5	8.5	8	6.58	6.18
April – September	65.1	61.4	65.1	9.1	8.4	7.53	6.42
May – August	64.3	60.4	64	9.2	8.4	7.58	6.38
By station							
1	70.7	61.7	71.0	13.0	6.9	10.49	5.88
2	63.1	61.6	62.8	7.8	7.7	6.04	5.76
3	75.18	68.23	75.05	10.2	6.3	8.68	5.74
4	64.55	59.50	64.10	9.8	8.3	8.02	6.30
5	62.19	60.63	61.84	6.3	6	4.87	4.59
6	67.48	61.05	67.77	10.2	6.8	8.32	5.28
7	58.23	60.28	57.87	8.6	7.6	5.57	5.34
8	68.50	60.05	68.46	12.6	7.9	10.73	6.32
9	61.72	59.35	61.14	8	7.8	6.48	5.92

the RMSE errors ranged from 6.15 to 9.87 %, respectively. The smallest MAPE errors were observed in May and September, and the largest in July (9.5 %). The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for relative air humidity are characteristic of stations 5 and 2, and the largest – 1 and 8.

Data for water vapor pressure deficit for the period April-September are obtained with satisfactory accuracy (Fig. 4). The MAPE error was 46.2 % [23], and the RMSE was 0.21 kPa (Table 5). Depending on the observation period and station, data with unsatisfactory accuracy were also obtained. To improve the accuracy of relative air humidity, a correction factor of 0.95 was calculated. When applied, the accuracy of the data obtained increases (Fig. 4b), and the MAPE and RMSE errors decrease by 2.9 % and 0.01 kPa, respectively. With a decrease in the observation period to May-August, the MAPE error decreased by 14.2 %, while the RMSE error remained almost unchanged. Over the years of observation, the MAPE errors ranged from 23 % (2018) to 78.3 % (2015), and the RMSE errors ranged from 0.16 to 0.24 kPa, respectively. The smallest MAPE errors were observed from July to September, and the largest in April. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for water vapor pressure deficit are characteristic of stations 5, 7, and 9, and the largest – 2 and 6. As can be seen from Table 5, even with complete agreement between the data obtained from the automatic and virtual weather stations, the errors in the results obtained are significant. This is due to the averaging of data for this period, while all calculations were performed for daily data.



a) actual b) refined

Fig. 4. Regression analysis to check the water vapor pressure deficit, kPa

5. MAPE and RMSE errors for water vapor pressure deficit, kPa

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
1	2	3	4	5	6	7	8
By year							
2013	1.04	1.10	1.04	29.6	27.4	0.19	0.18
2014	1.03	1.09	1.04	60.3	56.2	0.21	0.21
2015	0.94	1.03	0.98	78.3	72.3	0.16	0.14
2016	1.01	1.10	1.05	26.8	24.1	0.18	0.16
2017	1.07	1.07	1.02	30.6	29.0	0.22	0.24
2018	1.21	1.22	1.16	23	22.3	0.24	0.25
2019	1.08	1.06	1.01	32.7	31.9	0.22	0.23
2020	1.07	1.10	1.05	30.1	28.7	0.23	0.24
2021	0.73	0.82	0.78	67.8	62.9	0.21	0.19
By month							
April	0.46	0.50	0.47	83.1	77.2	0.13	0.13
May	0.72	0.77	0.73	41.8	39.0	0.17	0.16
June	1.03	1.13	1.07	37.8	34.5	0.24	0.22

Continuation of Table 5

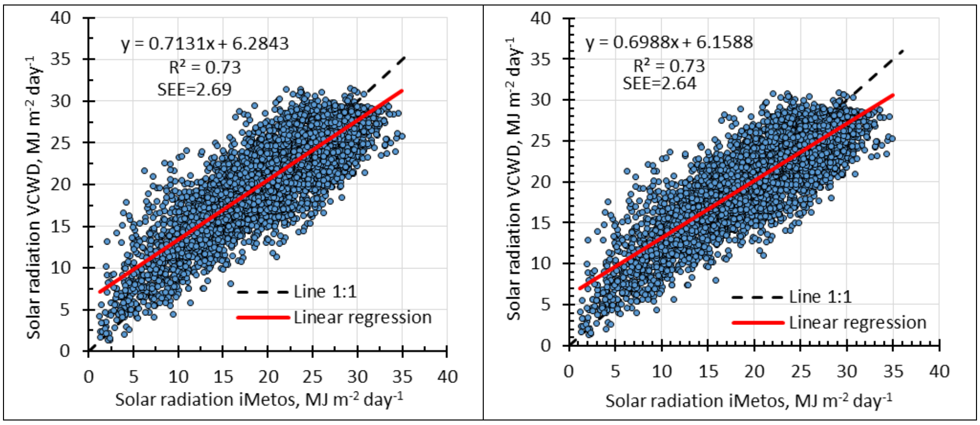
1	2	3	4	5	6	7	8
July	1.29	1.36	1.29	26.6	24.6	0.25	0.24
August	1.52	1.55	1.47	21.8	20.9	0.25	0.26
September	0.94	0.94	0.89	28.4	26.9	0.17	0.18
April – September	1.02	1.07	1.01	46.2	43	0.21	0.20
May – August	1.14	1.20	1.14	32	29.8	0.22	0.22
By station							
1	0.77	1.05	0.75	53.5	25.1	0.35	0.18
2	1.08	1.09	1.06	64.4	62.2	0.17	0.17
3	0.69	0.80	0.70	42.8	33.9	0.20	0.15
4	1.01	1.11	0.97	50.3	41.3	0.19	0.19
5	1.11	1.08	1.13	16.2	16.8	0.17	0.17
6	0.76	0.83	0.75	76.5	67.4	0.17	0.17
7	1.20	1.03	1.17	20.6	18.7	0.27	0.18
8	1.0	1.07	0.91	55.8	48.5	0.22	0.24
9	1.11	1.12	1.06	29.2	28.1	0.18	0.20

Data for solar radiation are obtained with good accuracy (Fig. 5). The MAPE error was 17.4 % [23], and the RMSE was 3.41 MJ/m²·day (Table 6). To improve the accuracy of solar radiation, a correction factor of 0.98 was calculated. When the correction factor is applied, the accuracy of the data obtained increases (Fig. 5b), and the MAPE and RMSE errors decrease by 0.6 % and 0.06 MJ/m²·day, respectively. With the reduction of the observation period to May-August, the MAPE error decreased by 2.3 %, while the RMSE error remained almost unchanged. Over the years of observation, the MAPE errors ranged from 12.2 % (2019) to 26.8 % (2014), and the RMSE errors ranged from 2.80 to 4.85 MJ/m²·day, respectively. The smallest MAPE errors were observed in July and August, and the largest in April and September. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for solar radiation are characteristic of stations 1 and 2, and the largest for stations 3 and 4.

Automatic weather stations measure wind speed in m/s at a height of 2 m, while virtual weather stations measure wind speed in km/h at a height of 10 m. Therefore, the obtained wind speed data must be converted to m/s for a height of 2 m [21]. The wind speed data is obtained with unsatisfactory accuracy (Fig. 6). The MAPE error was 104.3 % [23], and the RMSE was 1.2 m/s (Table 7). To improve the accuracy of wind speed, a correction factor of 0.64 was calculated. When applied, the accuracy of the data obtained increases (Fig. 5b), and the MAPE and RMSE errors decrease by 55.9 % and 0.42 m/s, respectively. With a reduction in the observation period to May-August, the MAPE error increased by 5.2 %, and the RMSE error remained almost unchanged. Over the years of observation, the MAPE errors ranged from 73.5 % (2013) to 137 % (2014), and the RMSE errors ranged from 0.9 to 1.75 m/s, respectively. The smallest MAPE errors were observed in April and July, and the largest in June and August. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest error for wind speed is characteristic of station 5, and the largest – of station 2. According to data from the Askania-Nova state weather station, the average wind speed at a height of 2 m for the period April-September is 2.5 m/s [26].

Table 7 shows that the data from the virtual station is more reliable. This may be due to the incorrect installation of automatic stations, in which wind speed sensors may be located in the vicinity of buildings or trees.

Currently, the Penman-Monette FAO56-PM method [21] is widely used for irrigation management. The Visual Crossing Weather Data virtual meteorological station provides access to all the climate data needed to calculate ET. Based on the results of the assessment of the calculated reference evapotranspiration using meteorological data obtained from VWS Visual Crossing Weather Data for the period April-September, its good accuracy was established (Fig. 7). The average absolute percentage error was 13.7 % [23], and the root mean square error was 0.62 mm (Table 8).

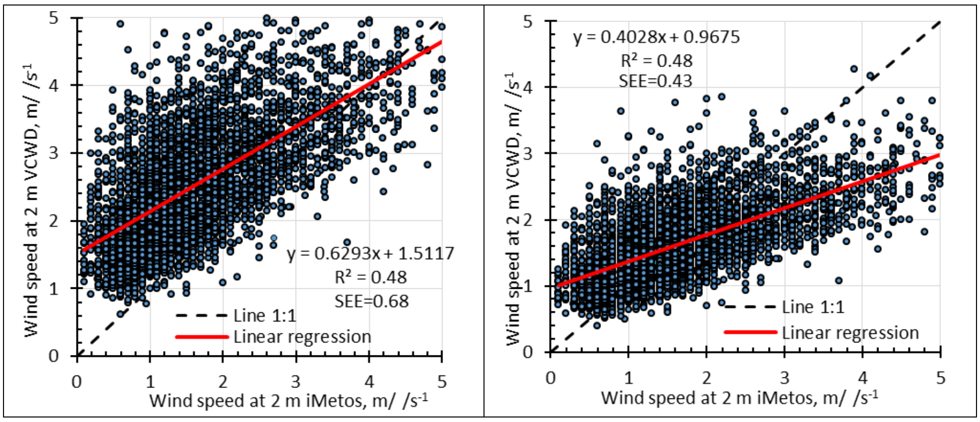


a) actual b) refined

Fig. 5. Regression analysis for checking solar radiation, MJ/m^2 ·day

6. MAPE and RMSE errors for solar radiation, MJ/m²·day

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
By year							
2013	19.23	22.78	22.33	25.5	23.5	4.71	4.36
2014	18.67	22.34	21.89	26.8	24.9	4.85	4.50
2015	19.24	20.60	20.19	15.1	14.2	2.95	2.79
2016	18.78	19.84	19.44	17.3	16.4	3.10	2.98
2017	20.82	21.00	20.58	16.6	16.4	2.94	2.96
2018	21.33	21.76	21.32	14.3	14	3.0	2.98
2019	21.71	21.08	20.66	12.2	12.6	2.80	2.94
2020	21.90	21.21	20.78	12.4	12.8	2.98	3.13
2021	20.20	19.70	19.30	16.2	16.4	3.38	3.47
By month							
April	17.08	18.82	18.44	25	24.6	3.84	3.69
May	21.13	22.02	21.58	15.2	14.6	3.44	3.35
June	22.84	23.55	23.08	16.8	16	3.91	3.84
July	23.34	23.98	23.51	13.9	13.5	3.52	3.46
August	20.85	21.52	21.09	14.6	14.3	3.20	3.13
September	14.59	15.71	15.39	19.4	18.6	2.91	2.79
April – September	20.21	21.14	20.72	17.4	16.8	3.41	3.35
May – August	22.04	22.77	22.31	15.1	14.7	3.52	3.44
By station							
1	25.05	22.88	25.17	10	8.6	3.35	2.54
2	20.74	22.02	20.70	11	9.8	2.60	2.27
3	21.91	19.97	21.97	19.5	18	4.23	3.62
4	18.26	21.21	18.24	26.9	18	4.47	3.27
5	20.55	20.68	20.68	14.8	14.8	2.94	2.94
6	21.08	20.19	21.20	18.1	13.1	3.15	3
7	20.93	20.76	20.76	17.4	14.6	2.81	2.81
8	20.68	20.26	20.46	14.3	14.3	2.92	2.89
9	20.48	20.81	20.39	14.3	14.1	2.86	2.85



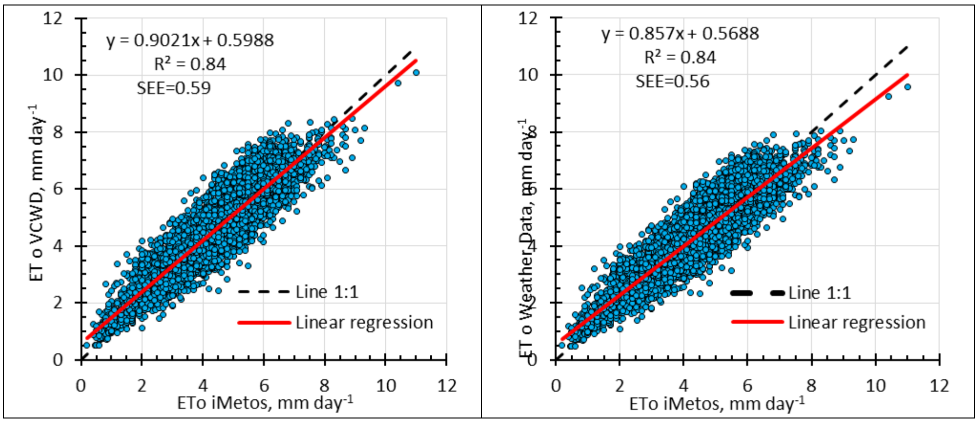
a) actual b) refined

Fig. 6. Regression analysis to verify wind speed, m/s

7. MAPE and RMSE errors for wind speed, m/s

Date/time	iMetos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
By year							
2013	2,05	3,12	1,99	73,5	29,1	1,31	0,70
2014	1,79	3,16	2,02	137,1	121,3	1,75	1,08
2015	1,66	2,48	1,59	128,1	62,6	1,07	0,78
2016	1,80	2,36	1,51	56,9	31,3	0,90	0,84
2017	1,83	2,60	1,67	74,0	33,6	1,09	0,83
2018	1,65	2,43	1,55	80,9	35,3	1,12	0,80
2019	1,41	2,45	1,57	94,4	30,9	1,17	0,46
2020	1,52	2,41	1,54	107,0	45,6	1,16	0,79
2021	1,53	2,35	1,51	103,6	47	1,09	0,70
By month							
April	2,24	2,86	1,83	81,5	49,5	1,09	1,11
May	1,69	2,53	1,62	106,2	51,5	1,10	0,71
June	1,43	2,46	1,58	118,8	49,2	1,23	0,59
July	1,46	2,37	1,51	96,4	39,3	1,11	0,58
August	1,65	2,59	1,66	116,5	53,7	1,26	0,80
September	1,77	2,80	1,79	106,3	47	1,38	0,86
April – September	1,71	2,60	1,67	104,3	48,4	1,20	0,78
May – August	1,56	2,49	1,59	109,5	48,4	1,18	0,67
By station							
1	-	-	-	-	-	-	-
2	1,35	2,65	1,33	169,4	58,4	1,54	0,66
3	2,10	2,54	2,06	55,5	39,7	1,0	0,92
4	2,32	2,75	2,28	56,4	42,5	0,84	0,72
5	2,06	2,38	2,02	33,5	24	0,63	0,57
6	1,77	2,37	1,73	52,6	27,3	0,81	0,57
7	1,39	2,48	1,36	101,0	27,4	1,22	0,48
8	1,43	2,38	1,43	66,6	37,2	0,60	0,51
9	1,25	2,41	1,25	133,3	41,9	1,34	0,54

Note: Wind speed was not measured at station 1.



a) actual b) refined

Fig. 7. Regression analysis for ET verification, mm/day

8. MAPE and RMSE errors for reference evapotranspiration, mm

Date/time	Metos	VCWD		MAPE		RMSE	
		actual	refined	actual	revised	actual	revised
By year							
2013	4,69	4,94	4,70	16,2	14,7	0,75	0,70
2014	4,55	4,88	4,64	15,3	13,3	0,72	0,64
2015	4,38	4,35	4,13	12,2	12,1	0,55	0,62
2016	4,22	4,34	4,13	12,5	11,9	0,61	0,59
2017	4,29	4,45	4,22	12,8	11,8	0,60	0,57
2018	4,58	4,80	4,56	13,7	12,3	0,71	0,66
2019	4,32	4,50	4,27	11,7	10,6	0,56	0,52
2020	4,25	4,47	4,24	13,9	12,3	0,63	0,58
2021	3,85	3,94	3,75	14,4	13,9	0,59	0,58
By month							
April	2,89	2,92	2,77	16,6	15,87	0,48	0,51
May	4,11	4,17	3,97	11,8	11,43	0,54	0,56
June	4,93	5,18	4,92	13,2	12,09	0,72	0,66
July	5,29	5,52	5,24	11,5	10,48	0,69	0,64
August	5,12	5,35	5,08	12	10,79	0,7	0,66
September	3,26	3,46	3,29	17,3	15,40	0,62	0,58
April – September	4,27	4,43	4,21	13,7	12,7	0,62	0,60
May – August	4,86	5,05	4,80	12,1	11,2	0,66	0,63
By station							
1	4,62	4,74	4,60	8,6	7,9	0,45	0,43
2	4,52	4,68	4,54	12,1	11,4	0,58	0,56
3	4,12	3,9	4,06	13,9	13,7	0,59	0,54
4	4,39	4,63	4,36	15,8	13,8	0,72	0,67
5	4,55	4,39	4,56	11	10,7	0,57	0,55
6	4,34	4,31	4,36	10,9	11	0,52	0,52
7	4,12	4,35	4,13	12,1	10,5	0,57	0,5
8	3,93	4,36	3,92	16,5	11,2	0,64	0,47
9	4,06	4,53	4,08	16,5	12,5	0,76	0,57

To improve the accuracy of reference evapotranspiration, a correction factor of 0.95 was calculated. When the correction factor is applied, the accuracy of the data obtained increases (Fig. 7b), and the MAPE and RMSE errors decrease by 1 % and 0.02 mm, respectively. With the reduction of the observation period to May-August (when almost all irrigation is carried out), the MAPE error decreased by 1.6 %, and the RMSE remained almost unchanged. Over the years of observation, the MAPE errors ranged from 11.7 % (2019) to 16.2 % (2013), and the RMSE errors ranged from 0.59 to 0.75 mm, respectively. The smallest MAPE errors were observed in May and July, and the largest in April and September. The accuracy of the data obtained also depended on the iMetos station and its location. Thus, the smallest errors for reference evapotranspiration are characteristic of stations 1, 5, and 6, and the largest are characteristic of stations 8 and 9.

Despite all the errors in the input data analyzed above, the accuracy of ET calculations based on data from the Visual Crossing Weather Data virtual weather station is 86 %, and the RMSE error is 0.62 mm. Applying a correction factor for the May-August period increases the accuracy of calculations to 89 %. The comparative analysis confirms the possibility of using meteorological data from VWS Visual Crossing Weather Data to calculate ETo for the purpose of further calculating the actual evapotranspiration (ETc) of agricultural crops using the FAO56-PM methodology [21].

The use of refined meteorological data should have increased the accuracy of ET calculations, but the MAPE and RMSE errors, on the contrary, increased by 4.8 % and 0.15 mm, respectively. Only for 8 stations was a decrease in MAPE and RMSE errors recorded, by 6.1 % and 0.17 mm, respectively. In our opinion, this is due to the fact that the correction coefficients were different for each station, and the use of the average coefficient did not lead to the desired result. Also, the use of a separate correction coefficient for each meteorological indicator causes technical difficulties in mass ET calculations. Therefore, the use of a single correction coefficient of 0.95 for the conditions of southern Ukraine in ET calculations is a more rational solution.

Conclusions.

1. Based on the analysis of meteorological data obtained from the Visual Crossing Weather Data virtual meteorological station, their accuracy has been established. Thus, data on air temperature and relative humidity are received with high accuracy, with MAPE and RMSE errors of 4.5 % and 0.94 °C and 9.1 % and 7.53 %, respectively.
2. Dew point temperature and solar radiation are characterized by good accuracy, with MAPE and RMSE errors of 20.9 % and 1.44 °C and 17.4 % and 3.41 MJ/m²·day, respectively. Dew point temperature data can also be obtained with satisfactory accuracy depending on the observation period.
3. The MAPE and RMSE errors for water vapor pressure deficit are 46.2 % and 0.21 kPa, respectively, which corresponds to satisfactory accuracy. Depending on the observation period, water vapor pressure deficit data can be obtained with unsatisfactory accuracy.
4. Wind speed data at a height of 2 m obtained with unsatisfactory accuracy, with MAPE and RMSE errors of 104.3 % and 1.2 m/s, respectively.
5. To improve the accuracy of the meteorological data obtained, correction factors were calculated, and when applied, the accuracy of all meteorological data obtained is improved.
6. The results of the research confirm the possibility of calculating ET using data from the Visual Crossing Weather Data virtual meteorological station for the period April-September with good accuracy. The MAPE and RMSE errors were 13.7 % and 0.62 mm, respectively.
7. To improve the accuracy of ET calculations in southern Ukraine, a correction factor of 0.95 should be used. Taking this into account, the accuracy of ET calculations for the period May-August increases to 89 %, and the RMSE is 0.63 mm.
8. The use of refined meteorological data reduces the accuracy of ET calculations by 4.8 % and increases the RMSE by 0.15 mm.
9. Based on the results of the research, a web application will be developed to calculate ETo and ETS using the FAO56-RM methodology with data from VWS Visual Crossing Weather Data.

Conflicts of interest: the authors declare no conflict of interest.

Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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УДК 631.67

ОЦІНКА ТОЧНОСТІ МЕТЕОРОЛОГІЧНИХ ДАНИХ, ОТРИМАНИХ З ВІРТУАЛЬНОЇ МЕТЕОСТАНЦІЇ З МЕТОЮ ОЦІНКИ ET_O ДЛЯ УМОВ ПІВДНЯ УКРАЇНИ

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Анотація. *У статті наведено оцінювання точності метеорологічних даних, які отримуються з віртуальної метеорологічної станції Visual Crossing Weather Data (VWS VCWD) та розрахункової еталонної евапотранспірації (ETo) за цими даними для умов Півдня України. Встановлено, що дані температури й відносної вологості повітря, отримуються з високою точністю, похибки MAPE та RMSE яких відповідно становлять 4,5 % та 0,94 °C й 9,1 % та і 7,53 %. Для температури точки роси й сонячної радіації притаманна добра точність, похибки MAPE та RMSE яких відповідно становлять 20,9 % та 1,44 °C й 17,4 % та 3,41 МДж/м²·доб. Дані температури точки роси також можуть бути отримані із задовільною точністю залежно від періоду спостережень. Похибки MAPE та RMSE для дефіциту тиску водяної пари відповідно становлять 46,2 % та 0,21 кПа, що відповідає задовільний точності. Залежно від періоду спостережень дані дефіциту тиску водяної пари також можуть бути отримані із незадовільною точністю. Дані про швидкість вітру на висоті 2 м, отримано з незадовільної точністю, похибки MAPE та RMSE відповідно становлять 104,3 % та 1,20 м/с. Для підвищення точності отриманих метеорологічних даних були розраховані поправочні коефіцієнти, за умови їх застосування точність всіх отриманих метеорологічних даних підвищується. Підтверджено можливість розрахунку ETo за даними віртуальної метеорологічної станції Visual Crossing Weather Data за період квітень-вересень з доброю точністю. Похибка MAPE становила 13,7 %, а RMSE – 0,62 мм. Для підвищення точності розрахунку ETo в умовах Півдня України необхідно використовувати поправочний коефіцієнт, який становить 0,95. З урахуванням якого точність розрахунку ETo за період травень-серпень підвищується до 89 %, а RMSE становить 0,63 мм. Використання уточнених метеорологічних даних знижують точність розрахунку ETo на 4,8 %, а RMSE підвищують на 0,15 мм. За результатами проведених досліджень буде розроблено веб додаток для розрахунку ETo та ETc за методикою FAO56-PM з використанням даних з VWS Visual Crossing Weather Data.*

Ключові слова: *віртуальна метеостанція, метеорологічні дані, еталонна евапотранспірація, точність, похибки MAPE та RMSE*