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Influence of synoptic weather conditions on atmometers on the Delmarva Peninsula, USA

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A R T I C L E I N F O

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A B S T R A C T

Reference evapotranspiration data from atmometers at three locations on the Delmarva Peninsula (USA) were compared to Penman-Monteith reference evapotranspiration (ET_o) data across two growing seasons. Atmometer reference evapotranspiration (ET_a) was found to underestimate ET_o by 22.8% in 2016 and 30.4% in 2017. Stepwise linear regression was used to examine the relationship between both ET datasets and local meteorological conditions measured by Delaware Environmental Observing System (DEOS) mesonet stations that were co-located with the atmometers. Variability of ET_a and ET_o are well explained (R^2 equal to 0.890 and 0.956, respectively) by a combination of meteorological variables, though the R^2 in 2017 ($R^2 = 0.754$) was notably lower than in 2016 ($R^2 = 0.890$). The ET datasets were further examined by partitioning the data into days with similar synoptic conditions using a temporal synoptic index (TSI). Using the TSI results, three dominant synoptic categories were defined during the study period: High Pressure (HP), Southwest Flow (SW), and Cold Fronts (CF). Overall, the similarity between ET_a and ET_o was greatest on HP days, followed by CF and SW days. This relationship was primarily driven by wind speed, which had the greatest influence on ET_a-ET_o differences under all synoptic weather patterns. The 2016 growing season consisted of more days with synoptic conditions that are associated with smaller ET_a -ET_o differences than the 2017 growing season. Thus, changes in synoptic category frequency impact the nature of the ET_a-ET_o relationship from season to season. This study improves upon previous atmometer comparison studies by associating atmometer correction factors with synoptic weather patterns and descriptions in order to improve the utility of atmometers and remove the need for expensive meteorological equipment to correct atmometer data.

1. Introduction

Irrigation is crucial to agricultural production and ensuring food security throughout the world (Carruthers et al., 1997). As farmland is increasingly converted to irrigated agriculture, more pressure will be placed on limited water resources (Pimentel et al., 2004). Thus, access to affordable, field-specific weather and climate information that optimizes irrigation is critical to the sustainability of irrigated agriculture and water resources. On the Delmarva peninsula, a region on the mid-Atlantic coast of the United States bounded by the Chesapeake Bay, Delaware Bay, and the Atlantic Ocean, irrigated agriculture has increased significantly in recent decades. Across the 14 counties that comprise the Delmarva peninsula, irrigated farmland has increased by 54.5% between 2002 and 2017 with 290,211 acres under irrigation (USDA National Agricultural Statistics Service 2022). In Delaware, a state located on the Delmarva peninsula, most irrigation decision makers utilize crop condition or soil "feel" methods to make irrigation decisions, however, approximately 8.4% leverage reference evapotranspiration (ET) data directly or from systems that provide reference ET data from mesoscale weather networks (mesonets) such as the Delaware Environmental Observing System (DEOS) to make irrigation decisions (USDA National Agricultural Statistics Service 2022). Therefore, the vast majority of Delaware farmers do not utilize sensors or reference ET data to make irrigation decisions, likely due to a lack of access to inexpensive, field-specific ET data. Operating mesonet-quality weather stations, like DEOS stations, to gather the data required to calculate reference ET is expensive, often with thousands of dollars in recurring costs per station. In addition, these types of stations require regular maintenance and well-sited locations to accurately reflect the mesoscale environment (Fiebrich et al., 2020). Due to the cost and

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maintenance, it is often impractical for agricultural producers to operate a weather station like those employed by mesonets to determine their irrigation needs. Thus, it is necessary to determine the utility and limitations of other, lower-cost means for quantifying reference evapotranspiration (ET) for irrigation management so as to properly utilize the finite water resources available on the Delmarva peninsula, while maximizing crop yield and ensuring the sustainability of farms.

Atmometers, often referred to as ET gauges, are scientific instruments that measure the rate of evaporation of a given surface (Livingston, 1915). Modern versions of these instruments utilize a porous plate design with a fabric-covered, ceramic cup that wicks distilled water from a reservoir into the atmosphere so as to simulate evapotranspiration. The fabric cover can be made of different materials in order to mimic the albedo and vapor emissivity of different reference vegetation surfaces. Most atmometer designs cost significantly less than a full meteorological station capable of measuring the parameters needed to compute reference evapotranspiration for a short grassy surface (ET_o), thus they provide a low-cost alternative to estimating crop water demand and irrigation requirements that is readily accessible to irrigation decision-makers.

Previous studies involving atmometers have compared their accuracy to common model-based methods for estimating reference ET, such as Jensen et al. (1990) or Allen et al. (1998). In some cases, the differences were considerable and varied. Gavilán and Castillo-Llanque (2009) reported a 9% underestimate of ET_o in a semi-arid area in Spain, while Alam and Elliott (2003) showed that atmometers slightly overestimated reference ET for an alfalfa reference surface (ET_r) by 4% in their semi-arid study area in Kansas. Meanwhile, Knox et al. (2011) found atmometers in a humid region of the United Kingdom underestimated ET_o by 17% on average across four growing seasons. In fact, many studies in humid locations of the United States (Florida, North Carolina, Missouri, and Arkansas) have also reported underestimates of reference ET, with differences ranging from 12 to 27.5% (Chen and Robinson, 2009; Diop et al., 2015; Irmak et al., 2005; Straatmann et al., 2018). Several of these studies found significant differences between atmometer values and reference ET in humid regions when precipitation or high wind speeds occurred. Some of these studies addressed these differences by developing statistical relationships using meteorological parameters to calibrate the atmometer measurements of reference ET to approximate modeled estimates of reference ET (Chen and Robinson, 2009; Diop et al., 2015; Gleason et al., 2013). These studies also recommended that data from atmometers be calibrated using local weather data before use in applications such as irrigation scheduling. Given that one of the potential benefits of atmometers is reducing the dependency on weather data from more expensive weather stations to determine reference ET, requiring weather data to calibrate the atmometer data may be impractical for many users (i.e., farmers, water resource managers, etc.). Rather, it is necessary to develop a robust understanding of atmometer performance relative to weather patterns, particularly large-scale, synoptic weather patterns. While many studies have examined the influence of local weather conditions on atmometer accuracy, the influence of synoptic-scale weather conditions on atmometer accuracy has yet to be explored. Understanding the influence of synoptic weather conditions on this relationship is important, as synoptic weather conditions define the large-scale thermal and moisture regimes that drive the day-to-day variations in reference ET. Thus, synoptic-scale weather conditions, along with commonly used weather terminology ascribed to such conditions, can offer a practical way to adjust atmometer measured ET_o to improve ET-driven activities, such as irrigation scheduling.

2. Data and methods

2.1. Reference evapotranspiration data

This study examined the relationship between atmometer measured and model estimated ET_o at three locations (Georgetown, Harbeson, and Seaford) in Sussex County, Delaware, USA (Fig. 1). These three sites were chosen because existing Delaware Environmental Observing System (DEOS) meteorological stations were in place with similar siting conditions near agricultural fields, which is the most relevant application for atmometer use in Delaware.

Located on the Delmarva Peninsula, Sussex County is the southernmost of three counties in Delaware (USA) with a humid, temperate climate characterized by an average temperature of 20.2 °C and total precipitation of 705 mm during the typical growing season (April – October) (Applied Climate Information Systems, 2022). Daily reference evapotranspiration (ET_o) for each location was estimated using the United Nations Food and Agriculture Organization (FAO) Penman-Monteith method for a reference grass surface defined in its Irrigation and Drainage Paper No. 56, hereafter known as FAO56-PM (Allen et al., 1998), which is given by,

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

where ET_o is reference evapotranspiration for short grassy surfaces (mm day^{-1}); R_n is net radiation (MJ m^{-2} day^{-1}); G is soil heat flux density (and $G = 0$ at daily time steps); T is mean daily air temperature (°C); u_2 is mean daily wind speed (m s^{-1}); γ is the psychrometric constant (kPa °C^{-1}); Δ is the slope of the saturation vapor pressure temperature curve

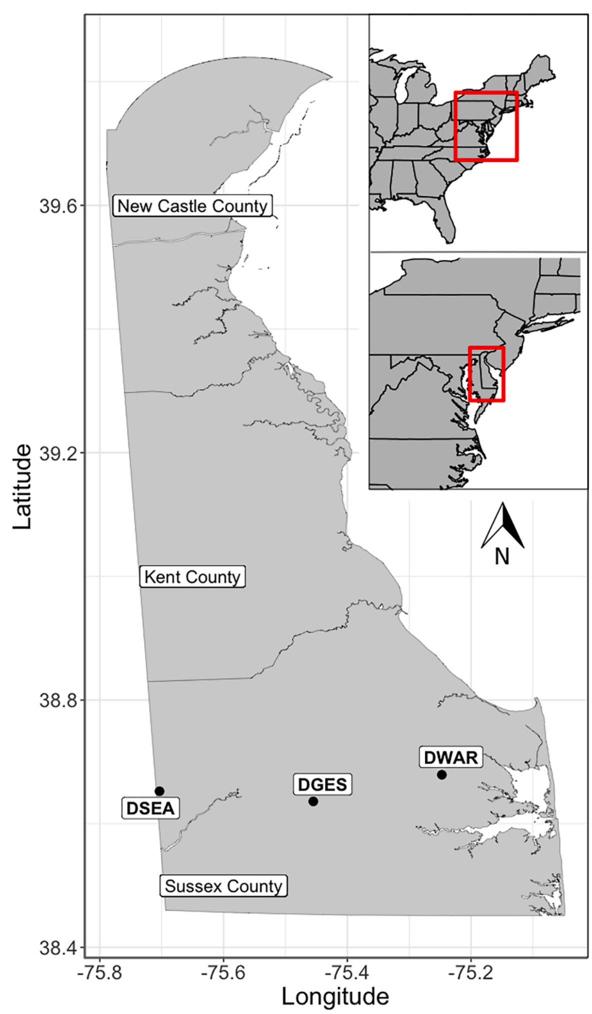

Fig. 1. Map of study area (Sussex County, Delaware, USA) showing the location of the three DEOS meteorological stations used in this study (DSEA - Seaford, DE; DGES - Georgetown, DE; DWAR - Harbeson, DE).

(kPa °C^{-1}); e_s is saturation vapor pressure (kPa); e_a is the mean actual vapor pressure at 2 m height (kPa). Daily meteorological data from DEOS mesonet stations at each study location were used as inputs into the FAO56-PM equation to compute ET_o. DEOS stations measure wind speed and incoming solar radiation at 3 m, while temperature and relative humidity measurements are measured at 2 m (Fig. 2; Leathers et al., 2020).

Since the FAO56-PM method for estimating ET_o is sensitive to wind speed, an analysis was performed to determine the difference between estimating ET_o using wind speed data from the standard DEOS anemometer height (3 m) and ET_o using estimated wind speed data at the height of the atmometer (1 m). The bias in ET_o was found to be negligible over the course of both growing seasons at approximately 20 mm per season. Therefore, no adjustments were deemed necessary to account for the height differences between the anemometer and the atmometer in this study.

Automated Model E atmometers from the ET Gage Company in Loveland, CO (USA) were used to take 30-minute reference ET measurements at each study location during the 2016 and 2017 growing seasons. The 30-minute reference ET data were subsequently aggregated for each day in the study period to create a daily time series of atmometer-measured reference evapotranspiration (ET_a). Each atmometer was outfitted with a #30 cover, which approximates the albedo and vapor emissivity of a short-grass reference surface, to simulate ET_o and connected to the datalogger pulse channel of the co-located mesonet station for data collection and storage. The atmometers were installed at a height of approximately 1 m per the manufacturer's recommendation. Atmometer data were collected from June 9th through August 31st of 2016 and 2017, approximately the peak of the irrigation season across the Delmarva Peninsula.

Fig. 2. Example of DEOS meteorological station used in this study (Station at Seaford, DE shown here). The atmometer (white cylinder object on the left) was installed similarly at each site - mounted to a 4 × 4 wooden post approximately one meter high over a managed reference (grassy) surface.

2.2. *Temporal synoptic index (TSI)*

To determine the synoptic-scale atmospheric patterns associated with daily evapotranspiration, a Temporal Synoptic Index (TSI) approach was utilized (Kalkstein and Corrigan, 1986). The TSI uses meteorological observations from a single meteorological station to infer the synoptic-scale atmospheric pattern over a large region, in this case, the Mid-Atlantic region of the United States. The TSI has been used in a variety of other studies including pollution associated with aerosols and ozone (Brodie et al., 2017; Davis, 1991; Kalkstein and Corrigan, 1986), snowfall and snow ablation (Ellis and Leathers, 1996; Leathers and Ellis, 1996; Suriano, 2019), and the effects of atmospheric circulation on stream chemistry (Siegert et al., 2021). Four times daily (0900, 1500, 2100, 0300 UTC) meteorological observations of temperature, dew point temperature, sea level pressure, u and v wind components, and cloud cover were obtained for Philadelphia, PA, (WBAN 13739) the closest long-term, hourly observation site to Sussex County, DE with complete data for the period 1948 - 2021. An R-mode Principal Components Analysis (PCA) was conducted (unrotated) on the meteorological observations to determine the main modes of variability for each climatological season: winter (DJF), spring (MAM), summer (JJA), and autumn (SON). The PCA was conducted seasonally to limit variance due to the annual cycle (Siegert et al., 2021). PCA is a method to reduce the dimensionality of large datasets. The PCA procedure produces principal components; a set of new variables that are created by a linear combination of the original variables. The number of principal components retained for further analysis is less than the number of original variables, thus reducing the dimensions of the original dataset. In the case of the PCA for Philadelphia, five principal components were retained for each season (eigenvalues greater than 1.0) reducing the number of variables from 24 (six meteorological variables four times daily) to five principal components. For each season, the five principal components retained for further analysis explained 75% to 80% of the variance of the original dataset. A value for each principal component, the component score, was produced for each day. Within-group average linkage clustering is subsequently applied to the daily unrotated principal component scores (p-scores) to cluster days with similar scores into distinct synoptic types. The TSI produces a daily synoptic calendar so that each day from 1948 through 2021 is classified as a specific synoptic weather type. It is important to note that only summer synoptic weather types were evaluated in this study in order to coincide with the majority of the agricultural irrigation season on the Delmarva Peninsula. It is also important to mention that PCA and cluster analysis are used only in the TSI approach for defining a calendar of synoptic weather types during the study period and are used nowhere else in the subsequent analysis.

2.3. *Regression analysis and statistics*

Much of the analysis used in this study consisted of various regression techniques, particularly stepwise linear regression (SLR), to explore the influence of local meteorological and synoptic conditions on ET_a, ET_o, and the daily ET difference (ETD), such that

$$ETD = (ET_a - ET_o),$$

in millimeters. SLR is a multivariate regression approach that allows for a large set of explanatory variables to be reduced to a smaller subset of relevant variables that explain the majority of the variability (SAS Institute, 2021). Furthermore, the stepwise approach of SLR allows for relevant variables to be added to a regression model one at a time while providing for the total amount of variability explained by the combination of variables at each step. In this study, SLR was used to understand how the relationship between reference ET data (e.g., ET_o, ET_a, and ETD) and all associated local meteorological parameters measured at each station, including: air temperature, relative humidity, solar radiation, wind speed, rainfall, a binary rain / no rain indicator, and the volumetric water content of the soil at 5 cm, varied for each year of the study. This included examining the order of importance for each of the micrometeorological parameters, as well as the overall amount of variance explained by each SLR equation for each reference ET parameter for each year of the study. This same process was repeated following the partitioning of all daily reference ET data by synoptic category using the TSI synoptic calendar to define the synoptic category for each day during the study period. This step was performed to understand how the overall relationship between the micrometeorological parameters and each of the reference ET parameters varied depending on the synoptic conditions. The order of importance for each micrometeorological parameter was also compared and contrasted for each reference ET parameter and corresponding synoptic category. In essence, SLR was used to understand how the relationship between all reference ET parameters and micrometeorological parameters varied over time (e.g., variability between growing seasons) and synoptic weather situation. Goodness of fit metrics, such as the coefficient of determination (R^2) and root mean square error (RMSE), were calculated to interpret the relationships between the various micrometeorological variables and reference ET.

3. Results

An initial comparison of ET_a and ET_o was performed to determine how well the atmometers represent ET_o using the FAO56-PM method during the study period. As shown in previous atmometer studies conducted in humid, temperate locations in the United States (Chen and Robinson, 2009; Diop et al., 2015; Irmak et al., 2005; Straatmann et al., 2018), the atmometers used in this study tend to underestimate the amount of reference evapotranspiration relative to ET_o, particularly for ET_o values greater than 2 mm/day. Overall, average daily ET_a underestimated ET_o by 22.8% in 2016 and 30.4% in 22.8% in 2017, or 26.6% throughout the study period. Despite this bias, the ET_a varied in a similar manner to ET_o with R^2 equal to 0.78 using simple linear regression.

It is important to examine the cumulative, seasonal effects of the bias in ET_a, since every daily irrigation decision affects future irrigation decisions. Fig. 3 shows the seasonal ET_a and ET_o for 2016 and 2017 at each DEOS station location used in this study.

Note that for every station and growing season, seasonal ET_a underestimated seasonal ET_o, with seasonal ET differences ranging between 100 and 150 mm/season. While the daily ETDs tend to be relatively small and vary from day to day, these differences accumulate to

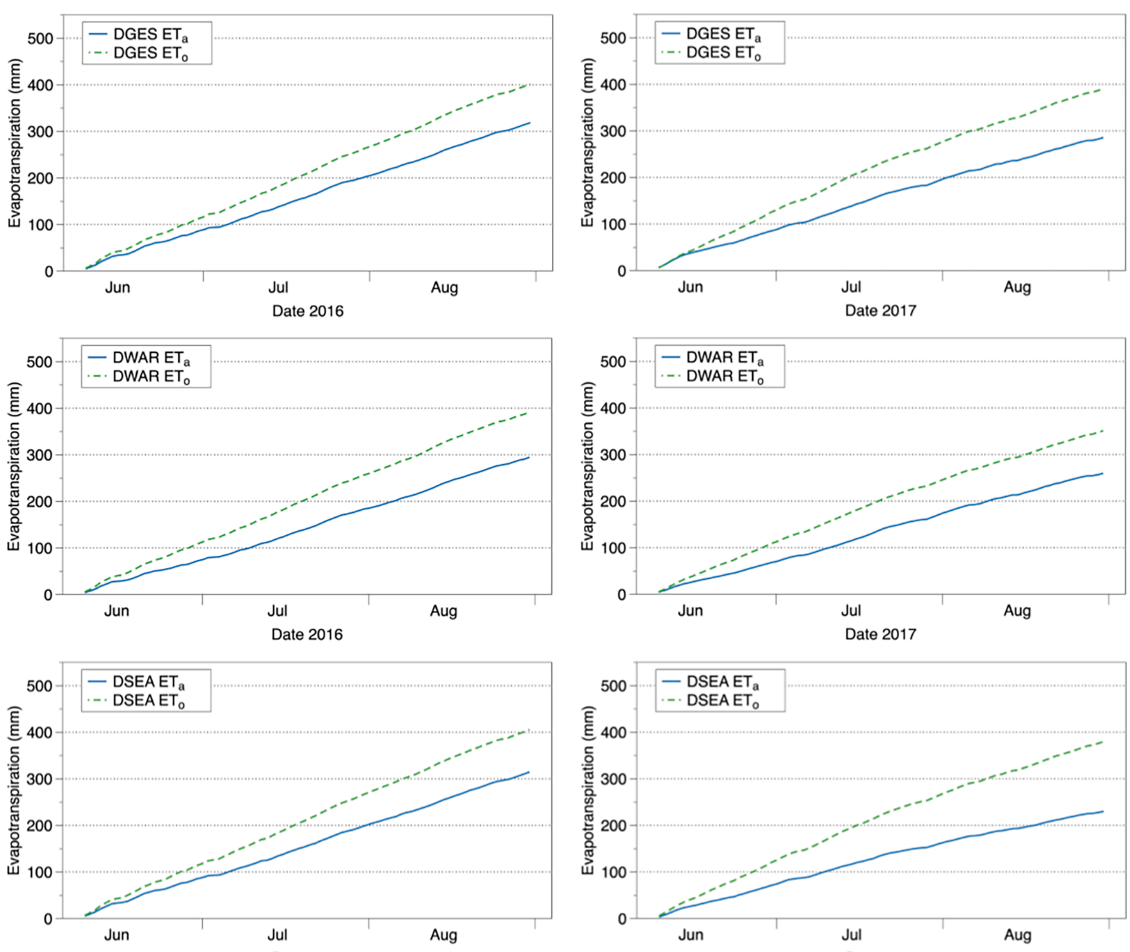

Fig. 3. Seasonal reference ET accumulation for each station (DGES: Georgetown, DE; DSEA: Seaford, DE; and DWAR: Harbeson, DE) from 2016 to 2017. Green dashed lines represent ET_o and blue solid lines represent ET_a.

relatively large seasonal differences, which have significant implications for water management strategies, such as irrigation scheduling decisions. Fig. 4 shows how the relationship between ET_a and ET_o varies over both growing seasons.

Daily ETDs tend to be largest in the early part (June-July) of both growing seasons, although this trend is slightly more pronounced in 2017 than 2016. Meanwhile, reference ET differences in August are slightly (~ 1 mm) smaller and less variable than earlier in the growing season, particularly in 2016. This variability in the relationship between ET_a and ET_o during the growing seasons and from one growing season to the next suggests that temporal variability in meteorological conditions at a larger scale may be an important factor in understanding this relationship.

To understand the influence of each local meteorological variable on reference ET, SLR was performed on daily ET_o, daily ET_a, as well as daily ETD for 2016, 2017, and both years combined (e.g., 2016–2017) across all stations (i.e., all station days). Results in Table 1 show that the variability of both ET_o and ET_a in 2016–2017, is primarily explained by solar radiation, air temperature, wind speed, and then relative humidity, in that order. Volumetric water content and precipitation variables show little or no value in explaining the variability of ET_a and ET_o.

Overall, the variability of ET_a and ET_o are well explained (R^2 equal to 0.890 and 0.956, respectively) by a combination of meteorological variables from the DEOS mesonet stations in 2016. R^2 values for 2017 are notably lower than 2016, particularly for ET_a with an R^2 value in 2017 of 0.754.

The variables contributing to daily ETD each year are ordered differently than for the individual reference ET parameters, ET_a and ET_o (Table 1). In 2016, the R^2 value reached 0.543 with a large number of meteorological variables contributing to the relationship, with wind speed and relative humidity being the most important. In 2017, the R^2 value dropped significantly to 0.319 with only wind speed and air temperature being used in the regression equation. This change in the relationship between the ET_a and ET_o for each growing season demonstrates how atmometers respond to different micrometeorological conditions, which fluctuate in response to changing synoptic weather conditions. This further suggests that distinctly different synoptic weather patterns likely characterized the two growing seasons and impacted the performance of the atmometers.

The Temporal Synoptic Index (TSI) analysis described in Section 2.2 originally identified 10 distinct synoptic weather types (patterns) that characterized daily weather conditions during the summer (June - August) season for the period 1948 through 2021. These were identified by compositing sea-level pressure and other atmospheric variables for all similar days in the synoptic calendar that resulted from the TSI analysis. For the years 2016 and 2017, six of these synoptic types were found to occur on at least 10 days in each growing season, comprising nearly 70% of the days for which atmometer data existed. These six synoptic types were further combined into three broadly similar synoptic categories by inspection of sea-level pressure, 500 hPa height, 2-meter temperature, and precipitation rate maps. Days that were associated with each of these synoptic categories were retained for analysis with reference ET data. Fig. 5 shows composited sea level pressure patterns for each of these three synoptic categories. Southwest Flow (SW; Fig. 5a) occurred on 51 days during the two irrigation seasons. This pattern is characterized by a strong Azores high pressure center that extends back to the North American continent providing a southwest flow of warm, moist air over the Delmarva Peninsula. This pattern has the largest mean ET_a and ET_o values, the highest air temperatures, wind speeds, and highest relative humidity values of the three major synoptic categories (Table 2). The Cold Front synoptic category (CF; Fig. 5b) has a low pressure center located over eastern Canada with the indication of a frontal system in the vicinity of the study area. This pattern has the largest average rainfall, largest frequency of precipitation and generally intermediate values for ET_a and ET_o (Table 2). High Pressure Overhead (HP; Fig. 5c) is characterized by high pressure over the study area. This category typically has the smallest average ET_a and ET_o values, and the lowest air temperature, wind speed, relative humidity, and precipitation values of the three major synoptic categories (Table 2).

Differences between ET_a and ET_o also vary considerably between the primary synoptic categories. An ET_a - ET_o standardized difference (ETD %) was calculated using the following formula:

Table 1
Stepwise linear regression (SLR) models for all stations by year and reference ET data parameter. The equation components considered for each SLR model were solar radiation (S), air temperature (A), wind speed (W), relative humidity (R), a binary rainfall (rain/no rain) parameter (B), and soil volumetric water content (V).

Year	ET data parameter	Equation components (in order of importance)	Adj. R^2	RMSE
2016	ET_a	A,R,S,W,B	0.890	0.37
	ET_o	S,A,W,R	0.956	0.23
	(ET_a – ET_o)	W,R,S,A,B	0.543	0.38
2017	ET_a	S,W,A,R	0.754	0.54
	ET_o	S,A,R,W	0.851	0.45
	(ET_a – ET_o)	W,A	0.319	0.59
2016–2017	ET_a	S,A,R,W	0.806	0.51
	ET_o	S,A,R,W	0.898	0.36
	(ET_a – ET_o)	W,R,S	0.335	0.54

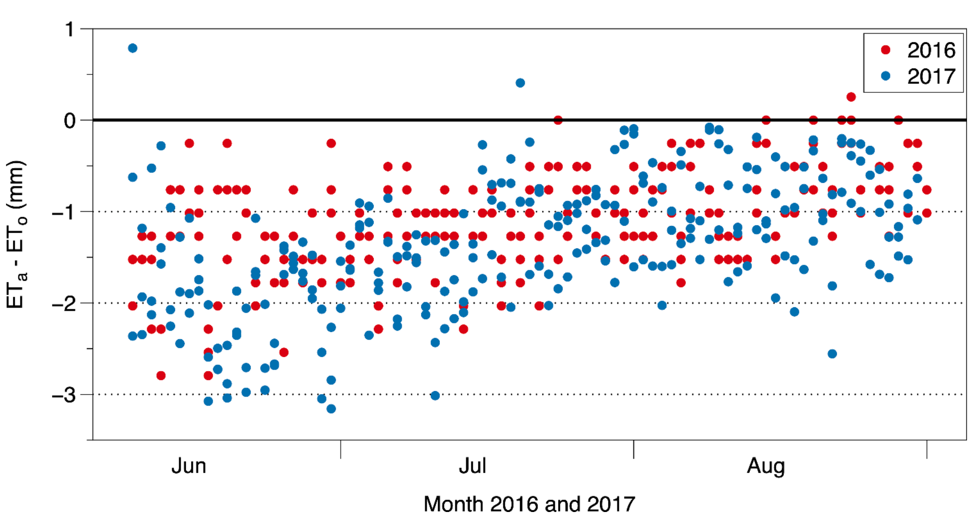

Fig. 4. Daily ET differences (ET_a - ET_o) for all stations for 2016 (red) and 2017 (blue).

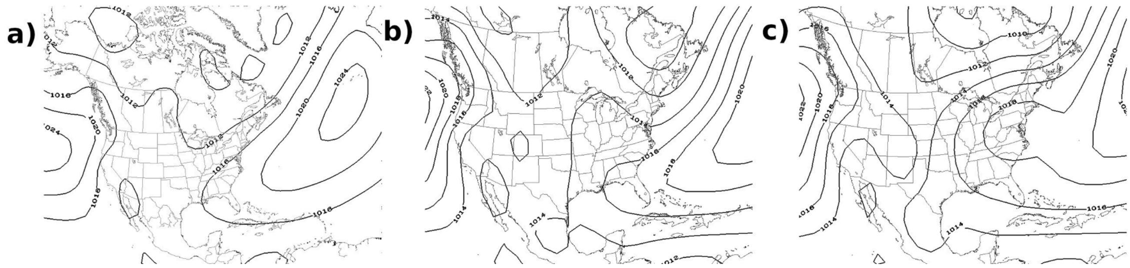

Fig. 5. Surface pressure (hPa) maps for major synoptic weather categories defined in the study: a) Southwest Flow (SW), b) Cold Front (CF), and c) High Pressure Overhead (HP).

Table 2
Average values for each meteorological parameter for the three primary synoptic categories identified. The abbreviation used for each meteorological parameter in the table are: atmometer reference evapotranspiration (ET_a), FAO56-PM reference evapotranspiration (ET_o), reference evapotranspiration difference in mm (ET_a – ET_o) and as a percentage (ETD), air temperature (AT), precipitation (P), binary precipitation (rain/no rain) parameter (BP), wind speed (WS), relative humidity (RH), solar radiation (SR), and soil volumetric water content (VWC).

Synoptic category	ET_a (mm)	ET_o (mm)	(ET_a – ET_o) (mm)	ETD (%)	AT (°C)	P (mm)	BP (unitless)	WS (m s^{-1})	RH (%)	SR (J m^{-2})	VWC (kg/kg)
Southwest Flow	3.6	4.9	−1.3	28.7	25.8	3.0	0.3	1.7	78.0	2.17E7	0.103
high Pressure Overhead	3.3	4.1	−0.8	21.8	21.1	0.5	0.1	1.4	75.3	2.11E7	0.128
Cold Front	3.5	4.7	−1.2	26.1	24.7	4.6	0.4	1.5	77.3	2.15E7	0.123

$$ETD\% = ABS\left[\frac{ET_a - ET_o}{ET_o}\right]$$

The standardized difference was used instead of the raw difference to account for variations in the raw reference ET between synoptic categories (ETD% in Table 2). The atmometer measurements and FAO56-PM estimates were most similar under a High Pressure (HP) synoptic category (Table 2) differing by approximately 22%. For this synoptic category, solar radiation, air temperature, relative humidity, and precipitation amount were the four meteorological variables that were significant in the stepwise multiple regression with the atmometer data (in that order; $R^2 = 0.761$; Table 3).

On CF days, the atmometer data was most highly correlated with air temperature, solar radiation, relative humidity, and wind speed, in that order ($R^2 = 0.832$; Table 3) and differed from the FAO56-PM measurements by 26%. Wind speed and a binary (rain/no rain) precipitation value were the major contributors to the differences on CF days (Table 3). Finally, SW days typically showed the largest difference between atmometer and FAO56-PM estimates of evapotranspiration with an average difference of 29%. On these days, solar radiation, air temperature, wind speed, and relative humidity were the meteorological variables associated with the majority of the variation in the atmometer measurements ($R^2 = 0.772$; Table 3). Wind speed alone was the variable associated with the differences between the two ET datasets on SW days (Table 3).

Table 3
Stepwise linear regression (SLR) models for all stations by synoptic category and reference ET data parameter. The equation components considered for each SLR model were solar radiation (S), air temperature (A), wind speed (W), relative humidity (R), Precipitation (P), a binary rainfall (rain/no rain) parameter (B), and soil volumetric water content (V).

Synoptic category	ET Data parameter	Equation components (in order of importance)	Adj. R^2	RMSE
Southwest Flow (SW)	ET_a	S,A,W,R	0.772	0.51
	ET_o	S,A,R,W	0.840	0.44
	(ET_a – ET_o)	W	0.367	0.57
Cold Front (CF)	ET_a	A,S,R,W	0.832	0.45
	ET_o	S,A,W,R,V	0.927	0.31
	(ET_a – ET_o)	W,B	0.330	0.49
High Pressure Overhead (HP)	ET_a	S,A,R,P	0.761	0.49
	ET_o	S,A,R,W	0.928	0.25
	(ET_a – ET_o)	W,P	0.111	0.56

Fig. 6 shows a scatterplot of the ET_a-ET_o data pairs ('+' signs) for the study period, the regression lines for all three synoptic categories, and the 1:1 line, which defines the ideal reference ET data relationship. Note the bias in atmometer reference ET, as nearly all reference ET data pairs were located above the 1:1 line, representing an underestimation of reference ET by the atmometer. All three regression lines are above the 1:1 line as well, which shows that the atmometer generally underestimates reference ET regardless of the synoptic weather conditions. However, it is important to note the trends in the regression lines differ, with HP days showing a clear improvement in the ET_a-ET_o relationship as reference ET increases. This same trend is true for SW and CF days, but to a much lesser extent. The tendency for the atmometers to be less accurate at lower reference ET rates is likely due to the effect of precipitation on the atmometer. This is supported by Irmak et al. (2005), which showed that precipitation tends to decrease the rate of evaporation from the atmometer by wetting the canvas cover, thus lowering the vapor pressure gradient between the surface of the instrument and the atmosphere.

Across all three synoptic categories, wind was the most important factor in the SLR equations for the ET differences. This likely indicates that the atmometers do not reasonably approximate a reference surface's exchange of water vapor between its canopy and the atmosphere due to turbulence (i.e., aerodynamic resistance). Precipitation variables were also important for the HP and CF synoptic patterns, which was likely due to the aforementioned effect on the vapor pressure gradient between the atmometer and the nearby atmosphere. In general, the higher the wind speed, the larger the differences between ET_a and ET_o on a given day regardless of the synoptic category. This finding is also consistent with previous work by Chen and Robinson (2009) and Gavilán and Castillo-Llanque (2009). However, it is important to note that the overall synoptic situation plays an equally important role in the

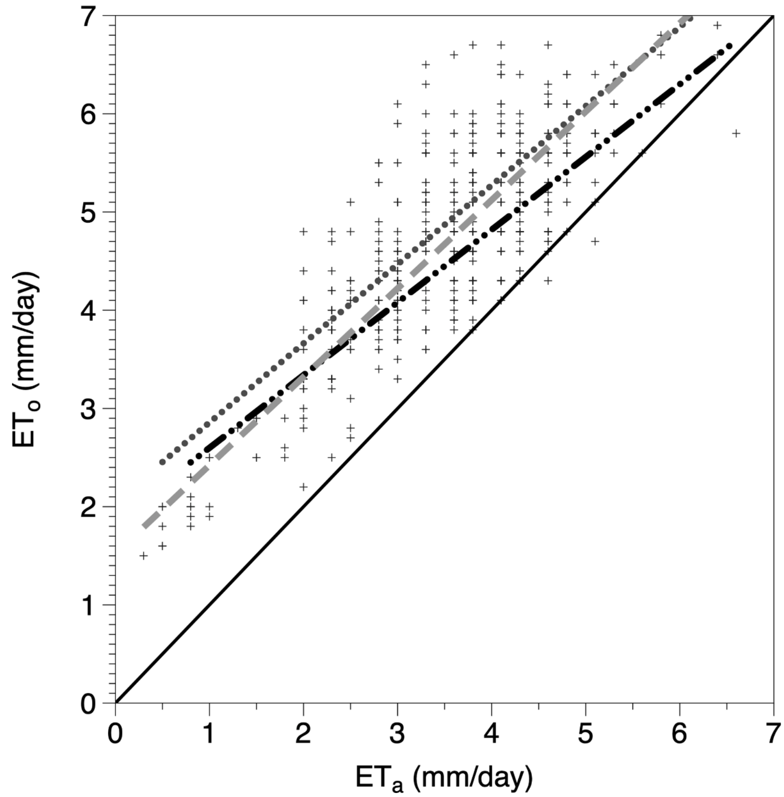

Fig. 6. Comparison of ET_a and ET_0 for all stations for the study period. The plus signs (+) represent each ET_a-ET_o pair from the study. The dotted line is the regression line for all Southwest Flow pairs, the dot-dash line is the regression line for all High Pressure Overhead pairs, the dashed line is the regression line for all Cold Front pairs, and the solid line is the one-to-one line.

similarity between atmometer and FAO56-PM reference ET estimates on any given day, with high pressure patterns leading to the most similar results from the two methodologies and warm windy days producing the largest differences. This explains the reason for the disparity of the regression results shown in Table 1. In 2016, the SLR equation using the micrometeorological parameters explained more variance in ET_a, ET_o and ETD than in 2017. This was likely because 2016 was dominated by more CF and HP synoptic patterns over the course of the irrigation season than 2017 (Fig. 7). Both are synoptic patterns that tend to decrease the difference between the atmometer and FAO56-PM methods and increase the explained variance in ET_a and ET_o, particularly HP days. Thus, changes in the synoptic category frequency can impact the atmometer- FAO56-PM relationship from season to season.

Developing regression equations that rely on data from weather stations to correct atmometers can present a significant barrier for most atmometer users. Instead, this study has identified three synoptic categories that can be used to characterize the general weather conditions for a given day and determined the average difference between ET_a and ET_o for each synoptic category. To improve the utility of this study to atmometer users, Table 4 presents the relationship between atmometer performance in the form average daily correction factors and synoptic conditions in practical, approachable language. This approach is supported by previous research by Frisvold and Murugesan (2013) and Agyekum et al. (2022), which showed that farmers in particular prefer general, impact-based weather terminology over highly technical weather terminology to make weather-based decisions. Other studies have shown that farmers prefer to use weather information from intermediaries, such as crop advisors and consultants, over traditional

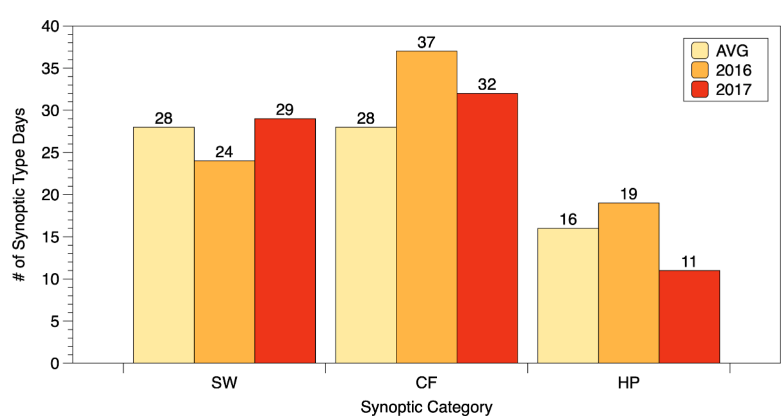

Fig. 7. Number of days with Southwest Flow (SF), Cold Front (CF), and High Pressure (HP) synoptic categories for each growing season (2016 and 2017). Average values (AVG) are for the period 1948–2021.

Table 4
Practical weather description table relating the average daily correction factor for atmometer measured reference ET and descriptions for the three synoptic weather categories identified in this study.

Synoptic category	Average daily atmometer ET_a correction (mm)	General meteorological conditions for Delaware
Southwest Flow	+ 1.3	• Warm, breezy conditions • Humid and mostly sunny. • Some precipitation is possible, but typically of the afternoon thunderstorm variety
Cold Front	+1.2	• Breezy, with a noticeable shift in wind direction • Precipitation likely when the front passes • Noticeable change in temperature and relative humidity after the front passes
High Pressure Overhead	+0.8	• Little to no wind • Sunny conditions with minimal cloud cover • Relatively cool morning temperatures • Very little to no precipitation

weather service and data providers (e.g., National Weather Service) (Haigh et al., 2018; Lu et al., 2021).

4. Summary and conclusions

As climate change affects the variability of moisture and the demand for limited water resources increases, particularly in areas where irrigation is expanding near populated areas, improved adaptation strategies will be necessary to ensure adequate water is available for all uses and applications. Consequently, exploring the potential application of tools, such as atmometers, to manage water accurately and sustainably is becoming increasingly important. This study analyzed how atmometers performed in the humid climate of Delaware, USA under varying synoptic weather conditions. Atmometer reference ET underestimated FAO56-PM reference ET by 26.6% across two growing seasons in Sussex County. This finding is within the range of underestimation found in previous atmometer comparison studies (Chen and Robinson, 2009; Diop et al., 2015; Irmak et al., 2005; Straatmann et al., 2018) performed in humid regions, though on the upper end of the range (e.g. 12% to 27%). Given that several studies conducted in humid regions have shown an underestimation of ET_o by atmometers, future research should consider testing or developing other atmometer covers with higher evaporative properties, particularly during windy conditions, than the current reference ET cover. Daily differences between ET_a and ET_o were small, but over the course of a growing season, the differences were significant, generally accumulating to approximately 100 mm. This is an important consideration when using an atmometer for irrigation management in Delaware and the surrounding region. While ET_a tends to be less than ET_o for most days during the growing season, the daily differences vary. Local meteorological conditions strongly correlate with both ET_a and ET_o, but variability in these relationships between growing seasons suggests synoptic weather conditions play a significant role in how well the atmometer measures reference ET.

However, unlike previous atmometer comparison studies which emphasized the influence of local meteorological conditions on atmometer performance, this study explored the influence of regional synoptic conditions on atmometer measured reference ET. Using a temporal synoptic index (TSI) to classify days into similar synoptic weather conditions, three dominant synoptic patterns/categories were observed during the study period: Southwest Flow, Cold Front, and High Pressure days. An analysis of absolute differences in reference ET under the three synoptic categories showed that High Pressure days tend to be when atmometer and FAO56-PM reference ET estimates agree most. In addition, a regression analysis of meteorological conditions for each synoptic category demonstrated that wind speed was the most important factor in accounting for differences between the FAO56-PM reference ET data and that measured by the atmometer. Further examination of the seasonal differences in synoptic category frequency demonstrated that more frequent High Pressure and Cold Front days, which tend to be associated with smaller ETDs than Southwest Flow days, affected the nature of the ET_a-ET_o relationship from season to season.

It is possible to use atmometers as a low-cost substitute for field-specific reference ET data on the Delmarva Peninsula, though it is important to consider the limitations and accuracy of these devices, particularly under certain synoptic weather conditions. By understanding the synoptic weather and general meteorological conditions that can lead to differences in ET_a and ET_o, atmometer users can better account for the day-to-day variability in the atmometer data, thus reducing the potential for crop damage or loss due to miscalculations of irrigation requirements for farm fields. Rather than developing regression equations that rely on data from expensive and difficult to maintain weather stations, this study identified and characterized general synoptic categories (e.g., High Pressure, Cold Front, Southwest Flow) whose descriptions are more accessible to non-meteorologists and associated those categories with reference ET correction factors to improve the utility of atmometers.

Future studies could investigate if the weather descriptions associated with each synoptic weather type shown in Table 4 are easy to implement by non-meteorologists and also whether the atmometer adjustments result in improved management of water resources, such as agricultural irrigation. Also, more field-based research on atmometers is needed to determine if they are practical for irrigation scheduling on the Delmarva Peninsula. In particular, field studies that use atmometers and other irrigation scheduling methodologies to prescribe irrigation treatments could prove useful, particularly if yield and crop health could be assessed. Finally, more work is needed to understand atmometer performance under climatological extremes, particularly drought, since that is when the need for irrigation is the greatest and the risk of crop failure is the largest.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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