Feasibility of Obtaining Surface Layer Moisture Flux Using an IR Thermometer

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Abstract: This paper evaluates the feasibility of a method using a single hand-held infrared (IR) thermometer and a mini tower of wet and dry paper towels to psychometrically obtain surface layer temperature and moisture gradients and fluxes. Sling Psychrometers have long been standard measuring devices for quantifying the thermodynamics of near-surface atmospheric gas–vapor mixtures, specifically moisture parameters. However, these devices are generally only used to measure temperature and humidity at one near-surface level. Multiple self-aspirating psychrometers can be used in a vertical configuration to measure temperature and moisture gradients and fluxes in the first 1–2 m of the surface layer. This study explores a way to make multiple vertical psychrometric measurements with a single non-contact IR temperature sensor rather than using two in situ thermometers at each level. The surface layer dry- and wet-bulb temperatures obtained using an IR Thermometer are compared to Kestrel 4000 Weather Meter and Bacharach Sling Psychrometer measurements under various atmospheric conditions and surface types to test the viability of the method. To evaluate the results obtained using this new approach, standard meteorological surface data are collected during each experiment, and moisture parameters are derived via psychrometric equations. The results indicate that, not only is the method possible and practical, but they suggest that the IR Thermometer method may provide more surface layer temperature and moisture gradient and flux sensitivity than other single instrument methods.

Keywords: infrared thermometer; wet-bulb temperature; moisture flux

1. Introduction

This study evaluates a method whereby a single non-contact infrared (IR) thermometer can be used to obtain both the vertical gradients and fluxes of air temperature and moisture content in the first 1–2 m of air above the ground. Since the IR Thermometer primarily quantifies the emissive temperature of material surfaces within its field of view (FOV), this paper outlines methods that allow the IR Thermometer to measure objects that are representative of the thermodynamic dry-bulb and wet-bulb temperatures. Standard psychrometric relationships and calculators can then be used with the obtained dry- and wet-bulb temperatures (and pressure) to obtain standard meteorological quantifications of air temperature and humidity from a single IR Thermometer. The technique used in this experiment involves an IR Thermometer and paper towel material, along with a Kestrel 4000 Weather Meter and Sling Psychrometer for validation. Infrared thermometers are used to measure the temperature of the surface in the FOV within which the pointing
laser (that typically is part of an IR Thermometer) is directed. A chief goal of this experiment is to establish how accurately a low-cost, procedurally simple, and relatively low maintenance IR Thermometer can quantify wet-bulb temperature when compared to standard psychrometric wet-bulb measurements and those derived from other moisture sensing devices.

The wet-bulb temperature, the temperature of an air parcel if cooled to a steady state via evaporation at constant pressure, provides a measure of the water vapor content of the air and is used to derive meteorological parameters, such as dew point temperature and relative humidity. Sling Psychrometers, (sometimes denoted as “Spsychrometers” or “Spsych” in this paper) are devices composed of two thermometers: one bulb is covered in a wet wick, whereas the other remains uncovered, utilized to quantify the physical and thermal properties of moist air. The dry-bulb temperature, which is essentially the ambient air temperature, is measured with the non-wick thermometer, whereas the wet-bulb temperature is obtained by evaporative cooling (a result of the slinging motion) of the moistened wick. To adequately measure the wet-bulb temperature, the psychrometer must be spun around at a speed of 2–3 revolutions per second for approximately 1.5–2 min until the wet-bulb thermometer reaches a constant value [1]. The World Meteorological Organization guidelines provide a broader range for acceptable ventilation rates, between 2.2 and 10 m s\(^{-1}\) [2]. Inconsistencies in measurements are generally associated with insufficient moistening of the cotton wick, low spin velocities or contaminated wicks. Furthermore, Sling Psychrometers can be affected by solar radiation, and measurements with direct sunlight on the thermometers during the ventilation process should be avoided. Additionally, to prevent physical damage to the device, measurements < 1 m above the ground are rarely performed.

The technique to use IR Thermometers is based on the same principles used by the Sling Psychrometer method and offers a fast, low risk and cost-effective method to measure temperature [3]. IR Thermometers exploit the property of all materials to emit electromagnetic radiation at temperatures above absolute zero [4]. The amount and primary wavelengths of the emitted energy are based on the temperature through Planck’s Law [5–7]. IR Thermography is a measurement technique based on the detection of radiation in the IR spectrum, generally in the ranges of 2.0–5.6 and 8.0–14.0 \(\mu\)m [5]. These two spectral bands are commonly utilized because atmospheric absorption is relatively small, thus enabling sufficient broadband radiation to reach the sensor. In turn, the temperature of a radiating surface can be inferred from the Stefan–Boltzmann equation [6–8], as shown in Equation (1):

\[
\text{Emitted Energy} = \epsilon \sigma T^4, \tag{1}
\]

where \(T\) is the temperature (K) of the emitting surface, \(\sigma\) is the Stefan–Boltzmann constant \(= 5.67 \times 10^{-8}\) W m\(^{-2}\) K\(^{-4}\) and \(\epsilon\) is the wavelength-dependent emissivity of the radiating surface. Emissivity is an expression used to characterize the optical properties of materials, in this case wet or dry white paper towels, as a ratio of the amount of energy actually emitted to the amount emitted from an ideal blackbody at the same temperature. In such circumstances, the values for emissivity can be between 0 (i.e., perfect reflector, a mirror) and 1 (i.e., perfect emitter, blackbody). A concern about IR Thermography is that no IR detectors measure temperature directly; temperature is interpreted through emissivity. However, this concern is greatly reduced or eliminated if the emissivity of the material being investigated is \(~1.0\) in the spectral bands where the detector is sensitive [9].

To complete the assessment, the IR Thermometer technique was evaluated for efficiency and versatility. Experimental documentation entailed collecting data multiple times a day for several weeks in order to capture diurnal changes and various atmospheric conditions. Data were collected over sand, grass and concrete surfaces to establish if there were any significant differences in how accurately an IR Thermometer measures air temperature over those various surfaces as compared to other methods. The technique’s versatility was also evaluated relative to freezing conditions to evaluate the use of an IR Thermometer for measuring ice-bulb temperature and converting that to humidity quan-
tifications. Ultimately, the research explored the viability of using a single IR Thermometer to profile temperature and humidity at different heights in the first meter above the ground to describe moisture and heat fluxes near the surface.

Perhaps the strongest example of previous efforts illustrating the merit of this new technique for standard atmospheric humidity measurements is that which was reported by Lee and Wang [10]. In their work, they used non-contact IR Thermometers to advance commercial digital psychrometers normally installed in greenhouses to monitor ambient conditions with the primary focus of reducing the logistics footprint associated with such psychrometers. The psychrometers described by Lee and Wang—based on a captive moist wick coupled to a water reservoir—must be checked by personnel on a recurring basis with little to no foreknowledge that the reservoir is at a satisfactory operating level. Lee and Wang subsequently developed an elegant evaporative model based on monitoring the internal wick’s wet-bulb temperature as determined by pointing a digital IR Thermometer at the wick and used that information to cue users when it was time to re-fill the internal water reservoir.

2. Methodology

2.1. Experimentation

In this research, the dry-bulb temperature was measured by pointing a Centech infrared thermometer at a dry paper towel approximately 15 cm away, a distance in which the paper towel completely fills the measurement spot defined by the Centech’s optical resolution [3]. By ensuring the paper towel completely filled the viewed spot, there was no additional thermal radiation sampled from the background environment, which could degrade the accuracy of the temperature measurement. To measure the wet-bulb temperature, the paper towel was wetted with water, and a handheld fan was oriented perpendicular to it to maintain airflow into the wet towel for up to 1 min to create proper ventilation and thus evaporative cooling. Similar to the guidelines associated with accurate Sling Psychrometer measurements, IR Thermometer data were collected in shaded conditions to avoid sunlight contamination.

Experiments were conducted during the summer of 2020 near the University of Dayton campus, located in Dayton OH (39.7589° N, 84.1916° W). Dry- and wet-bulb temperatures were measured in various atmospheric conditions and over various surfaces (e.g., grass, concrete, sand), which influence those same atmospheric conditions. Experiments were conducted at different times of day and sky cover, as well as during rain events, to determine the applicability and limitations of the IR Thermometer technique. Simultaneous measurements were collected with a Bacharach Sling Psychrometer and Kestrel 4000 Weather Meter, which are shown in Figure 1. These instruments provided validation data. Dew point temperature, relative humidity and barometric pressure data were also collected by the Kestrel for comparisons to parameters measured and derived by the IR Thermometer and psychrometer. Relative humidity and dew point temperature were evaluated using psychrometric relationships and Bolton’s equation (covered in Section 2.2).

Data collection procedures consisted of measuring atmospheric variables (e.g., dry-, wet-bulb temperature, pressure, relative humidity) with a Kestrel, followed directly with the IR Thermometer and Sling Psychrometer. Initial trials were conducted with a two-person team under a covered patio. While one individual held the paper and directed the airflow from the handheld fan toward the paper towel, the other person took temperature measurements by pointing the IR Thermometer at the center of the paper towel from approximately 15 cm away. Sling Psychrometer measurements were made by spinning the device around for approximately two minutes at the same height above the ground in which the paper towel was held.
Figure 1. Images of the instrumentation used to conduct and validate the infrared psychrometry experiment: (a) Control: Bacharach 0012-7012 Sling Psychrometer; (b) Control: Kestrel 4000 Weather Meter, and (c) Test: Centech infrared thermometer (also known as IR Thermometer).

Experiments were conducted in an outdoor, open environment. Shade was found to be a critical prerequisite, as is generally sought for psychrometer measurements, to ensure that sunlight and thus solar heating did not affect the data. The instrumentation required time to become acclimated to the surrounding environment; it was noted that the IR sensor yielded inaccurate measurements after being relocated from a warm to a cool environment or vice versa [3]. Eventually the experimental setup was modified to require only one individual to conduct measurements; this was conducted by securing paper towels to the arms and base of a lawn chair while allowing for unobstructed air flow from the fan to create evaporative cooling. The measurements were organized by surface type and were originally made by one device (e.g., Kestrel) over all three surfaces in succession prior to switching to another device. Subsequently, procedural modifications were made to measure temperatures above a surface with all three (i.e., Kestrel, Sling Psychrometer and IR Thermometer) instruments in succession prior to moving to another surface. This modification reduced data inconsistencies due to environmental changes occurring during the measurement period. Sand surface experiments were conducted on an on-campus volleyball court, where an umbrella was deployed to create a shaded environment. The total time required to take all measurements over the various surfaces was approximately 30 min; therefore, environmental changes that occurred over the measurement cycle created subtle yet occasionally noticeable differences in data.

As noted earlier, the IR Thermometer technique was applied during freezing conditions to evaluate the capability to measure ice-bulb temperature (trials 54–62 in Appendix A). Numerous attempts were made to use a walk-in freezer for testing; however, due to COVID-19 restrictions, this option was not available for experimental analysis. Therefore, experiments were conducted in the freezer of a standard-sized refrigerator. A Sling Psychrometer was not used due to limitations of the freezer space. The Kestrel and wet paper towel were placed in the freezer with the door closed for 45 s to acclimate to the extreme temperatures. Ice-bulb temperature was measured first with the IR Thermometer after opening the door to limit warm, higher moisture air intrusion into the freezer environment. However, this often yielded wet-bulb temperatures that exceeded the dry-bulb measurements, presumably due to deposition and/or condensation on the wet/frozen paper towel that resulted in latent heat release on that towel that did not affect the dry paper towel or dry Kestrel moisture sensor nearly as much. Data from the Kestrel were quickly recorded after the ice-bulb temperature was measured. Although it is possible to have ice-bulb temperatures higher than the dry-bulb temperatures in environments saturated with respect to liquid water, the differing Kestrel/IR results strongly suggest that...
a walk-in freezer or below-freezing outdoor conditions are necessary to validate that the IR sensor technique can be applied in zero and sub-zero °C conditions.

The means and standard deviations of the measured dry-bulb and wet-bulb temperatures obtained from the three instruments over the three different surface types are shown in Figures 2–4. Note that the depicted daily mean and standard deviation temperature measurements derived by each method are superimposed on each method’s final daily measurement. Results from preliminary trials demonstrated that the IR Thermometer technique could be utilized to quantify wet-bulb temperature and thus was expanded to determine its applicability to quantify vertical variations in wet-bulb temperatures, yielding a novel technique to measure moisture flux. As seen in Figure 5, paper towels were positioned on a wooden pole at several heights (i.e., 28, 46, 64, 81 and 99 cm) above ground level in a grassy, shaded area. As before, measurements were taken at various times of day and under varying sky conditions. The Kestrel was the only device used for validation measurements at each height, as the Sling Psychrometer is not a practical instrument to differentiate wet-bulb temperatures at relatively small height increments all within a meter of the ground.

![Figure 2](image_url)

**Figure 2.** (a) Individual observations, as well as the daily means and standard deviations (superimposed on the final daily observation) of dry-bulb (DB) temperatures as measured by the Kestrel, Sling Psychrometer and IR Thermometer over concrete. (b) Individual observations, daily means, and standard deviations of wet-bulb (WB) temperatures as measured by the Kestrel, Sling Psychrometer and IR Thermometer over concrete.
2.2. Conversion to Relative Humidity and Dew Point Temperature

Relative humidity and dew point temperature can be calculated using psychrometric relationships based on data obtained from the IR Thermometer and Kestrel measurements. Assuming the same temperature and pressure, relative humidity is a ratio of the vapor pressure of the air to the saturation vapor pressure [11],

\[ RH = \frac{e}{e_s}, \]

Bolton’s equation [12] is used to determine the saturation vapor pressure (hPa):

\[ e_s(T) = 6.112 \exp\left(\frac{17.67T}{T + 243.5}\right), \]

with \( T \) being dry-bulb temperature (°C) measured by the IR Thermometer. Vapor pressure is calculated using the psychrometric equation [13],

\[ e = e_{Tw} + \frac{c_{pd}P}{L_v \varepsilon} (T_w - T), \]

where \( c_{pd} \) is specific heat of dry air (J kg\(^{-1}\) K\(^{-1}\)) at constant pressure, \( P \) is the barometric pressure (hPa) measured by the Kestrel, \( L_v \) is the latent heat of vaporization (J kg\(^{-1}\)), \( \varepsilon \) is the molar mass of water over the molar mass of air (0.622), \( e \) is vapor pressure (hPa), \( e_{Tw} \) is the wet-bulb vapor pressure (hPa), \( T_w \) is the wet-bulb temperature (°C) and \( T \) is the ambient air or dry-bulb temperature (°C). Latent heat of vaporization tables were used to determine \( L_v \) values based on IR Thermometer measurements.
Figure 4. (a) Individual observations, as well as the daily means and standard deviations (superimposed on the final daily observation) of DB temperatures as measured by the Kestrel, Sling Psychrometer and IR Thermometer over sand. (b) Individual observations, daily means and standard deviations of wet-bulb (WB) temperature as measured by the Kestrel, Sling Psychrometer and IR Thermometer over sand.

Figure 5. Moisture flux experimental setup consisting of small paper towels positioned at various heights (28, 46, 64, 81 and 99 cm) above a grassy surface.
Dew point temperature ($T_d$ in °C), the temperature at which vapor pressure (or mixing ratio) and saturation vapor pressure (or saturation mixing ratio) are equivalent, is calculated using the vapor pressure from Equation (4) and the following equation [12]:

$$T_d = \frac{243.5 \ln \left( \frac{6.112}{e} \right)}{17.67 - \ln \left( \frac{6.112}{e} \right)},$$

(5)

In addition to the measurements and equations outlined above, a USAF psychrometric whiz wheel calculator (ML-322/UM), shown in Figure 6, was used to validate the use of an empirical Clausius–Clapeyron Equation (5) to derive dew point temperature from the IR Thermometer’s dry and wet-bulb temperature measurements. Relative humidity and vapor pressure are also outputs from the whiz wheel tool, which is an accurate representation of the full psychometric equations on a series of circular slide rules based on the following inputs: dry- and wet-bulb temperatures, as well as ambient atmospheric pressure. One limitation of the whiz wheel tool occurs with very large wet-bulb depressions (the $T_{drybulb} - T_{wetbulb}$ difference); this is due to the logarithmic nature of the scales and difficulty setting measurements on those scales.

![Figure 6. Psychrometric Calculator Model #ML-322/UM, provided by the United States Air Force.](image)

2.3. Statistical Analyses

In order to calculate the estimated standard deviation for the means displayed as uncertainty bars in Figures 2–4 and to statistically compare the measurements recorded by the control and test group instruments, two statistical approaches were applied. Firstly, a paired $t$-test assuming equal variances was applied to the control group (i.e., Kestrel and Sling Psychrometer) measurements. Subsequently, a single factor/one-way analysis of variance (ANOVA) procedure using SAS/JMP statistical software was performed for multiple means comparisons between the control and test (i.e., IR Thermometer) groups. Both procedures—the paired $t$-test and ANOVA—were implemented for the grass, concrete and sand surfaces, separately. For probability testing and significance analysis, a 5% alpha ($\alpha$) level was adopted.
3. Discussion of Statistical Analysis and Measurement Results

3.1. Paired t-Test for Controls (Kestrel and Sling Psychrometer) Assuming Equal Variances

The experiment was conducted for three different surface conditions, namely grass, concrete and sand surfaces. Table 1 shows the results of the paired t-test analysis of the Kestrel and Sling Psychrometer control group dry- and wet-bulb temperature measurements for ultimate assessment of the IR Thermometer test group measurements. By applying $p (T \leq t = 0.060)$ in the grassy area, the mean dry-bulb temperature values of 25.816 °C (Sdev, ±2.930) and 24.521 °C (Sdev, ±3.320), as measured by the Kestrel and Sling Psychrometer, respectively, are not significantly different for $\alpha \leq 0.05$. As further confirmation, the t-statistic value of 1.575 is not greater than the t-critical of 1.667 in Table 1. For concrete and sand surfaces, the values of $p (T \leq t)$ are 0.214 and 0.342, respectively. This, in turn, suggests that the Kestrel mean dry-bulb temperature measured over concrete of 23.668 (±4.640) °C and the mean of 22.770 (±4.930) °C derived using the Sling Psychrometer are not significantly different. Likewise, the mean dry-bulb temperature measurements over sand with the Kestrel and Sling Psychrometer of 25.364 °C (±3.240) and 24.747 °C (±3.750), respectively, are statistically equivalent. In aggregate, these conclusions are confirmed by noting that the corresponding concrete/sand t-statistics values (0.797 and 0.412) are less than the t-critical thresholds (1.667 and 1.725) for both the Kestrel and Sling Psychrometer; their dry-bulb temperature mean measurements over concrete and sand are effectively the same (Table 1).

Table 1. Paired t-test for a sample assuming equal variances between two control groups (Kestrel and Sling Psychrometer) measured for three different surfaces ($\alpha \leq 0.05$).

| Surface Type | Control Group | Dry-Bulb Temperature (°C) | Wet-Bulb Temperature (°C) |
|--------------|---------------|---------------------------|---------------------------|
|              | Mean          | Kestrel                   | Sling Phys                | Kestrel                   | Sling Phys                |
| Grass        | Mean          | 25.816                    | 24.521                    | 18.910                    | 19.128                    |
|              | Sdev (±)      | 2.930                     | 3.320                     | 2.710                     | 2.800                     |
|              | t-stat        | 1.575                     | −0.302                    | 0.382                     | 0.382                     |
|              | $p (T \leq t)$ one-tail | 0.060                    | 0.382                     | 0.060                     | 0.382                     |
|              | t-critical one-tail | 1.673                    | 1.673                     | 1.673                     | 1.673                     |
| Concrete     | Mean          | 23.668                    | 22.770                    | 18.378                    | 18.333                    |
|              | Sdev (±)      | 4.640                     | 4.930                     | 3.500                     | 3.470                     |
|              | t-stat        | 0.797                     | 0.055                     | 0.478                     | 0.478                     |
|              | $p (T \leq t)$ one-tail | 0.214                    | 0.478                     | 0.214                    | 0.478                     |
|              | t-critical one-tail | 1.670                    | 1.667                     | 1.670                    | 1.667                     |
| Sand         | Mean          | 25.364                    | 24.747                    | 18.944                    | 18.763                    |
|              | Sdev (±)      | 3.240                     | 3.750                     | 2.740                     | 2.960                     |
|              | t-stat        | 0.412                     | 0.1469                    | 0.441                     | 0.441                     |
|              | $p (T \leq t)$ one-tail | 0.342                    | 0.441                     | 0.342                    | 0.441                     |
|              | t-critical one-tail | 1.725                    | 1.725                     | 1.725                    | 1.725                     |

In the case of wet-bulb temperature measurements, means of 18.910 °C (±2.710) versus 19.128 °C (±2.800), 18.378 °C (±3.500) versus 18.333 °C (±3.470) and 18.944 °C (±2.740) versus 18.763 °C (±2.960) are statistically the same with $p (T \leq t)$ values 0.382, 0.478 and 0.441 at given $\alpha \leq 0.05$ for both the controls for all three surfaces. The calculated values for t-stat (−0.302, 0.055, and 0.149) are found to be lower in all three conditions compared to the t-critical (1.673, 1.667 and 1.725), which suggests that the means for wet-bulb temperatures are the same from these two controls (Table 1).

3.2. Single Factor ANOVA for Three Devices for Multiple Means Comparisons

This section largely deals with analysis of variance for comparison of the controls (i.e., Kestrel and Sling Psychrometer) and test (i.e., IR Thermometer) groups for dry and wet-bulb temperatures measured above grass, concrete and sand surfaces, the details of which are shown in Table 2a,b.
Table 2. (a) Single factor ANOVA for the three devices (Kest_DB, Spsych_DB and IR_DB) comprising control and test groups showing dry-bulb temperatures (°C) for grass, concrete and sand surfaces ($p < 0.05$). SS = Sum of squares; df = Degrees of freedom; MS = Mean square; F = F-ratio. (b) Single factor ANOVA for three devices (Kest_WB, Spsych_WB and IR_WB) comprising the control and test groups showing wet-bulb temperature (°C) for grass, concrete and sand surfaces ($p < 0.05$). SS = Sum of squares; df = Degrees of freedom; MS = Mean square; F = F-ratio.

### Table 2a: Dry-bulb Temperature (°C) Measurements

| Groups  | Count | Sum   | Mean  | Variance | Source of Variation | SS   | df  | MS     | F       | p-Value | F Crit |
|---------|-------|-------|-------|----------|---------------------|------|-----|--------|---------|---------|--------|
| GRASS   |       |       |       |          |                     |      |     |        |         |         |        |
| Kest_DB | 30    | 779.72| 25.991| 9.196    | Between Groups     | 24   | 2   | 12.153| 0.879   | 0.419   | 3.101  |
| Spsych_DB| 30    | 742.22| 24.741| 12.106   | Within Groups      | 1203 | 87  | 13.825|         |         |        |
| IR_DB   | 30    | 767.22| 25.574| 20.173   | Total               | 1227 | 89  |        |         |         |        |
| CONCRETE|       |       |       |          |                     |      |     |        |         |         |        |
| Kest_DB | 36    | 852.056| 23.668| 21.485   | Between Groups     | 48   | 2   | 24.127| 0.929   | 0.398   | 3.086  |
| Spsych_DB| 36    | 819.722| 22.770| 24.261   | Within Groups      | 2624 | 101 | 25.979|         |         |        |
| IR_DB   | 32    | 782.500| 24.453| 32.992   | Total               | 2627 | 103 |        |         |         |        |
| SAND    |       |       |       |          |                     |      |     |        |         |         |        |
| Kest_DB | 10    | 247.944| 7.674 |          | Between Groups     | 10   | 2   | 5.221 | 0.367   | 0.696   | 3.354  |
| Spsych_DB| 10    | 241.111| 10.696|          | Within Groups      | 384  | 27  | 14.222|         |         |        |
| IR_DB   | 10    | 255.556| 24.297|          | Total               | 394  | 29  |        |         |         |        |

### Table 2b: Wet-bulb Temperature (°C) Measurements

| Groups  | Count | Sum   | Mean  | Variance | Source of Variation | SS   | df  | MS     | F       | p-Value | F Crit |
|---------|-------|-------|-------|----------|---------------------|------|-----|--------|---------|---------|--------|
| GRASS   |       |       |       |          |                     |      |     |        |         |         |        |
| Kest_WB | 29    | 548.389| 18.910| 7.333    | Between Groups     | 24   | 2   | 12.198| 1.015   | 0.367   | 3.105  |
| Spsych_WB| 29    | 554.722| 19.128| 7.852    | Within Groups      | 1009 | 84  | 12.015|         |         |        |
| IR_WB   | 29    | 519.444| 17.912| 20.859   | Total               | 1034 | 86  |        |         |         |        |
| CONCRETE|       |       |       |          |                     |      |     |        |         |         |        |
| Kest_WB | 36    | 661.611| 18.378| 12.226   | Between Groups     | 13   | 2   | 6.274 | 0.417   | 0.660   | 3.086  |
| Spsych_WB| 36    | 660.000| 18.333| 12.019   | Within Groups      | 1521 | 101 | 15.056|         |         |        |
| IR_WB   | 32    | 563.333| 17.604| 21.678   | Total               | 1533 | 103 |        |         |         |        |
| SAND    |       |       |       |          |                     |      |     |        |         |         |        |
| Kest_WB | 11    | 208.389| 18.944| 7.533    | Between Groups     | 4    | 2   | 1.977 | 0.214   | 0.808   | 3.316  |
| Spsych_WB| 11    | 206.398| 18.763| 8.786    | Within Groups      | 277  | 30  | 9.233 |         |         |        |
| IR_WB   | 11    | 215.278| 19.571| 11.379   | Total               | 281  | 32  |        |         |         |        |

Table 2a,b show dry-bulb (DB) and wet-bulb (WB) temperature measurements by the control instruments and test instrument groups over grass, concrete and sand surface areas. The means of the dry-bulb temperatures measured by the Kestrel and Sling Psychrometer (control groups) and by the IR Thermometer (test group) for grass, concrete or sand are not statistically different at $p \leq 0.05$, primarily for two reasons: (i) the calculated $p$-values (0.419 for grass) appear to be much larger than the probability level at 5%; and (ii) the F-ratio between groups and within groups (0.879) is much smaller than the F-critical (3.101) for the grass area. The same trends can be observed for the Concrete and Sand surfaces in Table 2a.

The means of the wet-bulb temperatures measured by the Kestrel and Sling Psychrometer (control groups) and by the IR Thermometer (test group) for grass, concrete or sand shown in Table 2b are also not statistically different at $p \leq 0.05$ for two reasons similar to those of the dry-bulb cases: (i) the calculated $p$-values (0.367 for Grass) appear to be...
much larger than the probability level at 5%; and (ii) the F-ratio between groups and within groups (1.015) is significantly smaller than the F-critical (3.105) for the grass surface. The same trends are seen for the concrete and sand surfaces in Table 2b.

3.3. Dry- and Wet-Bulb Temperature Measurements over Grass, Concrete and Sand Surfaces

The statistical data analysis of the experimental results shows that the IR Thermometer and wet paper towel technique described here can reliably quantify wet-bulb temperature compared to direct psychrometric and Kestrel wet-bulb measurements. Although cloud cover and a slight breeze provided ideal conditions, the IR Thermometers proved to be fast and effective for wet-bulb temperature measurements in nearly all conditions. Figures 2–4 show that dry- and wet-bulb temperatures measured by the IR Thermometer align well with the control Kestrel and Sling Psychrometer data sets, with an average difference of less than 5%. Note that data from the freezer experiments are not included in this <5% difference. Deviations from the control measurements can be partially attributed to solar heating contamination associated with man-made shading from direct sunlight, more specifically over the sand surface site due to the lack of shade and the utilization of a dark-colored (black) umbrella to shield the instrumentation from sunlight. Partly cloudy days also led to atmospheric and solar irradiance variability on time scales which likely were shorter than the time required to make each measurement. As stated previously, the total time to conduct all measurements over any of the particular surfaces studied was approximately 30 min, leading to plenty of opportunities for changes in sky conditions. Additionally, instances with high winds in the vicinity created notable fluctuations in IR Thermometer readings. For example, trials ~30–40 were collected on 2 June 2020 when winds of 7.5 m s$^{-1}$ (15 kt) gusting to 10 + m s$^{-1}$ (20 + kt) were observed at a nearby airport and military base (see Appendix A for trial number to date/time mapping).

The IR Thermometer dry-bulb temperature peaks seen in Figures 2a, 3a and 4a at trials 20, 47 and 69 (8 May, 3 June and 11 June) are directly attributable to high solar irradiance during those trials, affecting both the actual temperatures of the emitting surface and the internal temperatures of the IR Thermometer (despite attempts to maintain shade). Neither the Kestrel nor the Sling Psychrometer air (dry-bulb) temperature measurements were as affected at these times. However, the wet-bulb temperature plots in Figures 2b, 3b and 4b show much smaller differences among the Kestrel, Sling Psychrometer and IR Thermometer values at trials 20, 47 and 69. This suggests that the IR Thermometer dry-bulb temperature differences are due to the emitting dry paper towel surface becoming significantly warmer than the air temperature on sunny days, rather than the IR Thermometer losing accuracy due to solar-irradiance-induced temperature gradients within the IR Thermometer.

As mentioned above, trials 30–40 (1 and 2 June) were affected by wind speeds higher than those usually recommended for stable Sling Psychrometer evaporative cooling. This is readily seen in the wet-bulb plots of Figures 2b and 3b (and relative humidity values as seen in Appendix A). The IR Thermometer values are significantly lower than those of the Kestrel and Sling Psychrometer. The authors postulate that the wet paper towel material can reach stable evaporative cooling at significantly lower ventilation rates than those required for a Sling Psychrometer because of the lower heat capacity and mass of the paper towel compared to the glass and alcohol in the Sling Psychrometer wet-bulb thermometer. Thus, although the high winds (up to 10 m s$^{-1}$) that occurred during trials ~30–40 were on the upper end of acceptable WMO ventilation rates for a Sling Psychrometer [2], such wind speeds were likely too high for the wet paper towel to remain at a steady temperature if water continued to evaporate from the material. It appears that ventilation rates of less than 5 m s$^{-1}$ are more favorable for the IR Thermometer Psychrometric method described in this work.

The table in Appendix A captures the time required in each trial to obtain a steady-state wet-bulb temperature measurement for each instrument. In all trials, the Sling Psychrometer required at least two minutes of slinging at about two revolutions per second to arrive at a steady wet-bulb temperature. The Kestrel and IR Thermometer required much less
time to measure a wet-bulb temperature—usually about 30 s—but the Kestrel did have a few trials that required more than 90 s to reach a steady wet-bulb temperature. In all trials, the Sling Psychrometer required more time to obtain a steady dry-bulb temperature than the Kestrel and IR method. Overall, using the IR Thermometer Psychrometer was the fastest way to measure wet-bulb and dry-bulb temperatures. The Kestrel did provide instantaneous moisture parameter (e.g., relative humidity, vapor pressure, dew point) calculations that were not automatically derived with the Sling Psychrometer or IR Thermometer Psychrometer.

To obtain dew point temperatures from wet- and dry-bulb temperatures, psychrometric calculations, such as those outlined in Section 2.2; psychometric tables; or a psychrometric whiz wheel, such as that shown in Figure 6, must be used. The Bacharach Sling Psychrometer has a psychrometric slide-rule as part of the instrument, but this simple tool assumes a constant (presumably sea-level) pressure and a constant $L_v$, thus leading to inaccuracies. As such, the built-in Bacharach slide-rule tool was not used in this study. Appendix A lists the dew point temperatures as calculated from wet- and dry-bulb temperatures measured by the Sling Psychrometer and the IR Thermometer, or as read directly from the Kestrel. The dew point values are plotted in Figure 7 for all instruments with lines connecting the trial data points to allow the differences to be more easily seen. The Kestrel-displayed dew point temperatures were derived via the Kestrel’s built-in algorithm. As is evident in Figure 7, the USAF whiz wheel and the psychrometric equations in Section 2.2 provided virtually the same results. The USAF whiz wheel was predominantly used to obtain the dew point temperatures for the Sling Psychrometer. Figure 7 also shows the high wind scenario discrepancies noted previously. In particular, there were seven trials (32, 33–35, 37–39) in which high winds resulted in excessive evaporative cooling of the paper towel target and unreliable IR wet-bulb temperatures, which in turn led to poor dew point temperature and relative humidity calculations.

![Figure 7. Dew point temperatures measured by the Kestrel (black) and derived from dry- and wet-bulb measurements collected by the Sling Psychrometer (red), infrared thermometer (blue) and whiz wheel calculator (green).](image)

The possible utility of using IR Thermometers/detectors to evaluate moisture and heat fluxes near the surface was also explored in this research. In separate experiments, it was found that the IR sensor could be used to sense wet- and dry-bulb temperature changes of 0.7 °C and 0.6 °C over vertical distances as small as 50 cm, respectively. The results of these experiments using the Kestrel, IR Thermometer and paper towel pieces are shown in Figure 8. Lines are used to connect the data points across the trial times only to allow the differences between the values of each instrument to be more easily viewed. As referenced earlier, Figure 5 shows the vertical placement of the paper towels, and all data are available in Appendix A. The plots in Figure 8 demonstrate that both the Kestrel and IR Thermometer are able to discern the expected daytime near-ground temperature gradient—in which, over transpiring grass, the dry-bulb temperature is expected to rise slightly with height (in the first meter [8]). However, the transpiring grass should also result.
in greater moisture near the ground; therefore, the wet-bulb temperature should drop with height in the first meter above the surface [8]. Figure 8b shows that the IR Thermometer captures a significant drop with height in wet-bulb temperature. Interestingly, the Kestrel (Figure 8a) shows little or no change in wet-bulb temperature with height. Figure 9 isolates the measurements for the highest and lowest positions so that the vertical gradients are more easily discernible in the plots. Section 4 expands on these observations to outline the physical basis which permits use of the IR Thermometer Psychrometer for moisture flux measurements.

Figure 8. Vertical variations in dry-bulb (solid lines) and wet-bulb (dashed lines) temperatures measured by (a) the Kestrel and (b) the infrared thermometer at 28, 46, 64, 81 and 99 cm above a grassy surface. Note: the Sling Psychrometer was not used in this part of the experiment because it was impractical and unsafe to spin the device near the ground.

Figure 9. Vertical variations in dry-bulb (solid lines) and wet-bulb (dashed lines) temperatures measured by (a) the Kestrel and (b) the infrared thermometer at 28 and 99 cm above a grassy surface.
4. Potential Flux Measurement Method

The word ‘flux’ can be defined in very simple terms: how much of something passes through a unit area, or a unit volume, per unit time. For instance, if 100 birds fly through a $1 \times 1 \text{ m}^2$ window each minute, then the flux of birds is $100 \text{ birds m}^{-2} \text{ min}^{-1}$. If the window was $5 \times 5 \text{ m}^2$, the flux would be $4 \text{ birds m}^{-2} \text{ min}^{-1}$. Therefore, the flux is dependent on: (i) the number of things crossing an area/volume, (ii) the size of an area/volume being crossed and (iii) the time it takes to cross this area or pass through this volume. In more scientific terms, the flux can be defined as the amount of flow of a fluid, the amount of radiation or the number of particles incident through a flat surface in a given time [14–16]. Flux is also synonymously stated as flow rate per unit area. In transport phenomena (heat transfer, mass transfer and fluid dynamics), flux is defined as the rate of flow of a property per unit area, which has the dimensions [quantity] [time]$^{-1}$ [area]$^{-1}$ [17].

There is a constant exchange of thermal energy, moisture (i.e., water vapor) and gases between the soil and the atmosphere. Atmospheric moisture is the resultant product of evapotranspiration and precipitation [14–16]. There are several procedures employed to measure heat and moisture flux. Their applications and usages are situational and, moreover, dependent on the nature of objects, equipment and resources. Each technique has its own advantages and disadvantages. Nonetheless, the proposed technique of using a handheld IR Thermometer for deriving the heat and moisture flux is inexpensive and easy to use for various ground and water surfaces, such as: a green and dry vegetation canopy, tree lines of a uniform surface/canopy, mixed vegetation with varying canopy heights, as well as seas, lakes, rivers and ponds. Although using an IR Thermometer to determine heat flux appears to be a relatively straightforward argument, using a standard handheld IR Thermometer to accurately evaluate moisture flux requires more discussion. The following suggests that the proposed use of an IR Thermometer Psychrometer indeed has merit.

Both sensible heat flux, $Q_H$ and moisture flux, $Q_E$ (also called latent heat flux) can be quantified per unit area from vertical profile measurements of temperature and specific humidity [8,18]. These vertical profile gradients can be obtained from the dry- and wet-bulb IR temperature measurements, as demonstrated with the paper towels oriented in a vertical fashion as described in the previous section. Specific humidity can be calculated from the obtained vapor pressures and ambient pressure via

$$q = \frac{0.622e}{P - 0.378e},$$  
(6)

where $q$ is the specific humidity of air vapor mixture, $e$ is the vapor pressure and $P$ is the atmospheric air pressure. According to Oke [8], $Q_H$ and $Q_E$ ($\text{W m}^{-2}$) are given by

$$Q_H = -\rho c_{pd} K_H \left( \frac{\partial T}{\partial z} - \Gamma \right),$$  
(7)

$$Q_E = -\rho L_v K_w \frac{\partial e}{\partial z}$$  
(8)

where $\rho$ is the air density ($\text{kg m}^{-3}$), $c_{pd}$ is the specific heat of dry air ($\text{J kg}^{-1} \text{ K}^{-1}$) at constant pressure, $K_H$ is the eddy conductivity or diffusivity for heat ($\text{m}^2 \text{s}^{-1}$), $\partial T/\partial z$ is the vertical temperature gradient derived from the dry-bulb temperatures, $\Gamma$ is the dry adiabatic lapse rate ($-9.8 \text{ K km}^{-1}$), $L_v$ is the latent heat of vaporization ($\text{J kg}^{-1}$), $K_w$ is the eddy diffusivity for water vapor ($\text{m}^2 \text{s}^{-1}$) and $\partial e/\partial z$ is the vertical moisture gradient derived from the wet-bulb temperatures. This method to obtain $Q_H$ and $Q_E$ however, requires knowledge of $K_H$ and $K_w$, which can vary significantly with location and environmental conditions.

Oke and Stull offer another method to quantify $Q_H$ and $Q_E$ that does not require values for the eddy diffusivities of heat and water vapor [8,18]. This is the Bowen’s Ratio ($\beta$) method that combines the ratio of $Q_H$ over $Q_E$ with a measurement of the net all-wave radiation obtained by a net pyrradiometer device ($Q^*$) and with the ground/surface
temperature flux \( (Q_G) \) measured with a ground heat flux plate or soil temperature probes at different depths. In this case, \( \beta \) can be found without \( K_H \) and \( K_w \) from:

\[
\beta = \frac{Q_H}{Q_E} = \frac{c_p d T}{L_v \Delta q}, \tag{9}
\]

and \( Q_H \) and \( Q_E \) are obtained from:

\[
Q_H = \beta (Q^* - Q_G) / (1 + \beta) \quad \text{and} \quad Q_E = \frac{Q^* - Q_G}{1 + \beta}, \tag{10}
\]

According to previous research, which suggests the physical basis for applying an IR Thermometer for moisture flux measurements, Mzad successfully measured temperature gradients and heat flux using an IR Thermometer for tribological applications \[19\]. Perhaps the strongest published evidence indicating our proposed inexpensive and simple handheld IR Thermometer has definite merit for assessing moisture flux is that authored by Lee and Wang \[10\], and noted earlier in this paper. In the course of design and demonstration of a more efficient wick central to their digital psychrometer commonly used in greenhouses, Lee and Wang developed a comprehensive evaporative model using an IR digital thermometer to quantitatively track moisture flux in their instrument’s captive wick, thus predicting when the wick’s water reservoir needed to be filled. Although the ultimate objective herein is to use the proposed IR Thermometer Psychrometer to assess the moisture flux between the Earth’s surface or surface canopy and the atmosphere, Lee and Wang highlighted the practicability of achieving relatively accurate moisture flux using an IR Thermometer and fundamental evaporative and psychrometric relationships. There are several interesting challenges to be explored using the IR Thermometer Psychrometer for earth–atmosphere moisture flux measurements, one of those being the determination of emissivity, with sufficient accuracy, for the various earth surface types that one is likely to encounter. To sum up the above, a combination of an IR Thermometer together with instrumentation to measure pressure (e.g., a Kestrel) appears to be an inexpensive alternative configuration with capabilities comparable to traditional soil/air moisture and temperature instrumentation suites normally employed for moisture flux measurements (see Appendix A of Oke \[8\]). In summary, the previous discussion supports the hypothesis that IR sensors/detectors can be used for determining near-surface moisture and heat fluxes.

5. Conclusions

This study describes a lower-cost, time-efficient method to obtain psychrometric wet- and dry-bulb temperatures using an infrared thermometer, hand-held fan and paper towels. It also demonstrates the viability of replacing multiple, vertically-stacked dry- and wet-bulb thermometers with a single non-contact IR temperature sensor to measure temperature and moisture gradients/fluxes in the first 1–2 m of the surface layer. The materials and tools used cost less than 50 USD total to acquire and operate. The IR technique to obtain the ambient air and wet-bulb temperatures was validated with Kestrel 4000 (discontinued; the Kestrel 5000 replacement typically costs 259 to 319 USD) and Bacharach Sling Psychrometer (typical cost: ~85 USD) measurements under various atmospheric conditions, as well as over different surface types to test the versatility of the method. Standard meteorological surface data were collected during each experiment, and moisture parameters were derived via psychrometric equations and were further compared to the results obtained with a USAF psychrometric whiz wheel. The IR method described herein was shown to be robust in many environmental settings—both indoors (see Appendix A, trials 54–62) and outdoors—if the IR Thermometer is shaded from direct sunlight, shielded from strong winds (>5 m s\(^{-1}\)) and in near equilibrium with its immediate surrounding environment. Moreover, wet-bulb measurements were on average \(-0.3\) K different from the control Kestrel wet-bulb values. Significantly, when the seven trials with high winds are removed,
this average Kestrel wet-bulb to IR wet-bulb difference is reduced to approximately the same average difference as it is when comparing Kestrel to Sling Psychrometer wet-bulb differences (<0.1 K). In general, it took at least two minutes of whirling/spinning the Sling Psychrometer to obtain a steady dry- and wet-bulb set of readings, whereas the IR Thermometer typically steadied in less than 30 s. Finally, the possible utility of using a single IR Thermometer/detector to evaluate moisture and heat fluxes near the surface was explored. Indeed, the case was made suggesting that the IR sensor can be used to sense wet-and dry-bulb temperature changes of 0.7 K and 0.6 K, respectively, over vertical distances as small as 50 cm, thus allowing surface layer temperature and moisture gradients/fluxes to be quantified. The feasibility of this single IR detector method to provide values of surface layer heat and moisture fluxes with reasonable certainty suggests the technique can be exploited with more efficiency and accuracy with a calibrated imaging IR camera or sensor array.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The measured and derived experimental data from trials conducted in Dayton OH in June–July 2020 are shown. In addition to the date and time, sky conditions and surface types were documented to explore the versatility and limitations of the IR Thermometer technique.
### Acknowledgments

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### Conflicts of Interest

The authors declare no conflict of interest.

### Appendix A

The measured and derived experimental data from trials conducted in Dayton OH in June–July 2020 are shown. In addition to the date and time, sky conditions and surface types were documented to explore the versatility and limitations of the IR Thermometer technique.

#### Figure A1

Experimental data conducted in Dayton OH in June–July 2020, Trials 1-47.

| Trial | Date       | Time      | Type (AED) | Wind Speed | Sky Condition | Surface Type | Temperature | Latency | Distance | Dew Point | RH (%) | Dew Point (°C) | Viscosity | Error | Error Rate |
|-------|-------------|-----------|------------|------------|---------------|--------------|--------------|----------|----------|------------|---------|-----------------|-----------|-------|------------|
| 1     | 3/8/2020   | 10:30 a.m.| early morning | 0.12       | N/A          | N/A          | N/A          | 0.5      | 100      | 0.0        | 0.12    | 0.5             | 0.12      | N/A   | N/A        |
| 2     | 3/8/2020   | 10:30 a.m.| early morning | 0.12       | N/A          | N/A          | N/A          | 0.5      | 100      | 0.0        | 0.12    | 0.5             | 0.12      | N/A   | N/A        |
| 3     | 3/8/2020   | 10:30 a.m.| early morning | 0.12       | N/A          | N/A          | N/A          | 0.5      | 100      | 0.0        | 0.12    | 0.5             | 0.12      | N/A   | N/A        |
| 4     | 3/8/2020   | 10:30 a.m.| early morning | 0.12       | N/A          | N/A          | N/A          | 0.5      | 100      | 0.0        | 0.12    | 0.5             | 0.12      | N/A   | N/A        |
| 5     | 3/8/2020   | 10:30 a.m.| early morning | 0.12       | N/A          | N/A          | N/A          | 0.5      | 100      | 0.0        | 0.12    | 0.5             | 0.12      | N/A   | N/A        |

Figure A1. Experimental data conducted in Dayton OH in June–July 2020, Trials 1–47.
| Date       | Time       | Location          | Trials  |
|------------|------------|-------------------|---------|
| 06/04/2020 | 4:30 p.m.  | Dayton OH         | 48-91   |
| 06/04/2020 | 11:00 a.m. | Dayton OH         | 48-91   |
| 06/04/2020 | 3:00 p.m.  | Dayton OH         | 48-91   |
| 06/04/2020 | 12:00 p.m. | Dayton OH         | 48-91   |
| 06/04/2020 | 11:00 a.m. | Dayton OH         | 48-91   |
| 06/04/2020 | 3:00 p.m.  | Dayton OH         | 48-91   |

Figure A2. Experimental data conducted in Dayton OH in June–July 2020, Trials 48–91.
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