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13. ABSTRACT *(Maximum 200 words)*
The wristwatch size automatic physiological and environmental monitor (WAPEM) is a miniature instrument worn on the wrist, capable of measuring relative humidity (RH), ambient temperature (Ta), solar radiation (SR), and human activity in a small durable enclosure. The purpose of this study was to evaluate newly installed Ta and RH microsensors in WAPEM. Three WAPEM prototypes, which included new Swiss sensors, two Kestrel 3000 pocket weather meters (Nielsen & Kellerman), and two psychrometers (Lambrecht), were tested to compare the environmental sensors (Ta and RH), both in a climatic chamber and outdoor in Israel. The tests in the climatic chamber were conducted at 16 different exposures consisting of different combinations of Ta (20 degree -40 degree C) and RH (35%-70%). The outdoor evaluation was conducted in ten different locations in Israel, near the Israeli Meteorological Service (IMS) stations during January 2004. Environmental stress indices, wet bulb globe temperature (WBGT) and environmental stress index (ESI), were calculated and compared with data collected by the different devices. Generally, the measurements of the new Swiss microsensors highly correlate with measurements from sensors used in the climatic chamber or by the IMS in outdoor environments. However, at Ta> 35 degree C significant differences were found between the chamber measurements and the WAPEM measurements. Therefore, further evaluation is needed for these Swiss microsensors at Ta> 35 degree C before they are permanently positioned and embedded in WAPEM.

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TECHNICAL TESTING OF THE WRISTWATCH SIZE AUTOMATIC PHYSIOLOGICAL AND ENVIRONMENTAL MONITOR (WAPEM): LABORATORY AND OUTDOOR EVALUATIONS OF ENVIRONMENTAL SENSORS PERFORMANCE

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ACKNOWLEDGMENTS

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This research was performed while the first author held a National Research Council Associateship Award at the US Army Research Institute of Environmental Medicine.

LIST OF ABBREVIATIONS AND ACRONYMS

ESI – environmental stress index

GR – global radiation

IMS – Israeli Meteorological Service

IR – infrared light sensor

PSI – physiological strain index

P – pyranometer

RH – relative humidity

$RH_{chamber}$ – relative humidity measured by the climatic chamber sensor

RH_{WAPEM} – relative humidity measured by the WAPEM sensor

SR – solar irradiance

T_a – dry bulb temperature

$T_{a,\ chamber}$ – ambient temperature measured by the climatic chamber sensor

$T_{a,\ WAPEM}$ – ambient temperature measured by the WAPEM sensor

T_g – black globe temperature

T_{wb} – wet bulb globe temperature

V_a – wind velocity

WAPEM – Wristwatch size automatic physiological and environmental monitor

WBGT – wet bulb globe temperature index

EXECUTIVE SUMMARY

The wristwatch size automatic physiological and environmental monitor (WAPEM) is a miniature instrument worn on the wrist, capable of measuring relative humidity (RH), ambient temperature (T_a), solar radiation (SR), and human activity in a small, water-resistant, durable enclosure. It is fitted with a 4-digit display that can be used to view each of these parameters by using selection buttons on the front face. When not in data mode, WAPEM serves as the wearer's primary timepiece. WAPEM can be programmed through a personal computer from a simple initialization of existing firmware to a complete rewrite of this firmware, because WAPEM is circuit reprogrammable. It is therefore possible to make changes to the WAPEM operational code and, in particular, the formulation of stress/strain algorithms used to make predictions based upon on-line measurements, or a history of humidity, temperature, SR, and human activity. The activity channel is designed to function for sleep scoring (ZCM), as well as monitoring daytime activity with the proportional channel (PIM). The proposed WAPEM is designed to provide the capability to quantify sleep loss and metabolic expenditures for the individual warfighter, and to enable personalized estimates of the effects of several key stressors on physical or mental performance in operational settings.

Three WAPEM prototypes, which included new Swiss sensors, two Kestrel 3000 pocket weather meters (Nielsen & Kellerman), and two psychrometers (Lambrecht), were tested to compare the environmental sensors (T_a and RH), both in a climatic chamber and outdoors in Israel. The tests in the climatic chamber were conducted at 16 different exposures consisting of different combinations of T_a (20º-40ºC) and RH (35%-70%). The outdoor evaluation was established in ten different locations in Israel, near the Israeli Meteorological Service stations (Jehuda Desert, Negev Desert, Eilat area, Dead Sea, Jerusalem, and Tel-Aviv). These sites differed in latitude and climatic conditions. This study was conducted during January 2004. Data analysis included comparisons between measurements by the new Swiss sensors and all the other sensors (Kestrel meters and psychrometers) and IMS data. Environmental stress indices, wet bulb globe temperature (WBGT) and environmental stress index (ESI), were calculated and compared with data collected by the different devices.

It was concluded from this study that the measurements of the new Swiss environmental micro-sensors in the WAPEM prototypes highly correlate with measurements from sensors used in the climatic chamber or by the Israeli Meteorological Service (IMS) in outdoor environments. However, at high ambient temperatures (>35ºC), significant differences were found between the chamber measurements and the WAPEM measurements. Therefore, further evaluation is needed for these Swiss microsensors at T_a>35ºC before these microsensors are positioned and embedded permanently in WAPEM.

INTRODUCTION

The evolution of strategies to manage heat injury risk in military settings has focused on the idea that if the prevailing heat stress can be adequately quantified, then appropriate counter measures can be implemented to optimize Soldiers' performance and minimize the risk of heat injury. Although physiological heat strain and the potential for heat injury are determined, to a great extent, by air temperature, humidity, solar radiation and wind speed, the Soldier's clothing characteristics, heat acclimatization status, and activity level also play a significant role. As the U.S. Army's warfighting doctrine evolves in the direction of lightened forces, increasing tactical mobility, and an emphasis on protective posture scenarios, the need to account for these complex interactions has increased. At the small unit level, where soldiers may be conducting their mission tasks in a hot shelter space, a crew compartment, or an outdoor environment, the capability to provide realtime tailored guidance requires the integration of reliable sensors and predictive model technologies in an ultra lightweight, friendly-to-use, wristwatch size automatic physiological and environmental monitor (WAPEM).

Existing military heat stress monitoring systems are based largely on the Wet Bulb Globe Temperature (WBGT). This system provides the user with a single temperature, or index, which can be used for looking up tables of recommended work/ rest cycle limits and hourly drinking water requirements that constitute current heat injury prevention doctrine (1, 2). The low cost mechanical device widely available to Army users is the Stortz WBGT Kit (NSN 6665-00-159-2218). The U.S. Navy has a more sophisticated electronic WBGT meter (NSN 6685-01-055-5298), intended primarily for use aboard ship. The inherent limitations of the WBGT in terms of applicability across a broad range of potential military scenarios and environments have been reported (3, 4, 5, 6, 11). These limitations can be attributed, in part, to early constraints on sensor and computational complexity (12), but a more fundamental limitation is the conceptual basis itself: WBGT is exclusively environmental and does not directly evaluate strain potential in the context of clothing and metabolic factors.

Mathematical models of human heat strain allow full consideration of the complex interactions of environment, clothing, acclimatization status, and metabolic heat production that ultimately determine soldier performance limits in a given scenario, although some predictive models are computationally very intensive. In early 1990, USARIEM proposed the consideration of a heat stress monitoring device that would integrate an environmental sensor suite with the calculator's heat strain prediction model software. This approach takes advantage of advances in sensor, display, and microprocessor technologies to enable direct read-out of work/rest cycle limits and hourly water requirements based on specified clothing and work rate scenarios. The merged monitor/calculator concept was endorsed by the material developer, U.S. Army Medical Material Development Activity (USAMMDA), Ft. Detrick, Frederick, MD. A recommendation (SGRD-UMA/ 24 Jan 1990, 1st End SGRD-UE-ZB/ 16 Jan 90) to develop an Organizational and Operational (O&O) Plan for the electronic heat stress monitor was sent to the Academy of Health Sciences (AHS), Ft. Sam Houston, TX (10). Following a meeting sponsored by the Office of The Surgeon General (OTSG) on the prevention and treatment of heat injuries, held at Natick, MA, in April 1990, the AHS prepared a draft concept statement, “Heat Stress Prediction and Prevention Program” (HSHA-CDS, 4 May 1990) that outlined a comprehensive hierarchical approach to the problem. That document provided the basis for the draft “O&O Plan for Environmental Health Monitoring Equipment (EHME)” (HSHA-CM, 7 May 91), which included the merged Heat Stress Monitor/ Calculator concept.

The WAPEM addresses requirements identified in the Index of Medical Cpability Issues, January 1992, prioritized number 4 of 26: “Inadequate Capability to Prevent/Minimize Endemic Disease/Environmental Injury.” Although an O&O Plan for a family of Environmental Health Monitoring Equipment (EHME) received preliminary approval in 1991, changes in the Concept Based Requirements System (CBRS) documentation formats necessitated a rewrite by AHS. At the present time, the formal, specific requirements documentation for WAPEM consists of a Mission Essential Needs Statement (MENS) and an Operational Requirements Document (ORD).

In a previous study (9), the three environmental sensors (air temperature, relative humidity, and global radiation (GR)) were evaluated in indoor and outdoor environments. It was found that GR, which was measured by Infra- red (IR) light sensor (Centro Vision, Model CD-1705), was reliable and accurate, but the T_a and RH sensors were needed to be replaced with more accurate sensors. The IR light sensor is located on the top panel of the WAPEM and has a peak sensitivity of 800-920 nm. The accuracy of this IR sensor was $\pm$5%, and the effects of temperature were negligible. The WAPEM IR light sensor circuitry provides a transconductance amplifier function. The current produced, proportional to 850 nm IR light intensity, is converted to a voltage proportional to light intensity. The scaling of the conversion is adjustable over a wide range. The linear voltage is proportional to light intensity (LIT), and output is measured by the 10 bit A/D converter, providing resolution over the determined range. The measurements are calibrated in $W \cdot m^{-2}$ under microprocessor control. In 2003 the WAPEM project was submitted and received a SBIR Phase I by Precision Control Design (PCD) Company located in Ft. Walton Beach, FL.

The purpose of this study was to evaluate and determine the accuracy of newly installed T_a and RH Swiss sensors in WAPEM across a broad range of controlled environmental conditions and under outdoor climatic conditions. The results and the conclusions from this study are important and critical for the future feasibility of the WAPEM concept and project.

METHODS

Three WAPEM prototypes, with newly installed T_a and RH Swiss microsensors (Sensirion, Switzerland), were used for sensor evaluation in two separate indoor and outdoor studies. Measurements were taken by the three WAPEMs (Precision Control Design, USA), two Kestrel 3000 pocket weather meters (Nielsen and Kellerman, USA), and two psychrometers (Lambrecht, Germany). The measurements obtained by the different devices were used to calculate environmental stress indices (WBGT and ESI).

INDOOR STUDY

For the indoor study, measurements were established in a climatically controlled test chamber at the Heller Institute of Medical Research, Israel. A test conditions matrix of the 16 different environments is shown in Table 1. This matrix supported both the sensor tests and software evaluations. WAPEM measurements at the 16 different test environments were taken by three prototypes to allow a statistical evaluation of sensors. The prototype WAPEM outputs (diagnostics screen) for T_a and RH were also

Table 1. Climatically controlled environmental test conditions for the WAPEM sensors.

Air Temperature (ºC)	Relative Humidity (%)
20.0	45.0
	50.0
	60.0
	70.0
25.0	50.0
	60.0
	70.0
30.0	40.0
	50.0
	60.0
	70.0
35.0	35.0
	50.0
	60.0
40.0	40.0
	45.0

compared with values measured using calibrated laboratory grade sensors, having an overall accuracy specification of ±0.2ºC and repeatability of ±0.5ºC for T_a, and ±1% for relative humidity.

OUTDOOR STUDY

The outdoor evaluation of the T_a and RH sensors was established in ten different locations in Israel with various latitudes and climate conditions, located in Jehuda Desert, Negev Desert, Eilat area, Dead Sea, Jerusalem, and Tel-Aviv. All the sites are official stations of the Israel Meteorological Service (IMS), which made their recording data available for our study. In general, data collection was measured and recorded each day at the different locations, between 09:00 and 17:00 at 10 min intervals. The same sensors were used in this study as for the indoor study. However, black globe temperature (T_g), wind velocity (V_a), and GR were also measured in the outdoor study.

Technical testing requirements are formally defined in the Test and Evaluation Master Plan (TEMP) for the WAPEM (memo, 2000). This protocol and subsequent USARIEM efforts focused on test requirement issues that relate directly to sensor accuracy and reliability of WAPEM. Sensor specifications, the performance requirements for the climatic sensors, are shown in Table 2.

Table 2. WAPEM's climatic-tested sensors (ambient temperature and relative humidity) system performance specifications.

SENSOR SYSTEM PERFORMANCE AND SPECIFICATIONS			
Parameter	Sensor type	Accuracy	Range
Air Temperature	Thermistor	± 0.5ºC	5 - 65ºC
Relative Humidity	Capacitive	± 5% RH	0 – 100% RH

SENSOR SPECIFICATIONS

<u>WAPEM Sensors</u>

The microsensors (SHT75, Sensirion, Switzerland) that were assembled in 5 WAPEMs were constructed on one unit and defined as high-precision relative humidity and temperature sensors for demanding applications. The sensors came in high-quality pin-type packaging (for 1.27 mm sockets). Owing full calibration and digital 2-wire output (CMOSens® technology), the SHT75 is fully interchangeable. In this way, it is possible to spare the elaborate and cost-intensive recalibration in the event of a humidity sensor replacement.

The sensor head is connected to the pins by a small bridge to minimize heat conduction and response time. All pins are gold plated to avoid corrosion, even under the harshest operating conditions. According to the manufacturer, this single chip sensor module, is fully calibrated with digital 2-wire output. The measured range for RH is 0%-100% and for T_a is -40º to 120ºC. The sensor is fully interchangeable without recalibration, and accuracy for RH is $\pm$2% and for T_g $\pm$0.4ºC at T_a of 5º-40ºC. The response time for measurements should be <3 sec. All of these specifications are within the performance requirements listed in Table 2.

Israel Meteorological Service (IMS) Sensors

The Israel Meteorological Service (IMS) collected weather measurements for the ten locations using their own equipment. The T_a and wet bulb temperature (T_{wb}) were measured with Campbell thermometers (Model HMP45C), and the relative humidity (RH) was measured with a Rotronic instrument (Model MP 100A). The three instruments were placed under a shelter (Stevenson screen). Under open sky, T_g was measured using the Vernon black globe thermometer and solar radiation (SR) was measured using the EPLAB radiometer (sensitivity of 285 to 2800 nm)

CALCULATIONS

All measurements and calculations were done in ºC. The wet bulb globe temperature (WBGT) index was calculated according to Yaglou and Minard (12), as follows:

$$WBGT=0.7T_{wb}+0.2T_g+0.1T_a.$$

The environmental stress index (ESI) was calculated according to Moran et al. (8), as follows:

$$ESI=0.62T_a-0.007RH+0.002SR+0.0043(T_a\cdot RH)-0.078(0.1+SR)^{-1}.$$

STATISTICAL ANALYSIS

Statistical analysis including two tail, paired T-test and Pearson correlation factor (R) was done. The T-test was used to find significant differences between readings from pairs of instruments (WAPEM vs. IMS, Kestrel, or psychrometer). Pearson correlation factor (R) was calculated to analyze the correlation between the instruments. All statistical contrasts were accepted at the P<0.05 level of significance.

RESULTS

INDOOR STUDY

Ambient Temperature Sensor

In general, the WAPEM's measurements for T_a at the different ambient temperatures (20º, 25º, 30º, 35º, and 40ºC) revealed no significant differences between the three T_a sensors installed in WAPEM at each of these exposures. Analysis of the T_a measurements in comparison to the chamber sensors, Kestrels, and the psychrometers are depicted in Figures 1-8. Pooled data from each type of sensor, measured at the same T_a but for different humidity conditions, are presented in Table 3. A more detailed presentation of measured data from each device is presented in Appendix A. Collectively, at temperatures $\leq$35ºC, the WAPEM's performances were within the accuracy defined as $\pm$0.5ºC. However, at climatic conditions of 40ºC, T_a measurements were significantly lower ($P<0.05$) by an average of 2.5ºC for the WAPEM sensors and by an average of 1.3ºC for the Kestrel.

Table 3. Mean±SD of ambient temperature (T_a) measured by 2 Psychrometers, 2 Kestrels, and the 3 new WAPEM sensors in the climatic chamber. T_a was calculated from pooled data measured at each different relative humidity.

Measured Ambient Temperatures (°C)					
Set point	Chamber	Psychrometers	Kestrels	WAPEMs	Chamber-WAPEM
20	20.17±0.12	20.65±0.32 20.17±0.29	20.57±0.19 20.50±0.21	20.38±0.20 20.40±0.19 20.21±0.27	0.21 0.23 0.04
25	24.91±0.10	25.03±0.51 25.05±0.57	24.73±0.32 24.60±0.32	24.68±0.42 24.55±0.41 24.38±0.26	0.26 0.36 0.53
30	29.85±0.15	30.58±0.46 30.29±0.40	29.76±0.39 29.61±0.32	29.59±0.31 29.48±0.32 29.51±0.24	0.26 0.37 0.34
35	35.02±0.18	35.35±0.66 35.00±0.61	35.06±0.45 34.87±0.38	34.82±0.60 34.71±0.51 35.00±0.32	0.20 0.31 0.02
40	40.04±0.24	40.29±0.80 40.34±0.73	*38.85±0.79 *38.66±0.65	*36.98±0.91 *37.72±1.11 *37.58±0.99	3.06 2.32 2.46

*Significant differences ($P<0.05$) from the measurements of the sensors' chamber

For the WAPEM, part of these significant differences were because of the extended time needed for these Swiss T_a sensors to reach equilibrium with the chamber environment. Analysis of the time response to reach equilibrium for the T_a sensors at $\leq$35ºC revealed that in a few exposures, the T_a sensors measured actual values only after 30 min [e.g., at 30ºC (Fig. 4 bottom)], 50 min [e.g., at 25ºC (Fig. 3 bottom)], and 60 min [e.g., at 25ºC (Fig. 4 top)]. At these exposures, the deviations were less than 1ºC from actual measurements. Analysis of the time response for equilibrium at 40ºC depicted that the sensors reached the required equilibrium temperature within 100 min (Fig. 8 top).

Relative Humidity

In all of the 16 tested exposures, measurements from the same three RH Swiss sensors were not significantly different from each other, as depicted in Table 4 and Figs. 1-8. In general, RH measurements by WAPEM were highly correlated to the chamber sensor. Analysis of the comparison between $RH_{chamber}$ and RH_{WAPEM} showed no significant differences in all of the exposures, apart from the exposure of 35ºC and 50%, when RH_{WAPEM} was lower by 8% from $RH_{chamber}$ (Fig. 7, top panel). Generally, slightly lower stable values (less than 6%) were observed in the different exposures (Table 4). However, analysis of the response time for the sensors to reach equilibrium revealed that at 25ºC and 30% RH, the sensors reached equilibrium only after 40 min, (Fig. 4 top) and at 40ºC 40%, only after 100 min (Fig. 8 bottom). Thus, significant differences ($P<0.05$) between RH_{WAPEM} and $RH_{chamber}$ were found during these periods for three exposures before RH_{WAPEM} measurements were stabilized. It is well noted that $RH_{Kestrel}$ was better correlated with $RH_{chamber}$. On the other hand, correlation between RH_p and $RH_{chamber}$ was low for a few exposures. The latter is probably due to the fact that the psychrometer measures T_{wb} rather than RH, which is later calculated from T_{wb}.

Table 4. Mean±SD of relative humidity (RH) measured by 2 Psychrometers (RH_P), 2 Kestrels (RH_K), and the 3 new WAPEM (RH_{WAPEM}) sensors in the climatic chamber.

Climatic chamber set point		RH_P (%)	RH_K (%)	RH_{WAPEM} (%)
T_a (°C)	RH (%)			
20	40	51±2 47±4	38±0 37±1	37±1 37±1 37±1
	45	48±1 48±0	44±1 44±1	43±0 43±1 43±0
	50	55±2 53±2	49±1 48±1	46±1 46±1 46±1
	60	62±2 64±0	62±1 62±1	58±1 58±0 57±1
	70	73±0 74±4	75±3 74±3	69±2 69±1
25	50	52±2 49±2	52±2 53±2	50±1 51±2
	60	65±2 64±0	63±2 62±1	57±1 58±1 57±1
	70	77±4 78±4	78±3 78±3	72±4 72±4
30	40	45±3 39±3	38±2 36±2	36±1 36±1 36±1
	50	50±2 51±2	50±1 50±2	47±1 48±2
	60	63±2 62±2	62±1 61±1	59±2 59±2 59±2
	70	73±3 71±1	76±1 75±0	70±1 69±0
35	40	36±1 36±3	34±1 33±1	34±1 33±1 33±1
	50	51±2 46±5	47±2 46±2	41±2 42±1 42±2
	60	62±2 62±3	59±1 59±1	55±1 55±1
40	40	39±2 41±3	37±1 36±2	39±2 37±3 37±3
	40	40±2 39±2	36±1 35±1	34±1 34±1
	45	48±2 43±3	44±1 42±1	44±2 44±2

Figure 1. WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements (S_1, S_2, S_3) compared with the Kestrel (K_1, K_2) and the Psychrometer (P_1, P_2) measurements in climatic chamber at T_a of 20ºC and RH of 45% (top) and 50% (bottom) during 60 min.

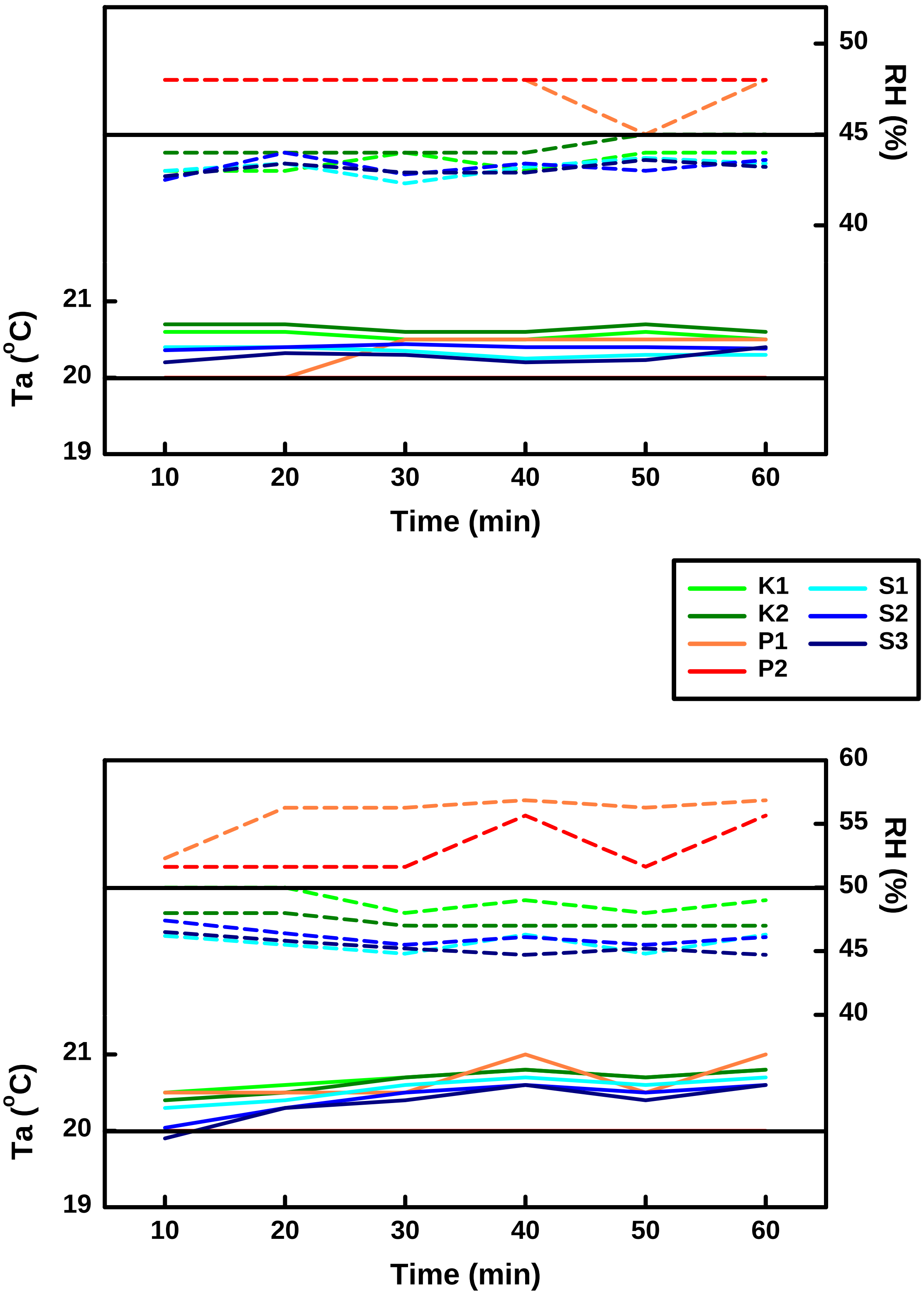


Figure 2. WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements (S_1, S_2, S_3) compared with the Kestrel (K_1, K_2) and the Psychrometer (P_1, P_2) measurements in climatic chamber at T_a of 20ºC and RH of 60% (top) and 70% (bottom) during 60 min.

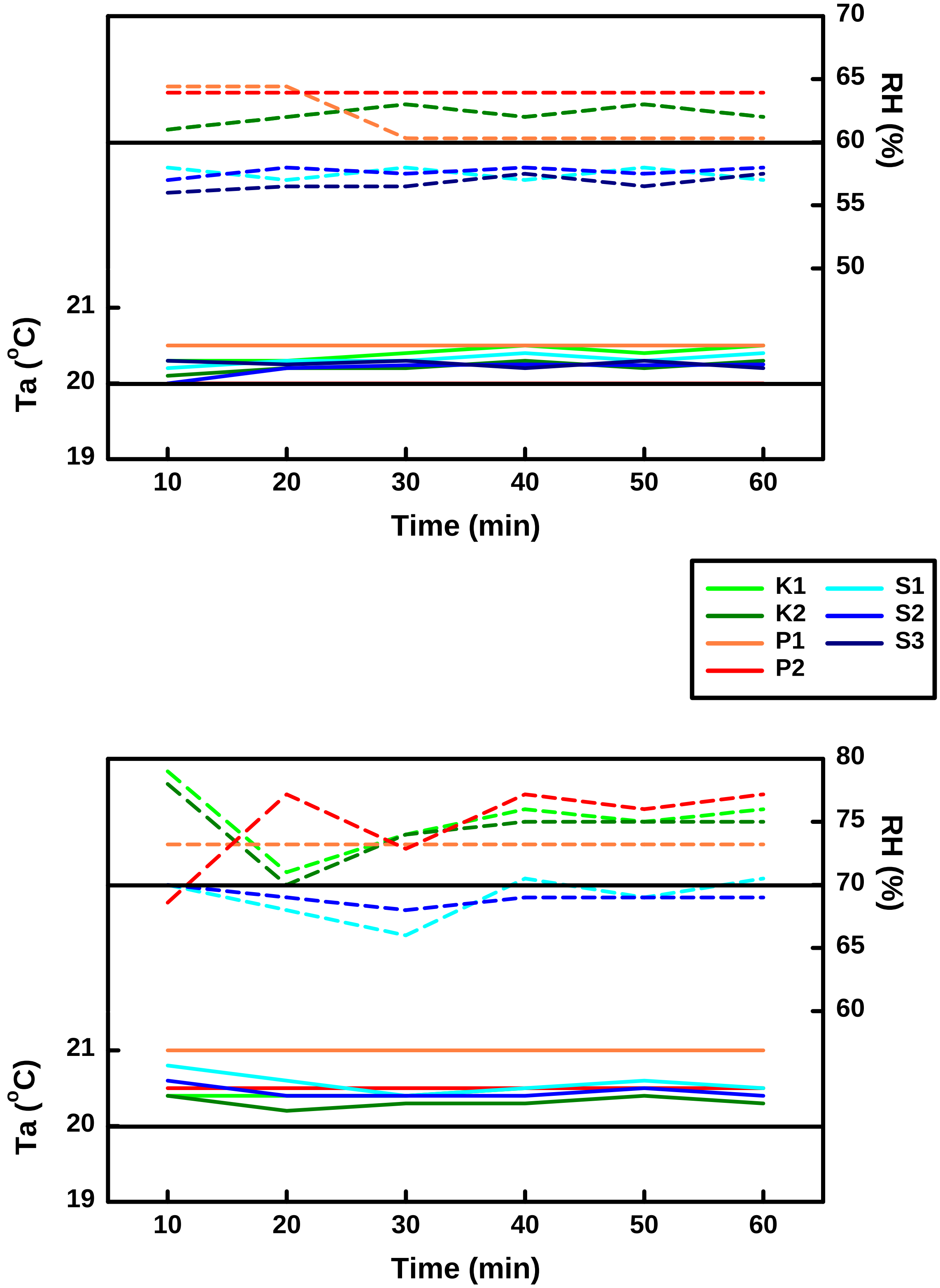


Figure 3. WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements (S_1, S_2, S_3) compared with the Kestrel (K_1, K_2) and the Psychrometer (P_1, P_2) measurements in climatic chamber at T_a of 25ºC and RH of 50% (top) and 60% (bottom) during 60 min.

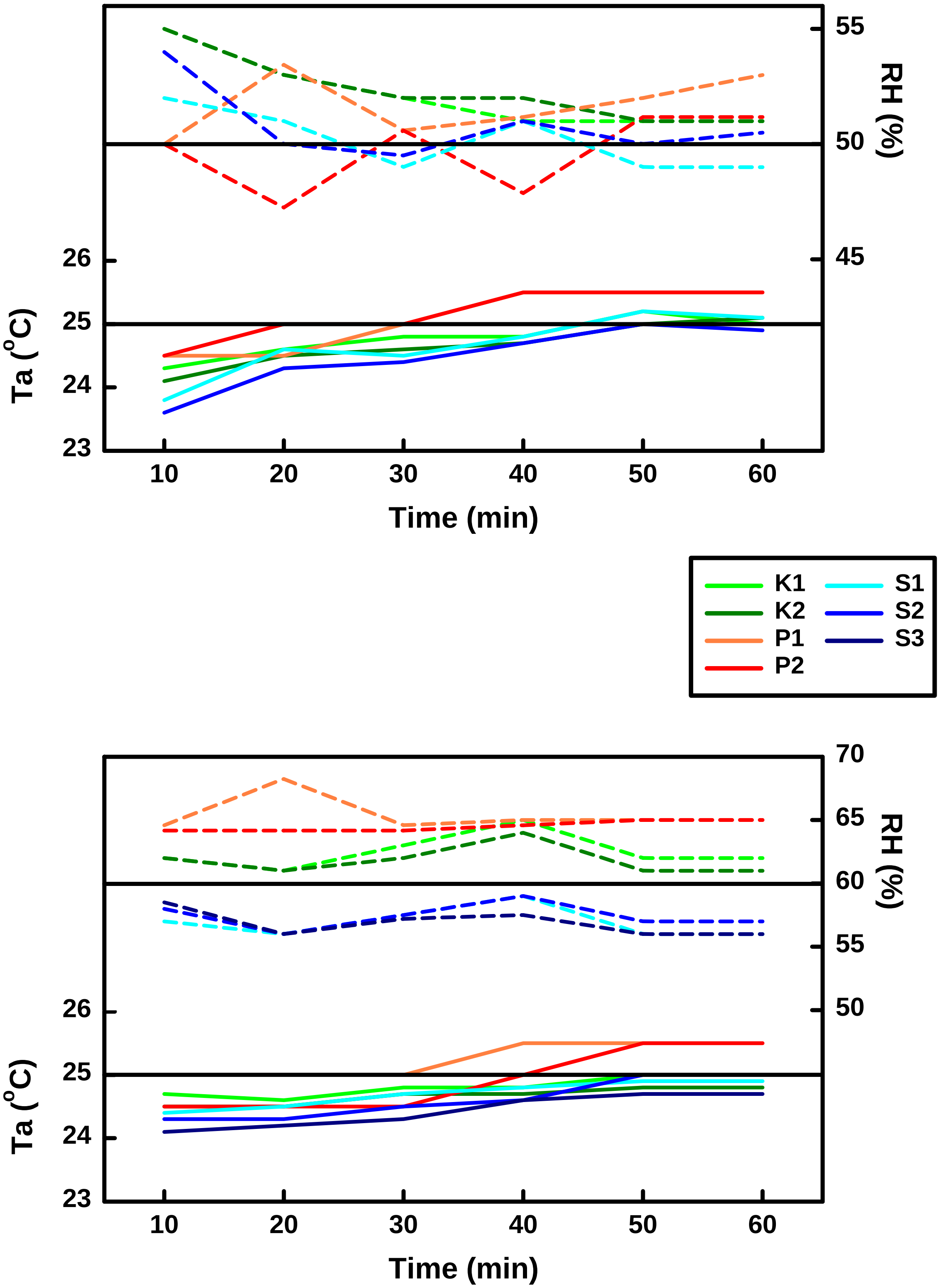


Figure 4. WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements (S_1, S_2, S_3) compared with the Kestrel (K_1, K_2) and the Psychrometer (P_1, P_2) measurements in climatic chamber at T_a of 25ºC and RH of 70% for 90 min (top) and T_a of 30ºC and RH of 40% for 60 min (bottom).

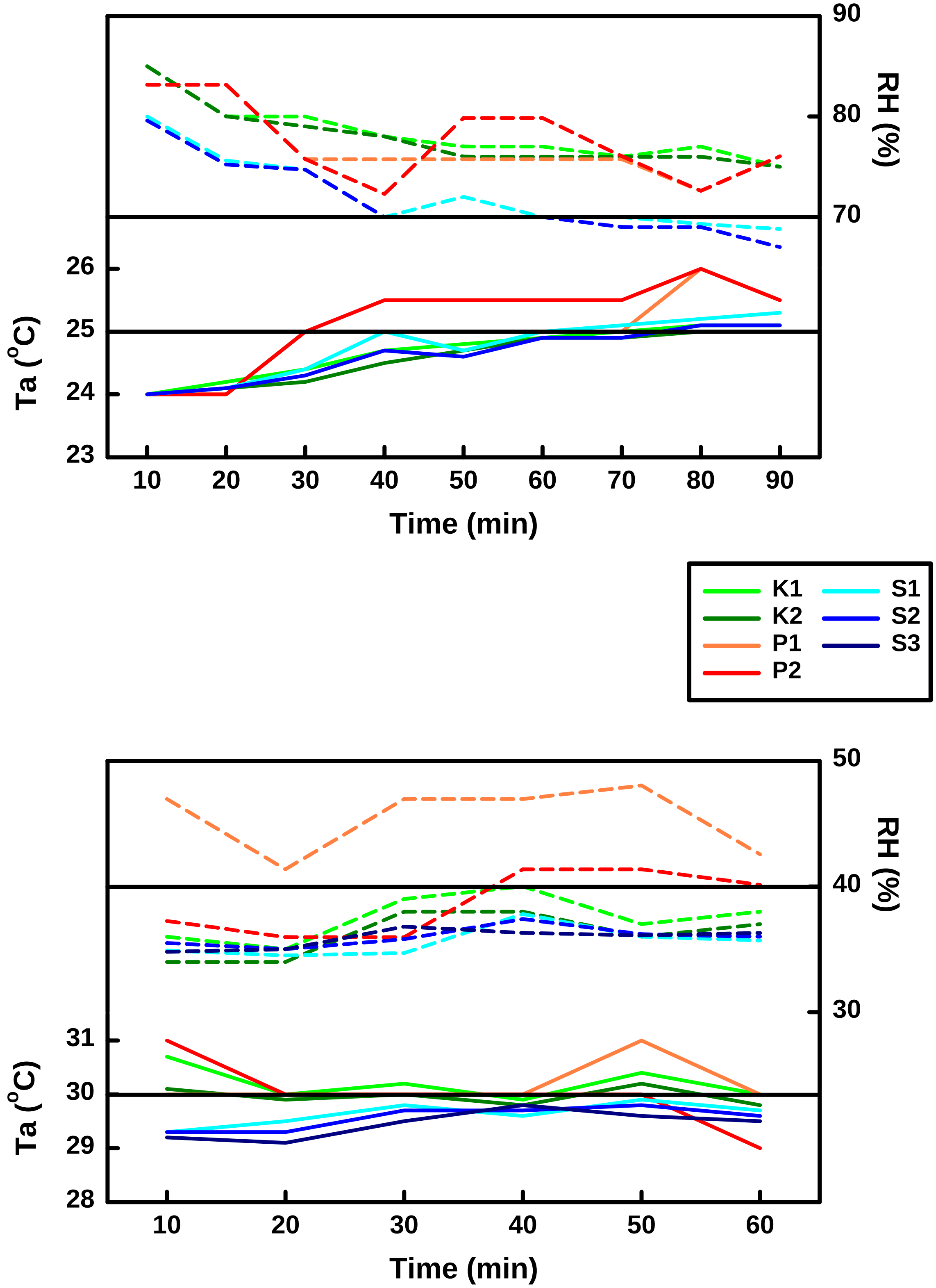


Figure 5. WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements (S_1, S_2, S_3) compared with the Kestrel (K_1, K_2) and the Psychrometer (P_1, P_2) measurements in climatic chamber at T_a of 30ºC and RH of 50% (top) and 60% (bottom) during 60 min.

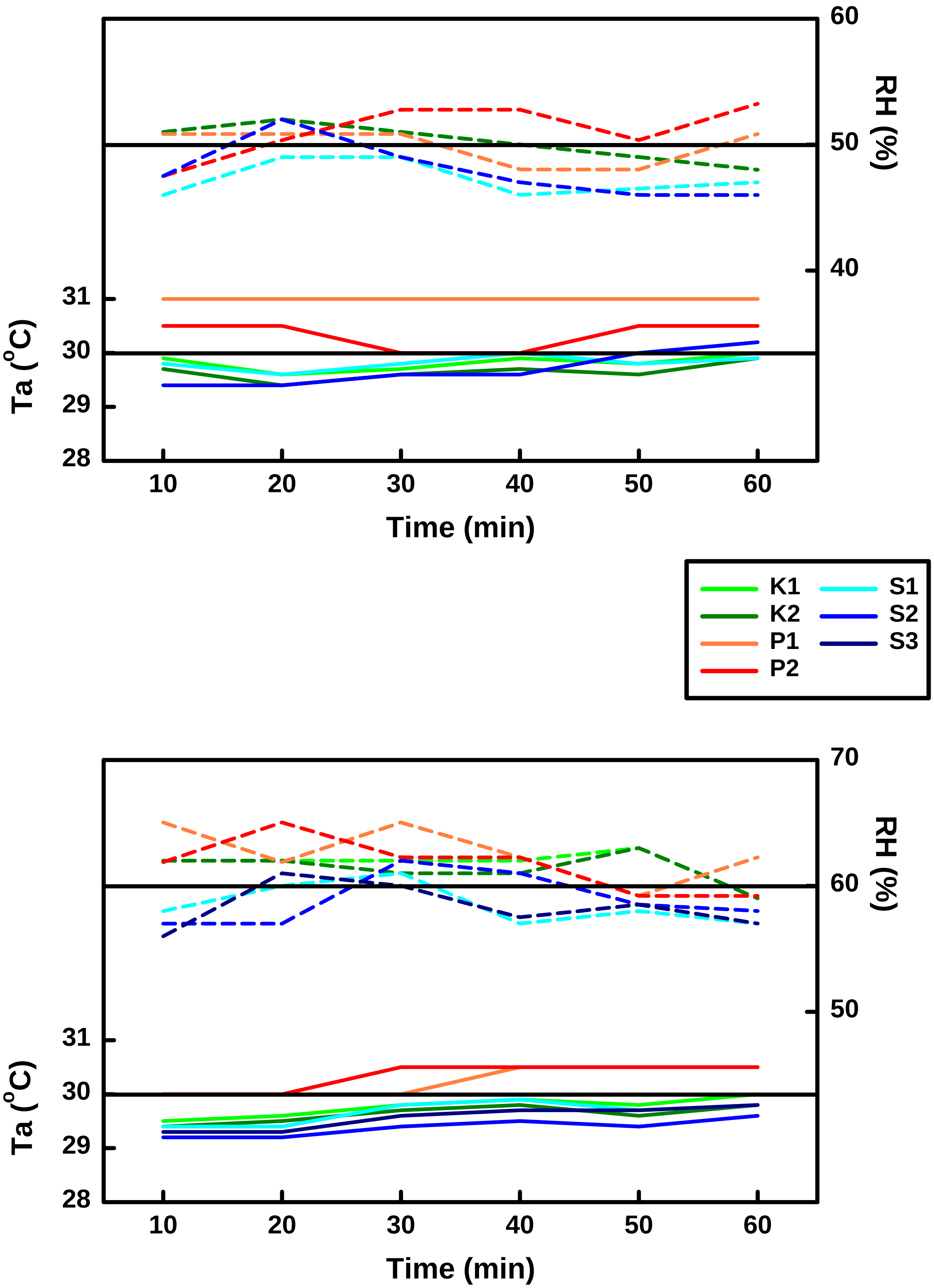


Figure 6. WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements (S_1, S_2, S_3) compared with the Kestrel (K_1, K_2) and the Psychrometer (P_1, P_2) measurements in climatic chamber at T_a of 30ºC and RH of 70% (top) and T_a of 35ºC and RH of 35% (bottom) during 60 min.

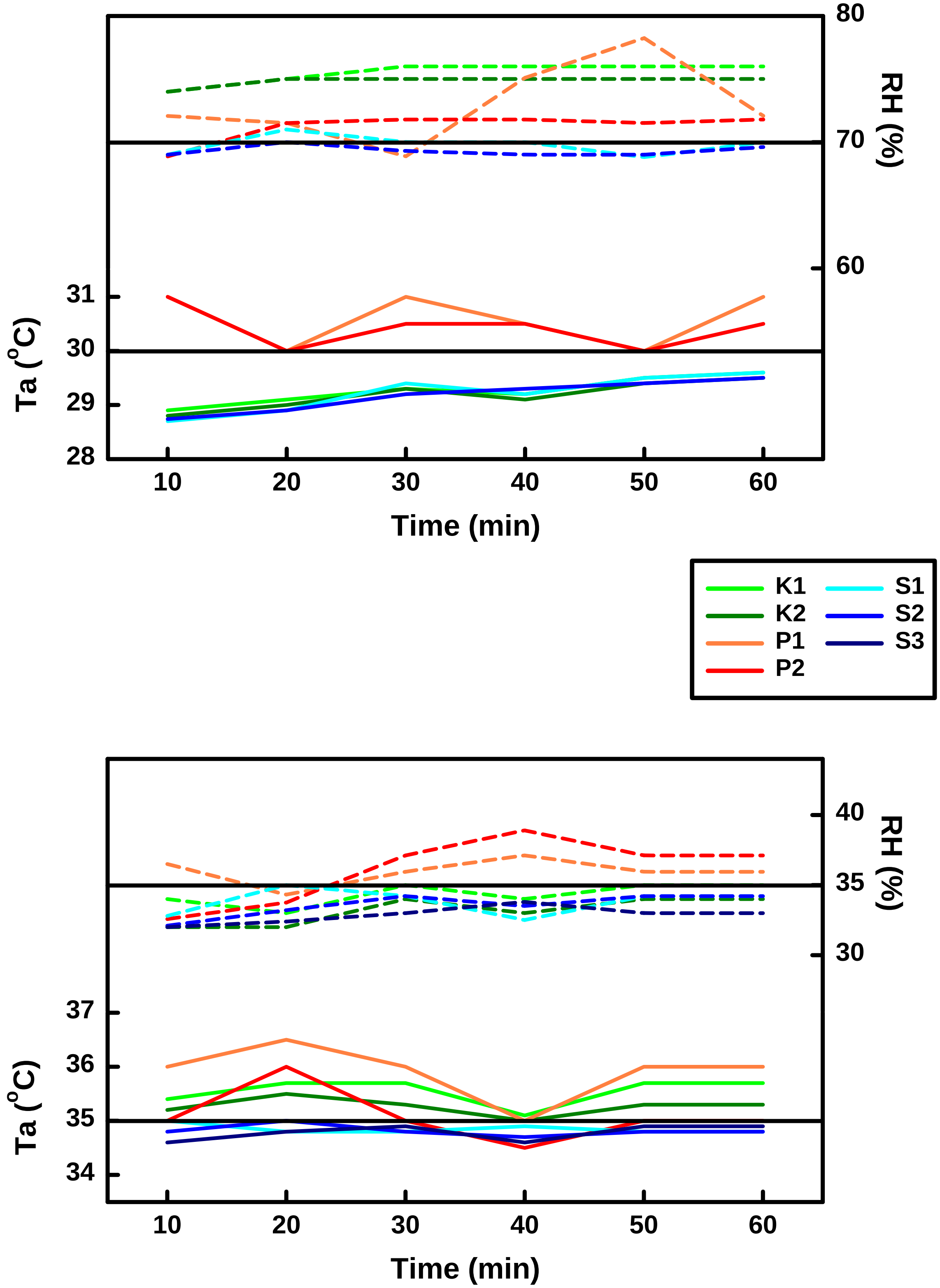


Figure 7. WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements (S_1, S_2, S_3) compared with the Kestrel (K_1, K_2) and the Psychrometer (P_1, P_2) measurements in climatic chamber at T_a of 35ºC and RH of 50% (top) and 60% (bottom) during 60 min.

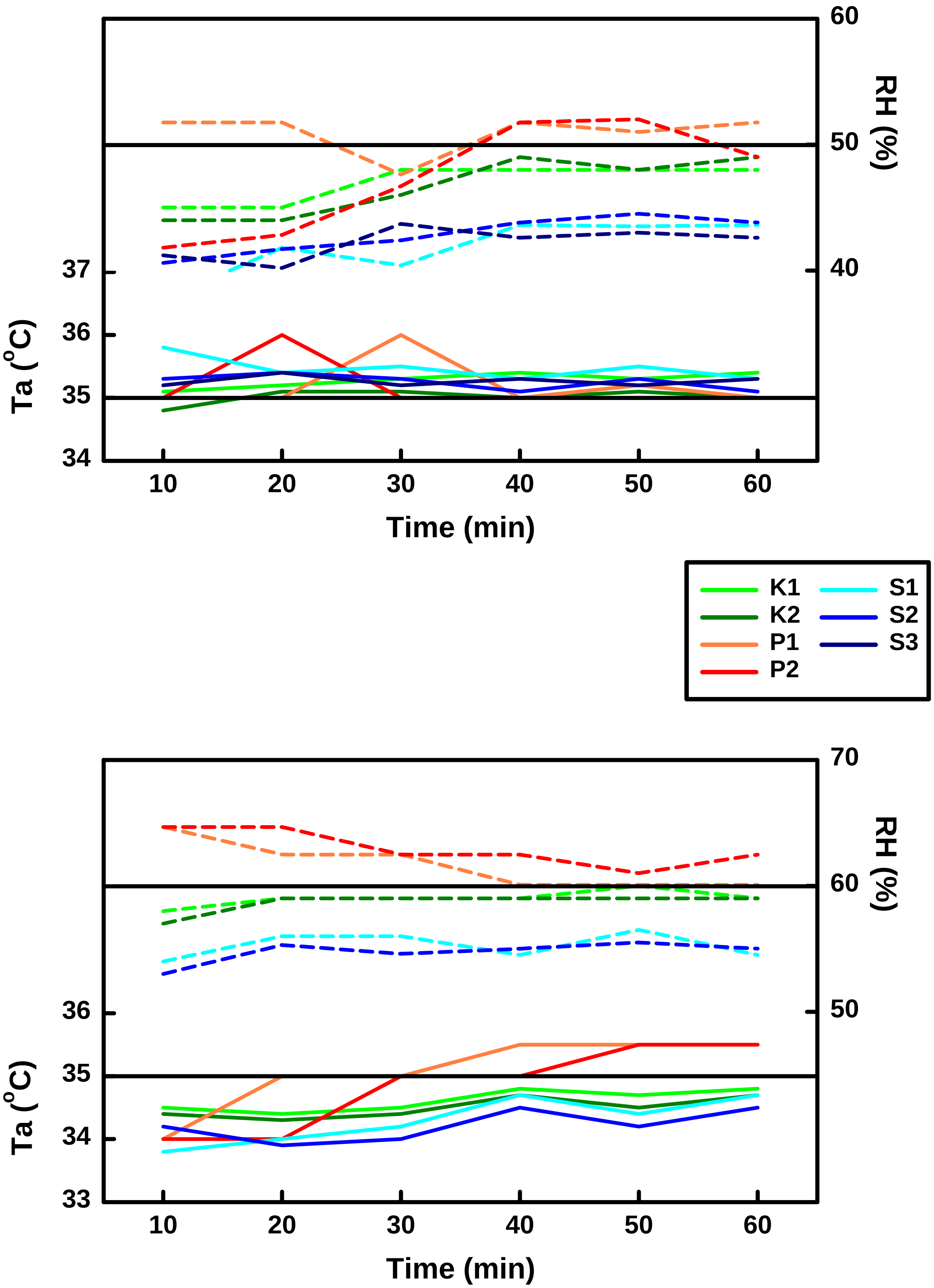
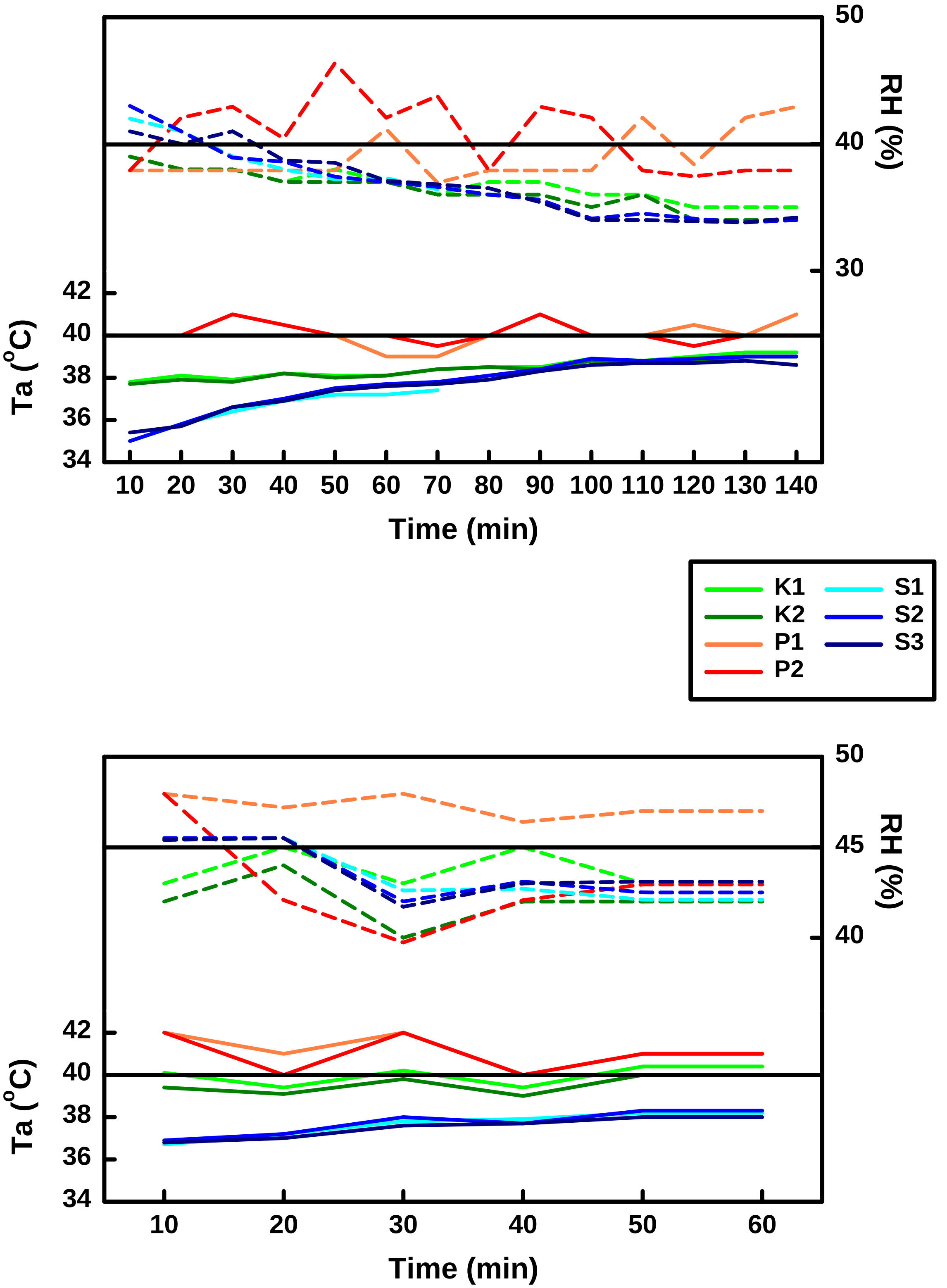


Figure 8. WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements (S_1, S_2, S_3) compared with the Kestrel (K_1, K_2) and the Psychrometer (P_1, P_2) measurements in climatic chamber at T_a of 40ºC and RH of 40% during 140 min (top) and 45% during 60 min (bottom).



OUTDOOR STUDY

Data collection was obtained for 10 days from ten different sites located mainly in the southern part of Israel (Negev Desert, Jehuda Desert, Dead Sea, and Eilat), and from the central region of Israel (Tel-Aviv and Jerusalem) from 09:00 till 16:00 at 10 min intervals. Mean±SD and a range of the environmental variables for the different sites measured by the IMS are presented in Table 5.

Table 5. Mean±SD and range of the Outdoor environmental test conditions recorded by the Israel Meteorological Service (IMS) at the sites WAPEM's sensors were tested.

Location	T_a ºC	RH %	V_a $m \cdot s^{-1}$	T_g ºC	T_{wb} ºC	GR $W \cdot m^{-2}$
Eilat-a	19.50±2.93 14.40-22.40	36±15 21-60	3.47±0.84 2.50-5.50	27.52±3.31 22.40-31.50	11.88±0.34 10.70-12.20	465±140 142-625
Eilat-b	20.47±2.35 14.40-22.80	35±11 26-63	2.63±0.60 1.10-3.70	29.00±3.37 19.30-33.00	12.58±0.50 11.00-1320	434±202 13-665
Yotveta	18.87±2.62 12.90-21.70	34±8 27-52	2.76±1.60 0.70-5.60	27.92±4.44 20.00-36.70	11.26±1.12 8.60-12.40	373±140 77-584
Hatzeva	18.22±1.20 15.00-19.40	39±3 35-46	2.37±0.91 0.30-3.40	29.88±2.12 24.30-33.70	11.48±0.59 9.80-12.10	370±138 77-584
Mitzpeh-Ramon	14.17±1.43 10.70-16.60	58±5 49-68	2.34±0.78 0.60-3.60	23.70±5.33 12.10-31.90	10.21±0.83 8.10-11.50	333±167 0-632
Tel-Aviv	16.77±1.01 14.24-17.85	53±2 50-57	2.61±0.92 0.40-4.00	27.77±3.22 18.20-35.80	12.99±0.35 10.50-13.50	343±175 119-691
Sdom	14.96±1.07 12.60-16.90	58±6 46-66	3.35±1.54 0.70-7.50	21.22±2.58 14.60-24.00	10.92±1.16 8.40-12.30	129±100 2-394
Dead Sea	19.63±2.77 14.40-22.60	56±9 45-72	1.70±0.85 0.40-4.40	30.56±7.12 14.00-39.30	14.60±1.36 11.80-16.10	348±195 4-571
Jerusalem	11.62±1.12 9.50-13.10	79±6 68-89	3.71±1.37 1.60-7.10	16.89±5.17 9.50-30.00	9.85±0.61 8.70-10.80	250±212 0-661
Beer-Sheba	18.15±2.40 11.80-20.70	52±11 37-75	1.76±0.47 0.70-2.70	27.84±5.37 15.00-36.80	12.89±1.01 9.70-13.90	318±148 2-561

Figs. 9-12 present the T_a and RH measurements from the three different types of sensors and from the IMS measurements. In general, very high correlation was found between the three Swiss sensors (R>0.985), with no significant differences between them (Tables 6-7). The Swiss sensors, the Kestrels, and the psychrometers highly correlated for T_a (Table 6). However, for RH the Swiss sensors and Kestrels highly correlated, but the psychrometer and WAPEM or Kestrel in two sites did not correlate (Fig. 9 top and Fig. 10 top) (Table 7). At these four sites, the Swiss sensors followed the same pattern as the Kestrel and the IMS for T_a and RH. The T_a values were significantly higher ($P<0.05$) in Hatezeva and Yotveta than all the other sensors by 0.5º-1.0ºC (Fig. 9 bottom, and Fig. 10 bottom). No significant differences were found for T_a in Eilat or Tel-Aviv. (Figs. 11-12 bottom panels). No significant differences were found in RH between WAPEM and Kestrel or IMS for all the four sites (Figs. 9-12, top panels).

Figs. 13-14 depict the comparisons between WBGT and ESI calculated by T_a and RH, which were measured by WAPEM (S_1), Kestrel (K_1), and IMS in the four locations (Hatzeva, Yotveta, Eilat, and Tel Aviv), which had the lowest correlations between ESI obtained from pooled data measured by WAPEM and WBGT obtained from pooled data measured by IMS (Table 8). We further analyzed data from these four locations for the interrelationships between the two indices (WBGT and ESI), calculated from the different sensors (Table 9). Collectively, all of the six modifications of calculated WBGT and ESI fall in a range of $\pm$1.5ºC (Figs. 13-14). In all of these four locations, the measurements by the WAPEM revealed very high correlations between WBGT and ESI. Analysis of the calculated heat stress indices revealed that ESI_{S1}, ESI_{S2}, or ESI_{S3}, and $WBGT_{S1}$, $WBGT_{S2}$, or $WBGT_{S3}$ highly correlated and presented similar dynamics and patterns.

Figs. 15-17 present data (T_a and RH) and the calculated ESI and WBGT from six different locations. WBGT was calculated from data measured by IMS (T_a, T_g, and T_{wb}), whereas ESI was calculated from the Swiss sensors and pyranometer (for SR). In these figures, ESI was slightly higher than WBGT by 0.2º-0.5ºC; however, very high correlations were found between these two indices. The highest measured ambient temperature was recorded in Eilat (22.8ºC), with a very high correlation (R=0.999) found between ESI and WBGT (Fig. 16 bottom).

Figure 9. WAPEM's relative humidity (top) and ambient temperature (bottom) measurements (S_1, S_2, S_3) compared with Kestrel (K_1, K_2), Psychrometer, and IMS measurements (P_1, P_2) from Hatzeva (Negev Desert).

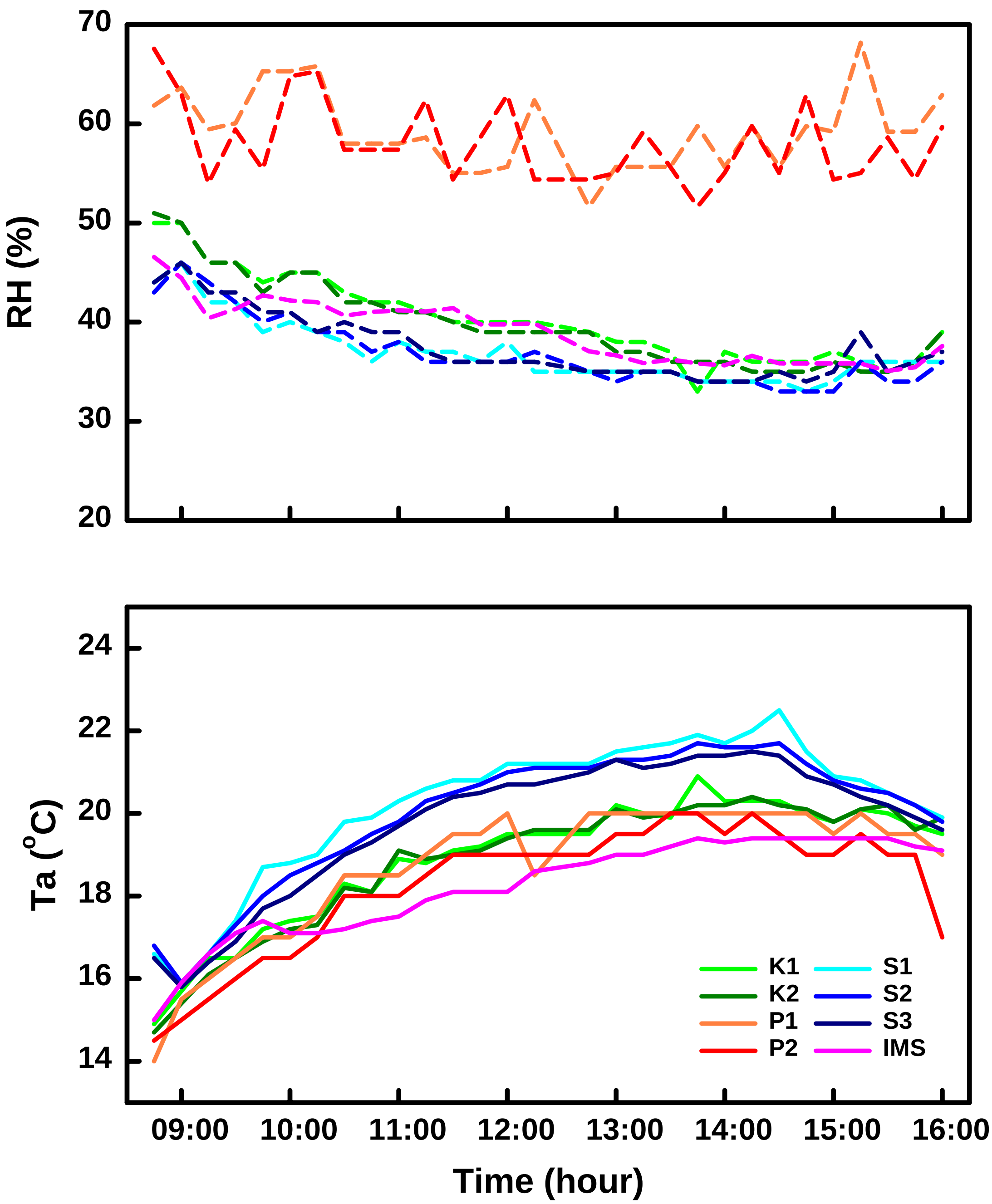


Figure 10. WAPEM's relative humidity (top) and ambient temperature (bottom) measurements (S_1, S_2, S_3) compared with Kestrel (K_1, K_2), Psychrometer, and IMS measurements (P_1, P_2) from Yotveta (Negev Desert).

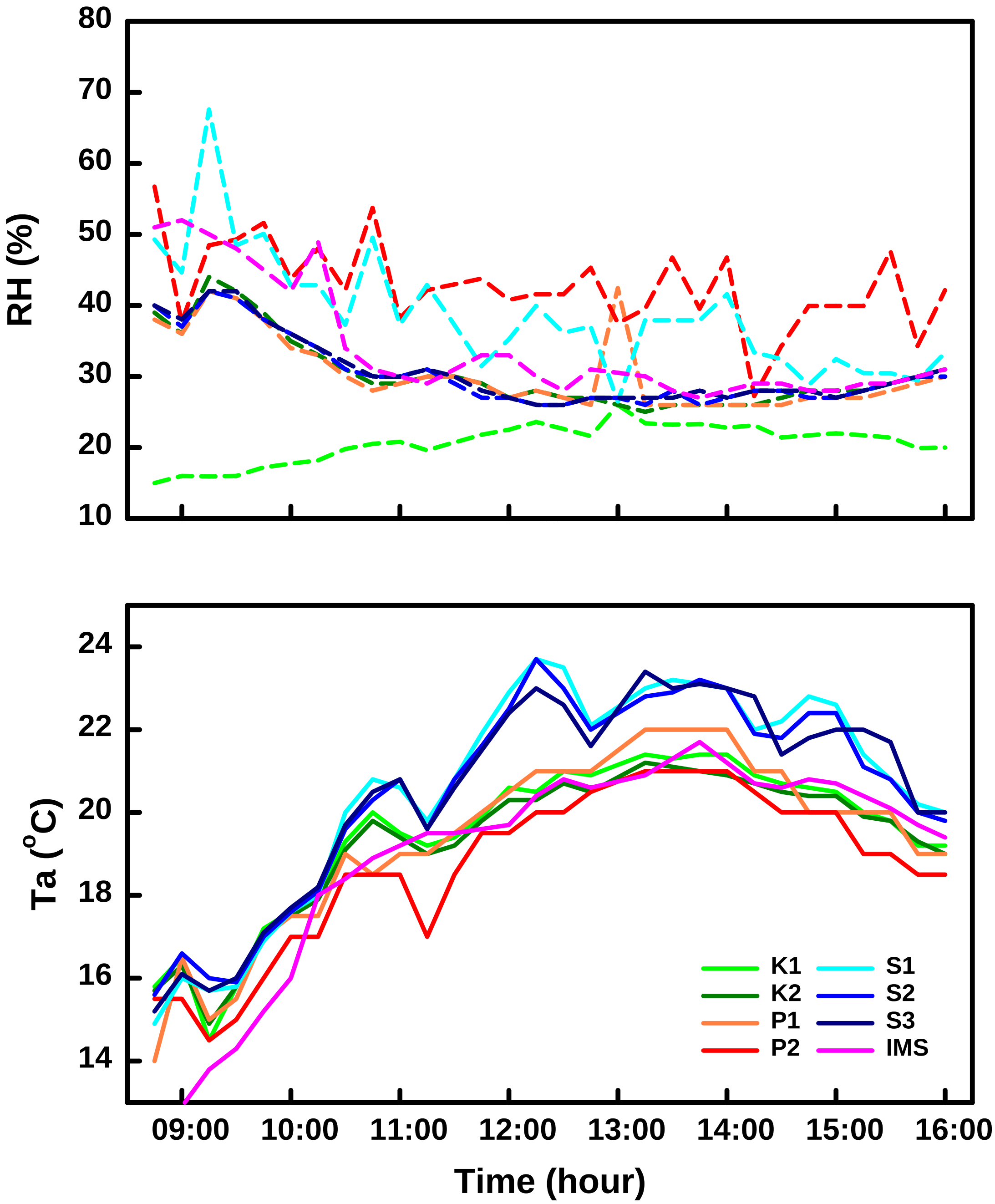


Figure 11. WAPEM's relative humidity (top) and ambient temperature (bottom) measurements (S_1, S_2, S_3) compared with Kestrel (K_1, K_2), Psychrometer, and IMS measurements (P_1, P_2) from Eilat.

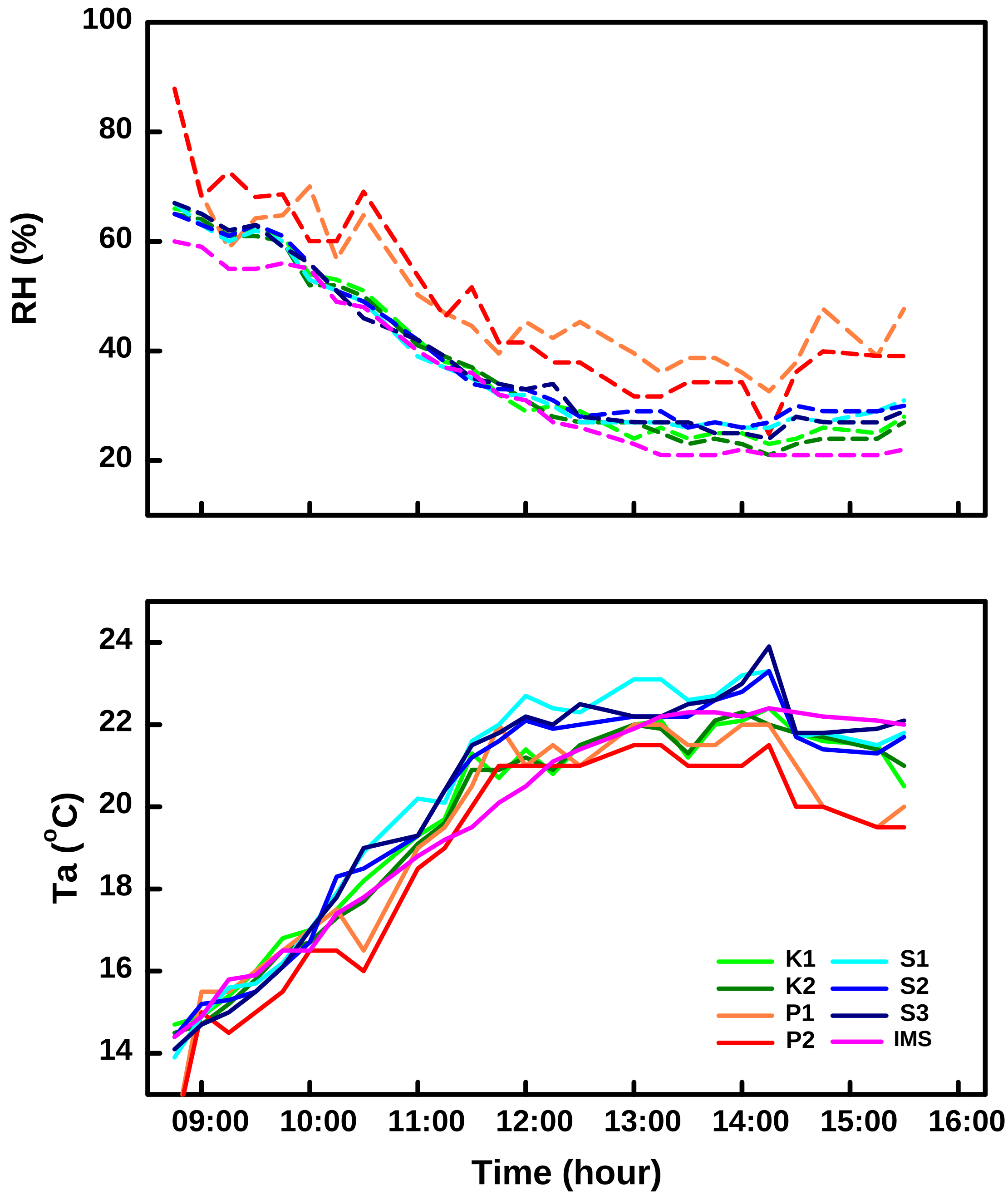


Figure 12. WAPEM's relative humidity (top) and ambient temperature (bottom) measurements (S_1, S_2, S_3) compared with Kestrel (K_1, K_2) Psychrometer, and IMS measurements (P_1, P_2) from Tel-Aviv.

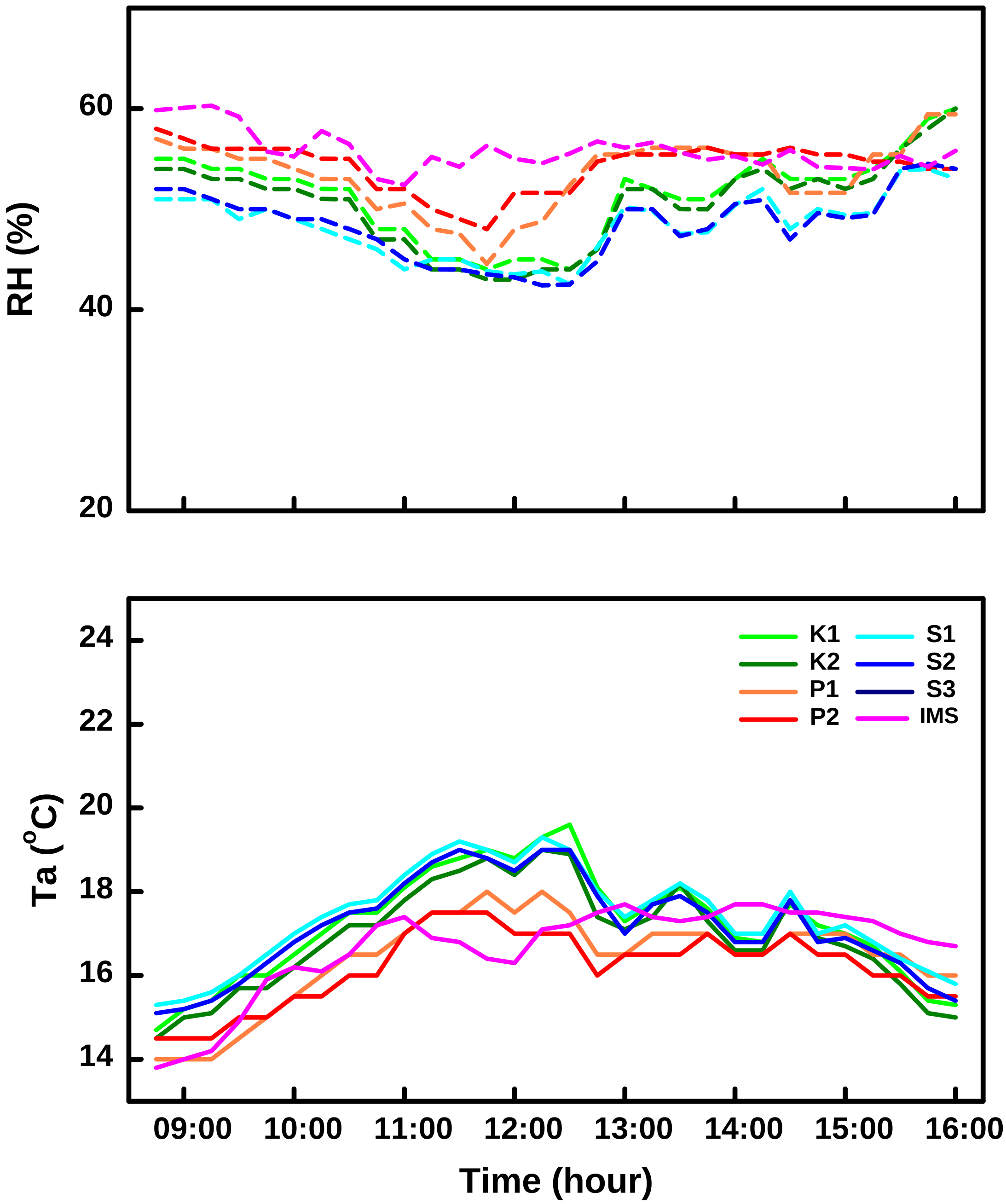


Table 6. Correlations coefficients (R) for T_a measurements between the psychrometer (P_1 and P_2), Kestrel (K_1 and K_2), WAPEM Swiss sensors (S_1, S_2, and S_3), and the IMS measured in Hatzeva, Yotveta, Eilat, and Tel-Aviv.

Hatzeva

	K_1	K_2	P_1	P_2	S_1	S_2	S_3	IMS
K_1	1	0.992	0.969	0.956	0.952	0.960	0.961	0.957
K_2	0.992	1	0.967	0.943	0.947	0.956	0.958	0.957
P_1	0.969	0.967	1	0.960	0.946	0.946	0.952	0.917
P_2	0.956	0.943	0.960	1	0.963	0.966	0.969	0.887
S_1	0.952	0.947	0.946	0.963	1	0.992	0.990	0.874
S_2	0.960	0.956	0.946	0.966	0.992	1	0.998	0.888
S_3	0.961	0.958	0.952	0.969	0.990	0.998	1	0.885
IMS	0.957	0.957	0.917	0.887	0.874	0.888	0.885	1

Yotveta

	K_1	K_2	P_1	P_2	S_1	S_2	S_3	IMS
K_1	1	0.998	0.970	0.975	0.969	0.965	0.972	0.959
K_2	0.998	1	0.970	0.976	0.974	0.969	0.980	0.968
P_1	0.970	0.970	1	0.966	0.961	0.962	0.972	0.943
P_2	0.975	0.976	0.966	1	0.961	0.966	0.968	0.935
S_1	0.969	0.974	0.961	0.961	1	0.996	0.985	0.954
S_2	0.965	0.969	0.962	0.966	0.996	1	0.986	0.946
S_3	0.972	0.980	0.972	0.968	0.985	0.986	1	0.960
IMS	0.959	0.968	0.943	0.935	0.954	0.946	0.960	1

Eilat

	K_1	K_2	P_1	P_2	S_1	S_2	S_3	IMS
K_1	1	0.997	0.944	0.961	0.985	0.985	0.986	0.971
K_2	0.997	1	0.948	0.965	0.985	0.986	0.987	0.978
P_1	0.944	0.948	1	0.991	0.964	0.957	0.947	0.910
P_2	0.961	0.965	0.991	1	0.977	0.970	0.963	0.926
S_1	0.985	0.985	0.964	0.977	1	0.993	0.991	0.957
S_2	0.985	0.986	0.957	0.970	0.993	1	0.996	0.964
S_3	0.986	0.987	0.947	0.963	0.991	0.996	1	0.966
IMS	0.971	0.978	0.910	0.926	0.957	0.964	0.966	1

Tel-Aviv

	K_1	K_2	P_1	P_2	S_1	S_2	IMS
K_1	1	0.993	0.869	0.874	0.984	0.987	0.858
K_2	0.993	1	0.875	0.889	0.985	0.984	0.861
P_1	0.869	0.875	1	0.952	0.879	0.866	0.955
P_2	0.874	0.889	0.952	1	0.887	0.876	0.924
S_1	0.984	0.985	0.879	0.887	1	0.997	0.862
S_2	0.987	0.984	0.866	0.876	0.997	1	0.852
IMS	0.858	0.861	0.955	0.924	0.862	0.852	1

Table 7. Correlations coefficients (R) for RH measurements between the psychrometer, calculated from T_{wb}, (P_1 and P_2), Kestrel (K_1 and K_2), WAPEM Swiss sensors (S_1, S_2, and S_3), and IMS measured in Hatzeva, Yotveta, Eilat, and Tel-Aviv.

Hatzeva

	K_1	K_2	P_1	P_2	S_1	S_2	S_3	IMS
K_1	1	0.982	0.345	0.356	0.919	0.940	0.911	0.930
K_2	0.982	1	0.360	0.358	0.931	0.944	0.911	0.930
P_1	0.345	0.360	1	0.363	0.410	0.456	0.531	0.340
P_2	0.356	0.358	0.363	1	0.328	0.268	0.282	0.336
S_1	0.919	0.931	0.410	0.328	1	0.955	0.947	0.833
S_2	0.940	0.944	0.456	0.268	0.955	1	0.962	0.844
S_3	0.911	0.911	0.531	0.282	0.947	0.962	1	0.888
IMS	0.957	0.957	0.917	0.887	0.874	0.888	0.885	1

Yotveta

	K_1	K_2	P_1	P_2	S_1	S_2	S_3	IMS
K_1	1	0.994	0.509	0.757	0.974	0.976	0.976	0.892
K_2	0.994	1	0.502	0.769	0.974	0.978	0.977	0.912
P_1	0.509	0.502	1	0.601	0.495	0.474	0.458	0.471
P_2	0.757	0.769	0.601	1	0.769	0.754	0.756	0.714
S_1	0.974	0.974	0.495	0.769	1	0.992	0.985	0.914
S_2	0.976	0.978	0.474	0.754	0.992	1	0.989	0.916
S_3	0.976	0.977	0.458	0.756	0.985	0.989	1	0.933
IMS	0.892	0.912	0.471	0.714	0.914	0.916	0.933	1

Eilat

	K_1	K_2	P_1	P_2	S_1	S_2	S_3	IMS
K_1	1	0.995	0.919	0.955	0.992	0.986	0.991	0.989
K_2	0.995	1	0.911	0.957	0.990	0.988	0.990	0.991
P_1	0.919	0.911	1	0.938	0.926	0.915	0.916	0.912
P_2	0.955	0.957	0.938	1	0.955	0.949	0.944	0.945
S_1	0.992	0.990	0.926	0.955	1	0.994	0.993	0.977
S_2	0.986	0.988	0.915	0.949	0.994	1	0.992	0.976
S_3	0.991	0.990	0.916	0.944	0.993	0.992	1	0.982
IMS	0.989	0.991	0.912	0.945	0.977	0.976	0.982	1

Tel-Aviv

	K_1	K_2	P_1	P_2	S_1	S_2	IMS
K_1	1	0.994	0.817	0.737	0.947	0.964	0.857
K_2	0.994	1	0.834	0.733	0.952	0.967	0.853
P_1	0.817	0.834	1	0.775	0.796	0.811	0.823
P_2	0.737	0.733	0.775	1	0.687	0.696	0.826
S_1	0.947	0.952	0.796	0.687	1	0.977	0.844
S_2	0.964	0.967	0.811	0.696	0.977	1	0.872
IMS	0.857	0.853	0.823	0.816	0.844	0.872	1

Table 8. Correlation coefficients (R) between WBGT obtained from pooled data measured by IMS, and ESI obtained from pooled data measured by WAPEM sensors at the ten testing locations.

Location	**R**
Mitzpeh- Ramon	0.973
Jerusalem	0.958
Eilat-a	0.942
Beer-Sheba	0.941
Sdom	0.904
Dead Sea	0.903
Eilat-b	0.903
Yotveta	0.781
Tel-Aviv	0.756
Hatzeva	0.753

Table 9. Correlations coefficients (R) for WBGT and ESI calculated by Kestrel (K_1 and K_2), WAPEM Swiss sensors (S_1, S_2, and S_3), and IMS obtained from Hatzeva, Yotveta, Eilat, and Tel-Aviv.

Hatzeva

	$WBGT_{S1}$	$WBGT_{S2}$	$WBGT_{S3}$	$WBGT_{K1}$	$WBGT_{K2}$	$WBGT_{IMS}$	ESI_{S1}	ESI_{S2}	ESI_{S3}	ESI_{K1}	ESI_{K2}	ESI_{IMS}
$WBGT_{S1}$	1	0.984	0.984	0.959	0.949	0.889	0.931	0.917	0.930	0.848	0.817	0.803
$WBGT_{S2}$	0.984	1	0.989	0.965	0.955	0.899	0.902	0.912	0.901	0.829	0.798	0.784
$WBGT_{S3}$	0.984	0.989	1	0.964	0.959	0.889	0.924	0.927	0.923	0.859	0.833	0.813
$WBGT_{K1}$	0.959	0.965	0.964	1	0.987	0.931	0.883	0.885	0.885	0.871	0.838	0.833
$WBGT_{K2}$	0.949	0.955	0.959	0.987	1	0.919	0.895	0.901	0.897	0.885	0.874	0.853
$WBGT_{IMS}$	0.889	0.899	0.889	0.931	0.919	1	0.751	0.751	0.753	0.726	0.699	0.788
ESI_{S1}	0.931	0.902	0.924	0.883	0.895	0.751	1	0.989	1.000	0.959	0.945	0.905
ESI_{S2}	0.917	0.912	0.927	0.885	0.901	0.751	0.989	1	0.989	0.960	0.950	0.907
ESI_{S3}	0.930	0.901	0.923	0.885	0.897	0.753	1.000	0.989	1	0.961	0.947	0.908
ESI_{K1}	0.848	0.829	0.859	0.871	0.885	0.726	0.959	0.960	0.961	1	0.990	0.955
ESI_{K2}	0.817	0.798	0.833	0.838	0.874	0.699	0.945	0.950	0.947	0.990	1	0.953
ESI_{IMS}	0.803	0.784	0.813	0.833	0.853	0.788	0.905	0.907	0.908	0.955	0.953	1

Yotveta

	$WBGT_{S1}$	$WBGT_{S2}$	$WBGT_{S3}$	$WBGT_{K1}$	$WBGT_{K2}$	$WBGT_{IMS}$	ESI_{S1}	ESI_{S2}	ESI_{S3}	ESI_{K1}	ESI_{K2}	ESI_{IMS}
$WBGT_{S1}$	1	0.994	0.998	0.936	0.934	0.970	0.865	0.857	0.864	0.883	0.892	0.836
$WBGT_{S2}$	0.994	1	0.987	0.943	0.941	0.962	0.839	0.842	0.839	0.863	0.870	0.805
$WBGT_{S3}$	0.998	0.987	1	0.944	0.944	0.960	0.842	0.838	0.841	0.871	0.889	0.833
$WBGT_{K1}$	0.936	0.943	0.944	1	0.997	0.951	0.664	0.654	0.663	0.760	0.759	0.677
$WBGT_{K2}$	0.934	0.941	0.944	0.997	1	0.950	0.649	0.640	0.648	0.738	0.742	0.662
$WBGT_{IMS}$	0.970	0.962	0.960	0.951	0.950	1	0.798	0.785	0.783	0.851	0.859	0.849
ESI_{S1}	0.865	0.839	0.842	0.664	0.649	0.798	1	0.994	1.000	0.963	0.971	0.940
ESI_{S2}	0.857	0.842	0.838	0.654	0.640	0.785	0.994	1	0.994	0.956	0.963	0.927
ESI_{S3}	0.864	0.839	0.841	0.663	0.648	0.783	1.000	0.994	1	0.963	0.971	0.939
ESI_{K1}	0.883	0.863	0.879	0.760	0.738	0.851	0.963	0.956	0.963	1	0.997	0.940
ESI_{K2}	0.892	0.870	0.889	0.759	0.742	0.859	0.971	0.963	0.971	0.997	1	0.948
ESI_{IMS}	0.836	0.805	0.833	0.677	0.662	0.849	0.940	0.927	0.939	0.940	0.948	1

Tabel 9 Continued.

Eilat

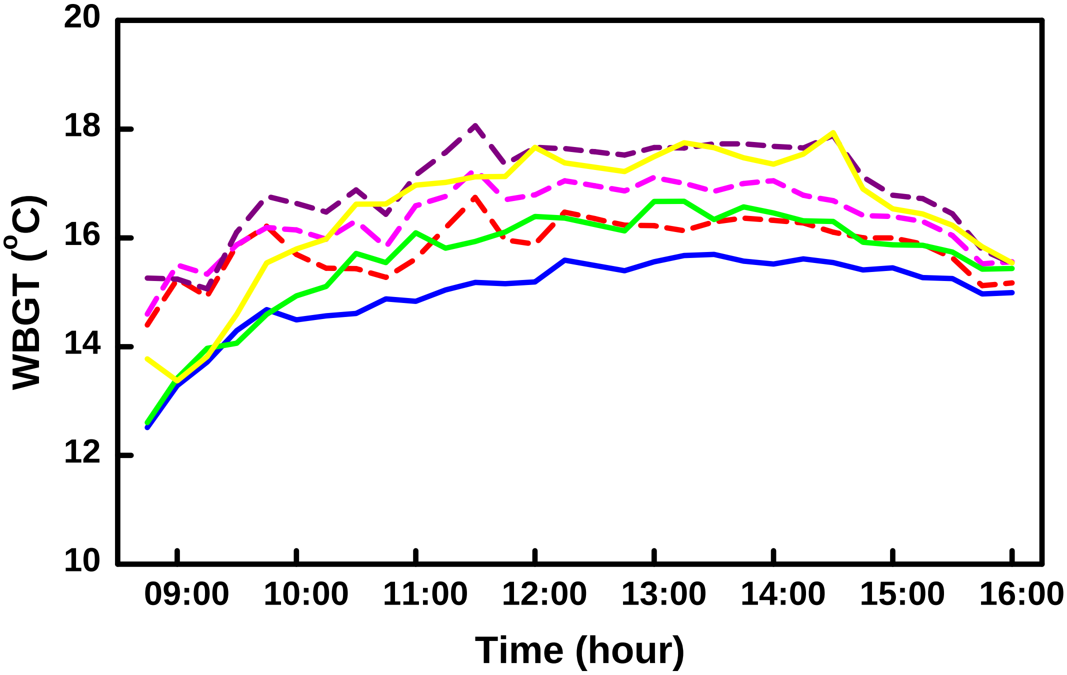
4

	$WBGT_{S1}$	$WBGT_{S2}$	$WBGT_{S3}$	$WBGT_{K1}$	$WBGT_{K2}$	$WBGT_{IMS}$	ESI_{S1}	ESI_{S2}	ESI_{S3}	ESI_{K1}	ESI_{K2}	ESI_{IMS}
$WBGT_{S1}$	1	0.999		0.983	0.994	0.980	0.995	0.996	0.995	0.991	0.993	0.974
$WBGT_{S2}$	0.999	1		0.985	0.995	0.981	0.991	0.996	0.991	0.990	0.992	0.972
$WBGT_{S3}$	0.998	0.998	1	0.984	0.993	0.995	0.993	0.996	0.993	0.990	0.993	0.971
$WBGT_{K1}$	0.983	0.985		1	0.986	0.893	0.972	0.979	0.993	0.979	0.980	0.899
$WBGT_{K2}$	0.994	0.995		0.986	1	0.962	0.987	0.989	0.972	0.996	0.997	0.958
$WBGT_{IMS}$	0.980	0.981		0.893	0.962	1	0.952	0.953	0.987	0.922	0.938	0.990
ESI_{S1}	0.995	0.991		0.972	0.987	0.952	1	0.997	0.985	0.990	0.993	0.965
ESI_{S2}	0.996	0.996		0.979	0.989	0.953	0.997	1	1.000	0.990	0.993	0.966
ESI_{S3}	0.995	0.991	0.993	0.972	0.987	0.985	1.000	0.997	1	0.990	0.993	0.965
ESI_{K1}	0.991	0.990		0.979	0.996	0.922	0.990	0.990	0.990	1	0.998	0.939
ESI_{K2}	0.993	0.992		0.980	0.997	0.938	0.993	0.993	0.993	0.998	1	0.954
ESI_{IMS}	0.974	0.972		0.899	0.958	0.990	0.965	0.966	0.965	0.939	0.954	1

Tel-Aviv

	$WBGT_{S1}$	$WBGT_{S2}$	$WBGT_{K1}$	$WBGT_{K2}$	$WBGT_{IMS}$	ESI_{S1}	ESI_{S2}	ESI_{K1}	ESI_{K2}	ESI_{IMS}
$WBGT_{S1}$	1	0.992	0.988	0.991	0.887	0.889	0.891	0.866	0.861	0.851
$WBGT_{S2}$	0.992	1	0.987	0.990	0.920	0.906	0.908	0.892	0.889	0.898
$WBGT_{K1}$	0.988	0.987	1	0.998	0.895	0.872	0.878	0.874	0.867	0.846
$WBGT_{K2}$	0.991	0.990	0.998	1	0.896	0.877	0.884	0.876	0.871	0.852
$WBGT_{IMS}$	0.887	0.920	0.895	0.896	1	0.756	0.749	0.764	0.763	0.913
ESI_{S1}	0.889	0.906	0.872	0.877	0.756	1	0.996	0.982	0.977	0.909
ESI_{S2}	0.891	0.908	0.878	0.884	0.749	0.996	1	0.982	0.975	0.898
ESI_{K1}	0.866	0.892	0.874	0.876	0.764	0.982	0.982	1	0.994	0.915
ESI_{K2}	0.861	0.889	0.867	0.871	0.763	0.977	0.975	0.994	1	0.916
ESI_{IMS}	0.851	0.898	0.846	0.852	0.913	0.909	0.898	0.915	0.916	1

Figure 13. A comparison between WBGT and ESI calculated by the WAPEM (S_1), Kestrel (K_1) and the Israeli Meteorological Service (IMS) from data collected in Hatzeva (top) and Yotveta (bottom).



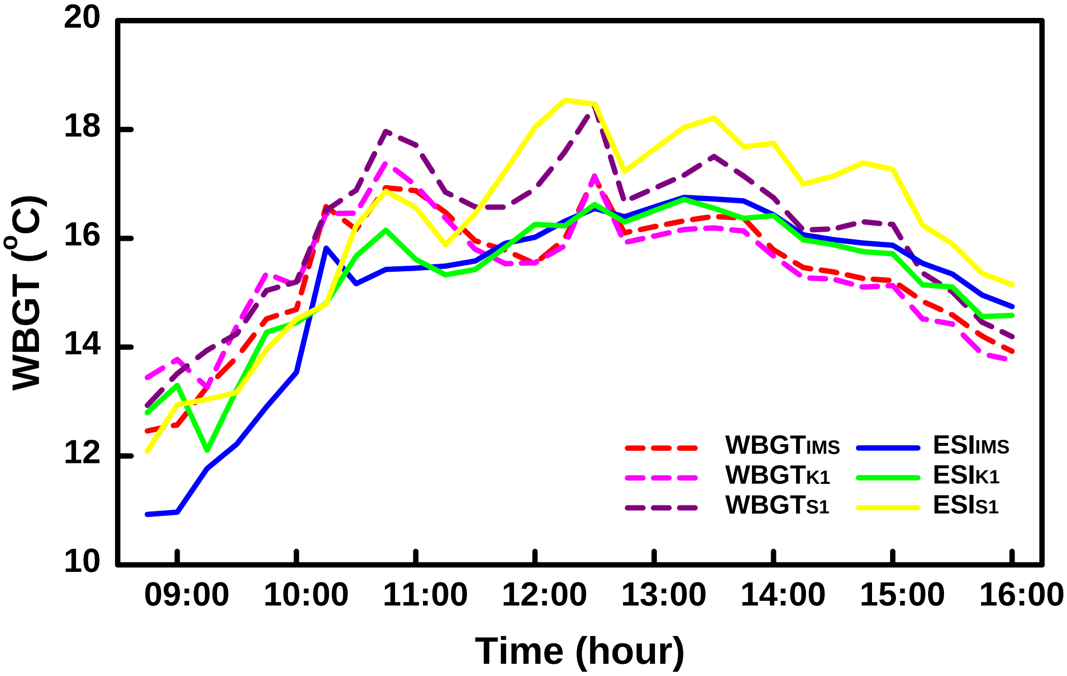


Figure 14. A comparison between WBGT and ESI calculated by the WAPEM (S_1), Kestrel (K_1) and the Israeli Meteorological Service (IMS) from data collected in Eilat (top) and Tel-Aviv (bottom).

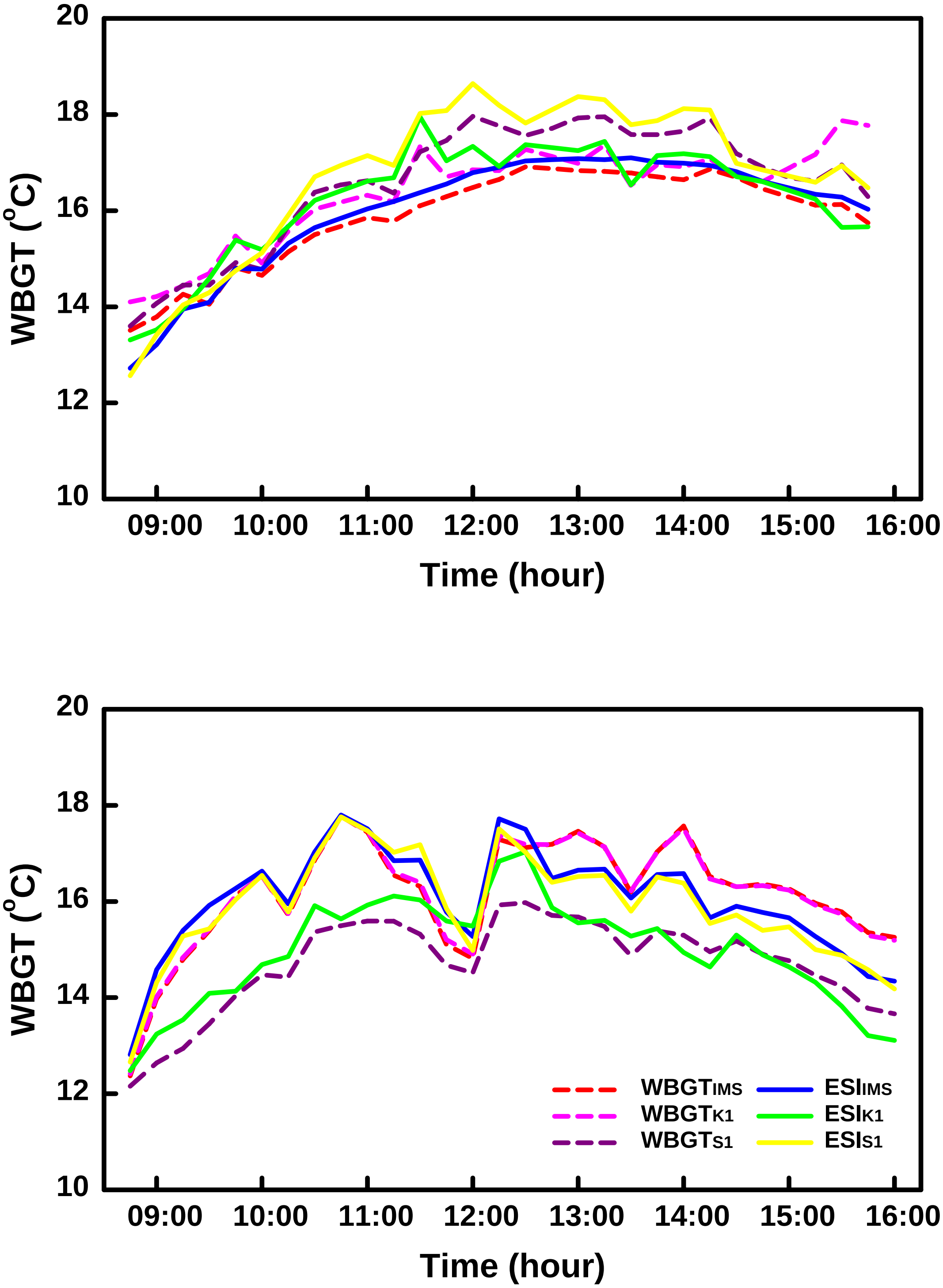
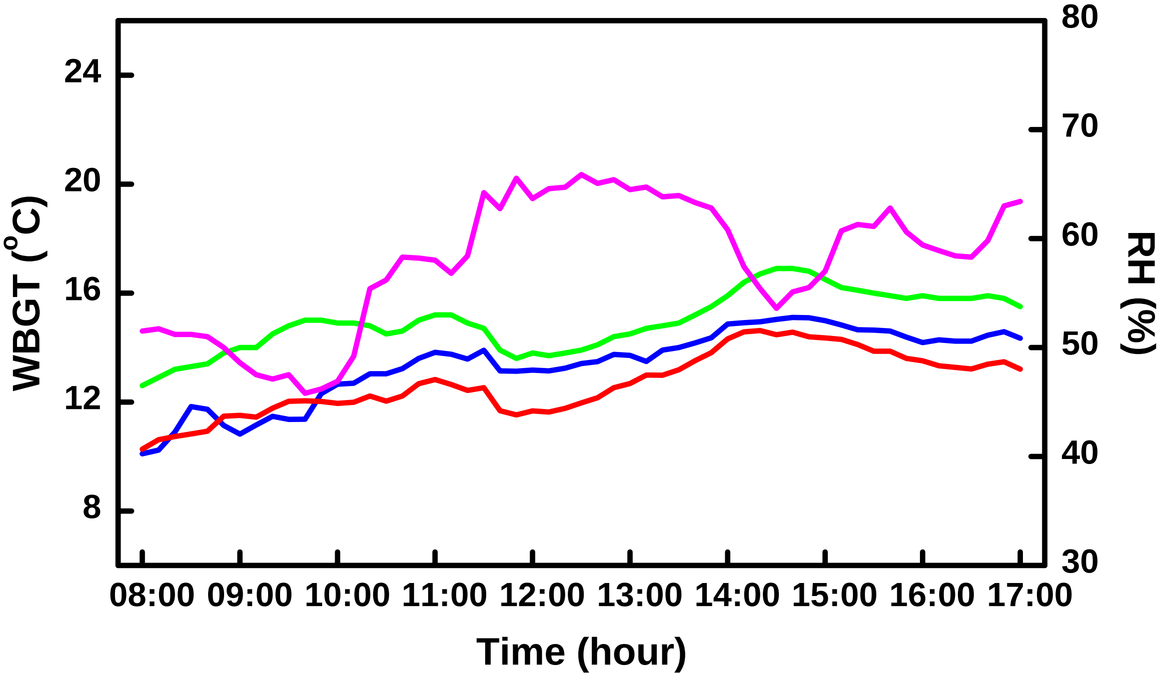


Figure 15. A comparison between WBGT calculated from data collected in Sdom (top) and Mitzpeh Ramon (bottom) by the Israeli Meteorological Service (IMS), and ESI calculated from the WAPEM's environmental sensors (T_a and RH).



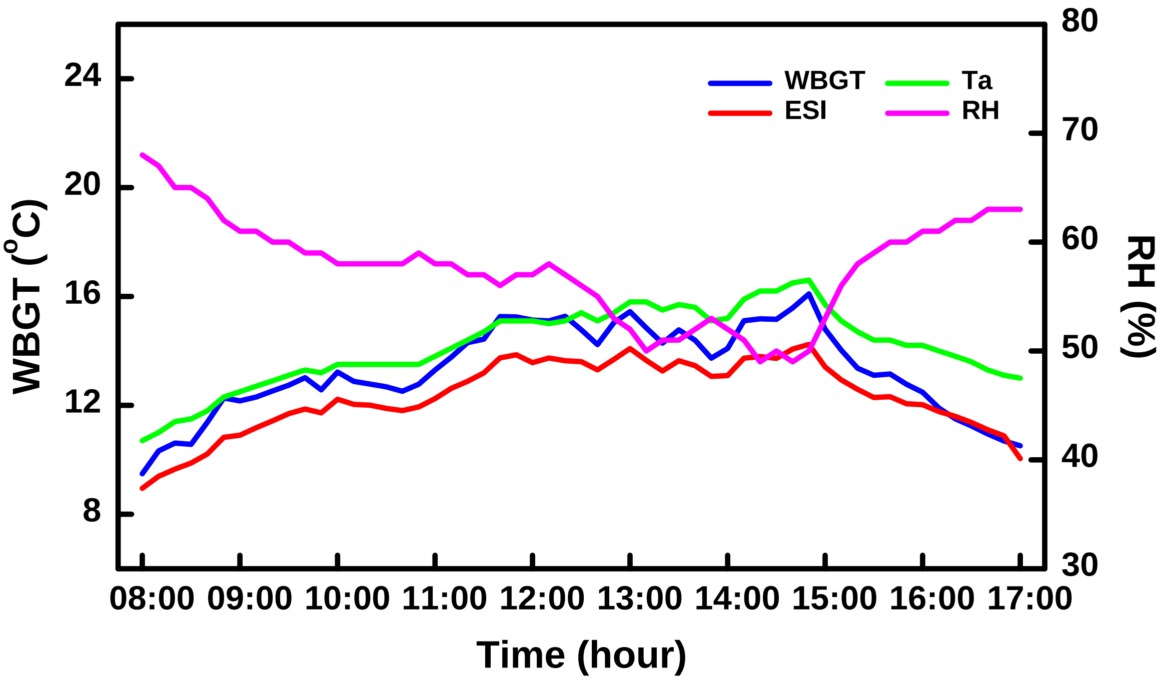


Figure 16. A comparison between WBGT calculated from data collected in Jerusalem (top) and Eilat (bottom) by the Israeli Meteorological Service (IMS), and ESI calculated from the WAPEM's environmental sensors (T_a and RH).

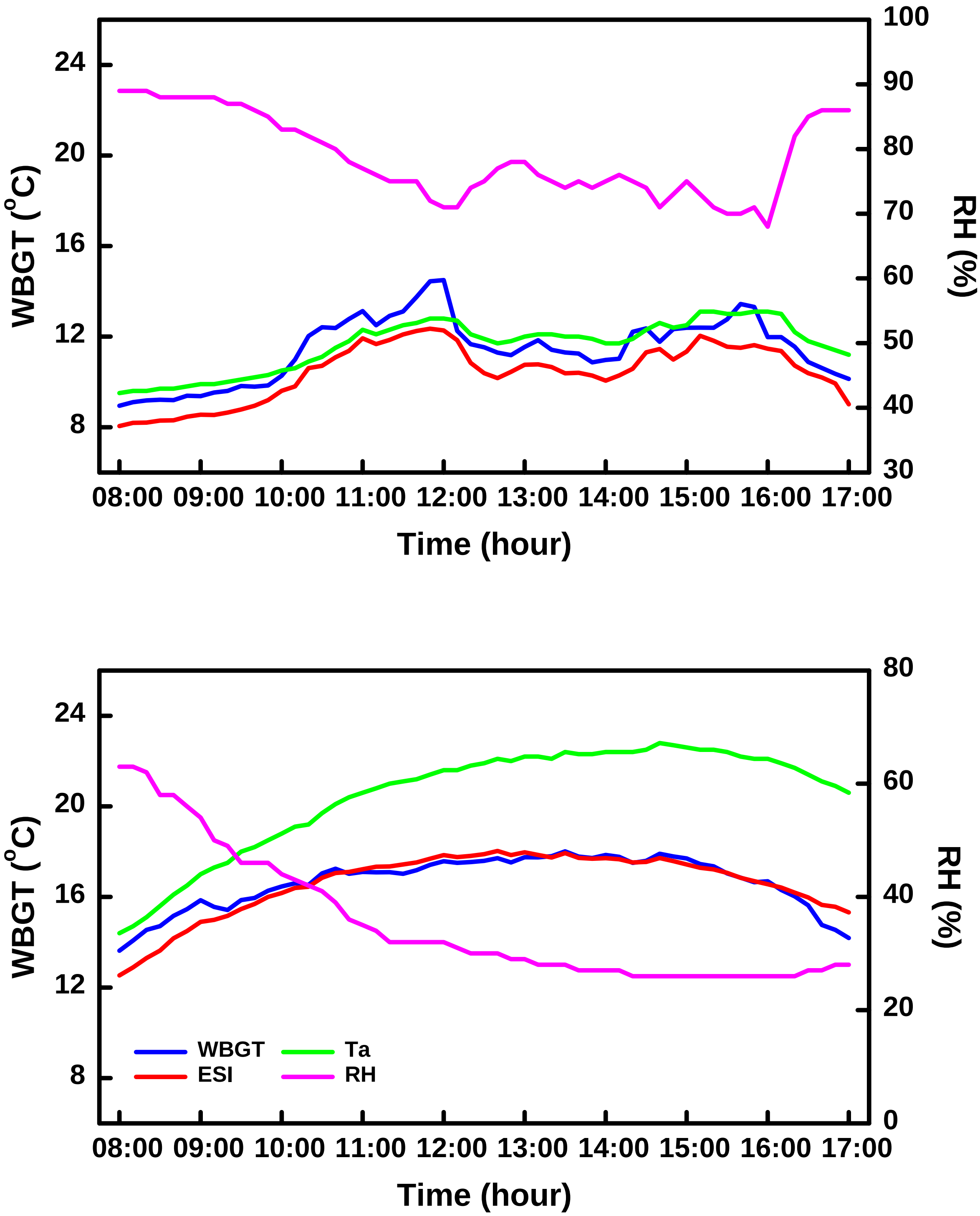
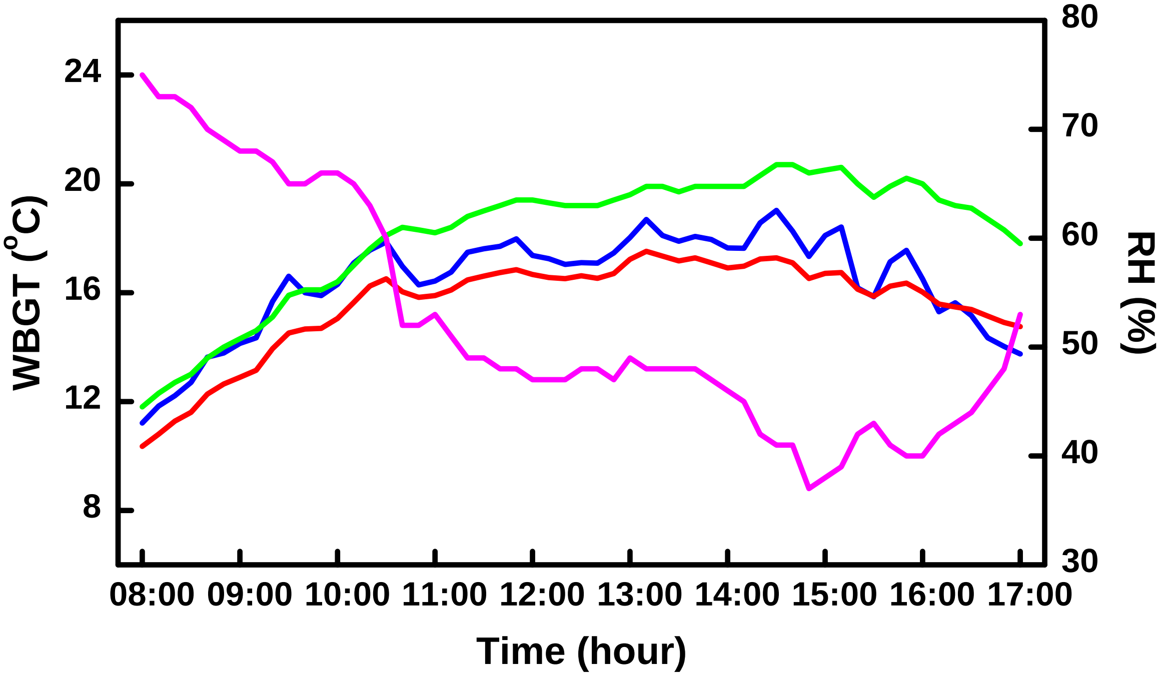
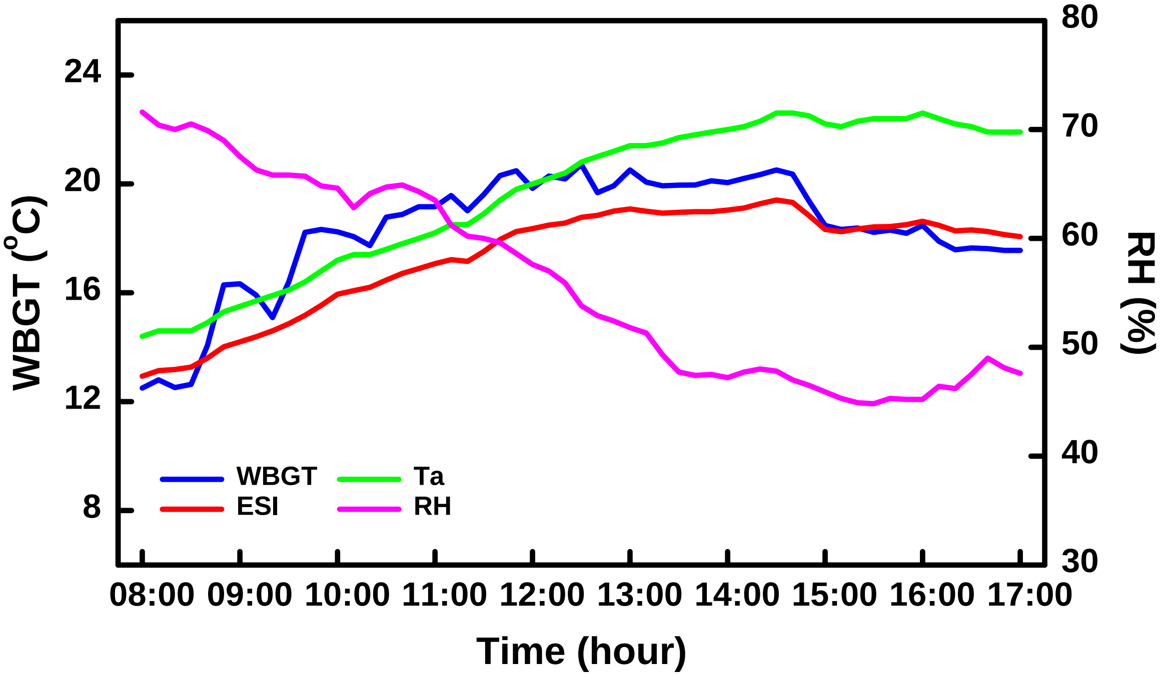


Figure 17. A comparison between WBGT calculated from data collected in Beer Sheba (top) and the Dead Sea (bottom) by the Israeli Meteorological Service (IMS), and ESI calculated from the WAPEM's environmental sensors (T_a and RH).





DISCUSSION

In this study, we evaluated the newly installed T_a and RH Swiss sensors in the WAPEM. The purpose was to assess the validity of these sensors to measure accurate T_a and RH in indoor and outdoor environments. The sensors were assembled in five WAPEM prototypes but, unfortunately, data could be measured only from three devices. The indoor study consisted of 13 tests at different combinations of T_a and RH in a climatic chamber, and the outdoor study was executed at 10 different locations in Israel.

Analysis of the performance of the three $T_{a,\ WAPEM}$ from the indoor study in the chamber exposures revealed no significant differences between these three sensors and between values measured by the $T_{a,\ chamber}$ at the 20.0º-35.0ºC exposures. However, at the 40ºC exposures, $T_{a,\ WAPEM}$ measurements differed significantly from $T_{a,\ chamber}$, and were found to underestimate values measured in the climatic chamber by 2.5º-3.5ºC ($P<0.05$). The magnitude of this error is beyond the testing requirement of 0.5ºC, as specified in Table 2. Assuming that the differences were due to the needed time to reach equilibrium by the WAPEM's sensors, we repeated and extended the 40ºC-40% RH tests from 60 min to 140 min and started this second exposure only after the 3 WAPEMs were placed in the chamber for 60 min at 35ºC. Despite this change, significantly lower differences of 1.0º-2.0ºC were found between $T_{a,\ WAPEM}$ and $T_{a,\ chamber}$ measurements ($P<0.05$). Therefore, it was concluded that further evaluation is needed for $T_{a,\ WAPEM}$ at >35ºC.

Analysis of the measurements from the indoor study of the RH_{WAPEM} from the 3 units tested showed, in general, no significant difference between these 3 sensors and between values measured by the $RH_{chamber}$. Collectively, slightly lower stable values (less than 5%) were observed during the different exposures, which are within the defined testing requirements. However, in a few exposures, RH_{WAPEM} reached equilibrium only after 40 min and 100 min (25ºC-70%RH and 40ºC-40% RH, respectively). Thus, the RH_{WAPEM} response time and the time for reaching stability should be further evaluated.

For the outdoor study, data collection was obtained for 10 days from different sites during January. Overall, the two types of sensors ($T_{a,\ WAPEM}$ and RH_{WAPEM}) were found reliable, with no significant differences between the values measured for each type during the different exposures. A higher correlation was found between $T_{a,\ WAPEM}$ and $T_{a,\ Kestrel}$ 0.984 and $R \geq 0.911$ for T_a and RH, respectively, when comparing the WAPEM sensors and the other sensors used in this study. However, high correlation ($R \geq 0.852$ and $R \geq 0.833$ for T_a and RH, respectively) was also found between WAPEM and IMS measurements.

The range of the measured meteorological variables at the different locations were categorized as comfort climate conditions. Therefore, the obtained stress indices, WBGT and ESI, which were constructed for heat stress evaluation, were limited in their assessment of the measured values. Thus, there is a need to further evaluate $T_{a,\ WAPEM}$ and RH_{WAPEM} and the obtained ESI and WBGT at warmer climates and under severe environmental stress. However, there is no doubt that the performance of the T_a and the RH sensors tested in this study should be considered as an immense improvement in comparison to the previous sensors installed in WAPEM and tested in 2001 (9).

The WAPEM has been designed to measure T_a, RH, and SR, and to calculate the ESI from these measurements. The ESI differs from other indices that have been suggested in the past in two critical ways: (1) This stress index, for the first time in history, uses direct measurements of SR and RH. When used in ESI, direct measurements of SR and RH are not as cumbersome as measuring T_g and T_{wb} for calculating the WBGT; (2) The three meteorological variables used in ESI should be characterized by fast-reading responses that take only a few seconds to reach equilibrium. For an index to be valid and practical, it should allow the comparison and evaluation of a combination of different meteorological parameters, as far as their influence on the individual is concerned. The index also helps to find different combinations of these parameters that cause equal subjective heat sensations. Moreover, the index must enable one to assess the different weights of each of the meteorological parameters on the individual (8).

Technical issues, which dominated system design decisions, included sensor requirements, unit size and weight, battery power requirements, protection, durability, user friendliness, and cost. Therefore, we decided on the construction of a wristwatch design that, apart from serving as a watch, has the capability to measure climatic variables (T_a, RH, and SR) and sleep scoring. A key element in the WAPEM design is the incorporation of a SR sensor to meet input requirements for the USARIEM heat strain model. In a previous study (7), GR was measured by the IR light sensor at 6 locations that differ in their height from sea level. In general, the range of the measurements for each day was wide. In analyzing the data from the 3 tested IR light sensors and the pyranometer, there were no significant differences ($P<0.05$) between these 3 sensors, which strengthens the reliability and validity of the IR light sensor to measure GR. Thus, the importance and the additional contribution of this study is in testing the feasibility of accurately measuring T_a and RH by WAPEM in order to calculate ESI. Thus, the high correlations found between ESI obtained from WAPEM and WBGT obtained from IMS serve as an encouragement to proceed with the WAPEM project, despite the limits that were found in some exposures.

In conclusion, further tests are required for the new WAPEM sensors in order to evaluate their accuracy above 35ºC, and the response time before reaching equilibrium. These tests should execute successfully on WAPEM prototypes assembled with the sensors (T_a and RH) actual location, including the SR sensor.

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APPENDIX A

Mean±SD of ambient temperature (T_a) measured by 2 Psychrometers (P), 2 Kestrels (K), and 3 WAPEM sensors in the climatic chamber.

Chamber set point		$T_{a, P}$	$T_{a, K}$	$T_{a, WAPEM}$
T_a (ºC)	RH (%)			
20	40	20.88±0.25 20.38±0.48	20.88±0.15 20.68±0.10	20.18±0.26 20.60±0.22 19.98±0.46
	45	20.33±0.26 20.00±0.00	20.55±0.05 20.65±0.05	20.33±0.06 20.40±0.03 20.28±0.08
	50	20.63±0.25 20.00±0.00	20.65±0.13 20.60±0.18	20.50±0.18 20.36±0.25 20.30±0.29
	60	20.50±0.00 20.00±0.00	20.38±0.10 20.20±0.08	20.30±0.08 20.17±0.12 20.26±0.05
	70	21.00±0.00 20.50±0.00	20.44±0.05 20.32±0.08	20.53±0.10 20.46±0.09
25	50	25.00±0.50 25.10±0.42	24.74±0.33 24.58±0.33	24.58±0.51 24.74±0.52
	60	25.20±0.15 24.80±0.13	24.78±0.27 24.64±0.45	24.66±0.21 24.54±0.29 24.38±0.26
	70	24.94±0.63 25.17±0.71	24.69±0.40 24.59±0.40	24.76±0.48 24.63±0.42
30	40	30.33±0.52 30.00±0.63	30.20±0.30 29.97±0.16	29.63±0.22 29.57±0.22 29.45±0.26
	50	31.00±0.00 30.36±0.24	29.81±0.13 29.64±0.15	29.79±0.15 29.71±0.30
	60	30.25±0.27 30.33±0.26	29.77±0.19 29.63±0.16	29.67±0.22 29.38±0.16 29.57±0.22
	70	30.64±0.48 30.43±0.35	29.33±0.29 29.26±0.31	29.29±0.37 29.26±0.36
35	40	35.88±0.63 35.13±0.63	35.48±0.29 35.25±0.21	34.88±0.10 34.83±0.13 34.73±0.15
	50	35.25±0.50 35.25±0.50	35.25±0.13 35.00±0.14	35.50±0.22 35.28±0.13 35.28±0.10
	60	35.00±0.61 34.70±0.67	34.58±0.16 34.46±0.15	34.22±0.35 34.16±0.23
40	40	39.96±0.50 40.11±0.45	38.48±0.47 38.38±0.44	36.56±0.88 37.75±1.26 37.64±1.12
	40	40.25±0.42 40.08±0.49	38.93±0.27 38.78±0.22	38.83±0.23 38.62±0.17
	45	41.20±0.84 41.00±1.00	39.90±0.47 39.46±0.43	37.56±0.60 37.62±0.57 37.42±0.50

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