REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
DECEMBER 2001

3. REPORT TYPE AND DATES COVERED
Technical Report

4. TITLE AND SUBTITLE
TECHNICAL TESTING OF A WRISTWATCH SIZE AUTOMATIC PHYSIOLOGICAL AND ENVIRONMENTAL MONITOR (WAPEM): LABORATORY AND OUTDOOR EVALUATIONS OF SENSOR PERFORMANCE

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Institute of Environmental Medicine
Kansas St, BLDG 42
NATICK, MA 01770-5007

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Institute of Environmental Medicine
Kansas St, BLDG 42
NATICK, MA 01770-5007

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Releas; Distribution Unlimited

ITION CODE

20011220 050

13. ABSTRACT *(Maximum 200 words)*

The wristwatch-size automatic physiological and environmental monitor (WAPEM) is a miniature instrument worn on the wrist that is capable of measuring relative humidity (RH), ambient temperature (Ta), solar radiation (SR), and human work activity in a small, water-resistant, durable enclosure. The WAPEM is fitted with a 4-digit display that can be used to view each of these parameters via selection buttons on the front face. When not in data mode, the WAPEM serves as the wearer's primary timepiece. Time is set in the usual digital manner with the front buttons. The lower side, near the buttons, houses the computer interface pins. The WAPEM can be programmed through these 7 pins. Programming ranges from a simple initialization of existing firmware to a complete rewrite of embedded firmware. The WAPEM is always in circuit re-programmable mode. It is therefore possible to make changes to the WAPEM operational code and embed various environmental stress/physiological strain algorithms. These can be used afterwards to make predictions from measured environmental variables and on-line human work activities. The work activity channel is designed for sleep scoring (zero crossing mode), as well as for monitoring daytime activity with the proportional channel mode. The WAPEM is also designed to quantify extent of sleep loss and metabolic expenditures for individual activity levels, and to enable personalized estimates of the effects of several key stressors on physical or mental performance in operational settings. This report discusses initial proof-of-concept hardware and the environmental testing of software prototypes. Three WAPEM prototypes were tested for 12 days to verify accuracy and repeatability of the environmental sensor operation (Ta and RH) in climatic chambers at USARIEM and in Israel. The SR sensor was tested outdoors at 6 different distances below and above sea level in Israel. It was concluded from this study that the WAPEM concept offers a robust, lightweight environmental stress/strain accessory useful to the warfighter. Future improvements to the WAPEM are suggested regarding the location, deployment, and accuracy of the specific environmental sensors.

14. SUBJECT TERMS
sensors, physiologic monitor, modeling

15. NUMBER OF PAGES
29

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	U

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18 298-102

USAPPC V1.00

USARIEM TECHNICAL REPORT T00-## T-02/6

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

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December 2001

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ACKNOWLEDGMENTS

This project is a joint collaborative effort between the U.S. Army Research Institute of Environmental Medicine and the Israel Defence Force. The work conducted in Israel was done with the assistance of Mr. Ziv Hersch and Mr. Liran Mendel. Dr. Arie Laor and Ms. Liron Shalit's contributions in the statistical analysis and evaluation of the environmental stress index are greatly appreciated. We are thankful for the cooperation and assistance of Mr. Jacob Mishaeli of the Israeli Meteorological Service. We also thank Mr Robert Conlan, President Precision Control Devices, Ft. Walton Beach, FL, for consultation services and the fabrication of the WAPEM.

LIST OF ABBREVIATIONS AND ACRONYMS

GR – global radiation

IR – infrared

RH – relative humidity

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

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

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

WAPEM – wristwatch-size automatic physiological and environmental monitor

WBGT – wet bulb globe temperature

P – pyranometer

AHS – Academy of Health Sciences

SR– Solar radiation (equivalent to solar irradiance)

LIT– Light intensity

PCD–Precision Design Control

PGR–predicts global radiation

O&O–organizational and operational

EHME–environmental health monitoring equipment

EXECUTIVE SUMMARY

The wristwatch-size automatic physiological and environmental monitor (WAPEM) is a miniature instrument worn on the wrist that is capable of measuring relative humidity (RH), ambient temperature (T_a), solar radiation (SR), and human work activity in a small, water-resistant, durable enclosure. Precision Control Devices (PCD, Inc. Ft Walton, FL) fabricated the WAPEM as a technical service contract. It follows design specifications from an proposal jointly developed by the authors. The WAPEM is fitted with a 4-digit display that can be used to view each of these parameters via selection buttons on the front face. When not in data mode, the WAPEM serves as the wearer's primary timepiece. Time is set in the usual digital manner with the front buttons. The lower side, near the buttons, houses the computer interface pins. The WAPEM can be programmed through these 7 pins. Programming ranges from a simple initialization of existing firmware to a complete rewrite of embedded firmware. The WAPEM is always in circuit re-programmable mode. It is therefore possible to make changes to the WAPEM operational code and embed various environmental stress/physiological strain algorithms. These can be used afterwards to make predictions from measured environmental variables and on-line human work activities. The work activity channel is designed for sleep scoring (zero crossing mode), as well as for monitoring daytime activity with the proportional channel mode. The WAPEM is also designed to quantify extent of sleep loss and metabolic expenditures for individual activity levels, and to enable personalized estimates of the effects of several key stressors on physical or mental performance in operational settings. This report discusses initial proof-of-concept hardware and the environmental testing of software prototypes. Three WAPEM prototypes were tested for 12 days to verify accuracy and repeatability of the environmental sensor operation (T_a and RH) in climatic chambers at USARIEM and in Israel. The SR sensor was tested outdoors at 6 different distances below and above sea level in Israel. It was concluded from this study that the WAPEM concept offers a robust, lightweight environmental stress/strain accessory useful to the warfighter. Future improvements to the WAPEM are suggested regarding the location, deployment, and accuracy of the specific environmental sensors.

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. This philosophy is reflected in current military heat injury prevention procedures (1,2,3) and also in industrial settings (5). Although physiological heat strain and the potential for heat injury are determined, to a great extent, by T_a, RH, SR, and wind speed, the soldier's clothing characteristics, acclimatization status, and activity level also play a significant role (10). As the 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 developed. At the small unit level, soldiers may be conducting their mission tasks in hot shelters or caves, tank crew compartments, or in various outdoor environments. Therefore, the capability to provide real time 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.

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 that 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 (2,3). The low-cost mechanical device widely available to Army users is the Stortz WBGT Kit (NSN 6665-00-159-2218). The Navy has an electronic WBGT meter (NSN 6685-01-055-5298), intended primarily for use aboard various ships. The inherent limitations of the WBGT in terms of applicability across a broad range of potential military scenarios and environments have been reported (4,5,6,8,12). These limitations can be attributed, in part, to early constraints on sensor and computational complexity (13), but a more fundamental limitation is the conceptual basis itself: WBGT is exclusively environmental and does not directly evaluate the physiologic 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, USARIEM has developed and implemented a useful heat strain prediction model (10). The model provides tailored guidance on maximum safe work times, optimal work/rest cycle limits, and hourly drinking water needs. The model is also implemented in a small heat stress monitor, HSM (5,11). Although very portable itself, the HSM requires the availability of measured data for the environmental inputs: air temperature, humidity, wind speed, and solar radiation.

The consideration of a heat stress-monitoring device that integrates an environmental sensor suite with heat strain prediction model software is a fruitful concept. 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 to develop an Organizational and Operational (O&O) Plan for the electronic heat stress monitor was sent to the Academy of Health Sciences (AHS), Fort Sam Houston,TX (SGRD-UMA/ 24 Jan 1990, 1st End SGRD-UE-ZB/ 16 Jan 90). Following a meeting sponsored by the Office of The Surgeon General on the prevention and treatment of heat injuries, held at Natick, MA, April 1990, the AHS prepared a draft concept statement, "Heat Stress Prediction and Prevention Program" that outlined a comprehensive hierarchical approach to the problem (HSHA-CDS, 4 May 1990). That document provided the basis for the draft "O&O Plan for Environmental Health Monitoring Equipment (EHME)", which included the merged Heat Stress Monitor/Calculator concept (HSHA-CM, 7 May 91). The HSM was successfully tested in Australian and has formed the basis of new directions in modeling of the environment with the warfighter (5).

The WAPEM, which was conceived as an outcome of extensive discussion between USARIEM and Israeli Defence Force scientists, addresses requirements identified in the index of medical capability issues, January 1992, prioritized number 4 of 26: "Inadequate Capability to Prevent/Minimize Endemic Disease/Environmental Injury." Although an O&O Plan for EHME received preliminary approval in 1991, changes in the Concept Based Requirements System 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 and an Operational Requirements Document.

Current status of the WAPEM project is a combined Concept Exploration and Definition/Demonstration and Validation (CED/DV) phase, with initial system fielding scheduled for 2002. Three units were delivered in June 2001, fabricated as part of a technical services contract to Precision Design Control (PCD), and funded as part of Scientific Technical Objectives STO U, Task B on biophysical devices research and development needs. USARIEM provided predictive model software and clothing parameter data to PCD for incorporation into the WAPEM and has been assigned responsibility for technical testing of the prototype WAPEMs.

The purpose of this study was to evaluate and determine the accuracy of the WAPEM's air temperature and relative humidity sensors across a broad range of controlled environmental conditions. In addition, the SR was evaluated under outdoor hot/dry and hot/wet climatic conditions at different heights from sea level.

METHODS

Three WAPEM prototypes were used for sensor evaluation in this study. For the T_a and RH sensors, measurements were established in a precise temperature controlled test chamber at USARIEM (21 exposures) and at the Heller Institute of Medical Research, Israel (6 exposures). A test conditions matrix of the 27 different environmental conditions is shown in Table 1. This matrix supported both the sensor tests and software evaluations. WAPEM measurements at the 27 different test environments were taken from the 3 prototypes to allow a statistical evaluation of sensor repeatability in identical environments. The prototype WAPEM outputs (diagnostics screen) for T_a and RH were compared with values measured using calibrated (National Bureau of Standards traceable) laboratory grade sensors having an overall accuracy specification of ±0.2°C and repeatability of ±0.5°C for T_a, and ±1% for RH. These measurements included an automated environmental data acquisition system at both USARIEM and the Heller Institute.

The evaluation of the IR light sensor was established in Israel in 6 different locations differing in height from sea level and using the same 3 WAPEM prototypes. Measurements comparing the globe temperature (T_g) and the WBGT index are published in another technical report (9). In this study we compared the IR light measured values with measurements from the EPLAB pyranometer PSP model with sensitivity of 285-2800 nm.

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

Location	Air Temperature (°C)	Relative Humidity (%)
USARIEM	15.0	50.0 80.0 90.0
	25.0	20.0 50.0 80.0
	30.0	20.0 30.0 50.0 75.0
	35.0	10.0 20.0 50.0 80.0
	40.0	10.0 20.0 50.0 65.0
	50.0	10.0 20.0 50.0
Heller Institute	30.0	50.0
	35.0	45.0 70.0
	40.0	40.0 50.0 60.0

Technical issues dominated the system design decisions, including sensor requirements, unit size and weight, battery power requirements, protection, durability, user friendliness and cost. Therefore, we decided on the construction of a wristwatch size design that, apart from serving as a watch, has the capability to measure climatic variables (T_a, RH, and SR) and sleep scanning (Figure 1). A key element in the WAPEM design is the incorporation of the SR input requirements for the USARIEM heat strain model.

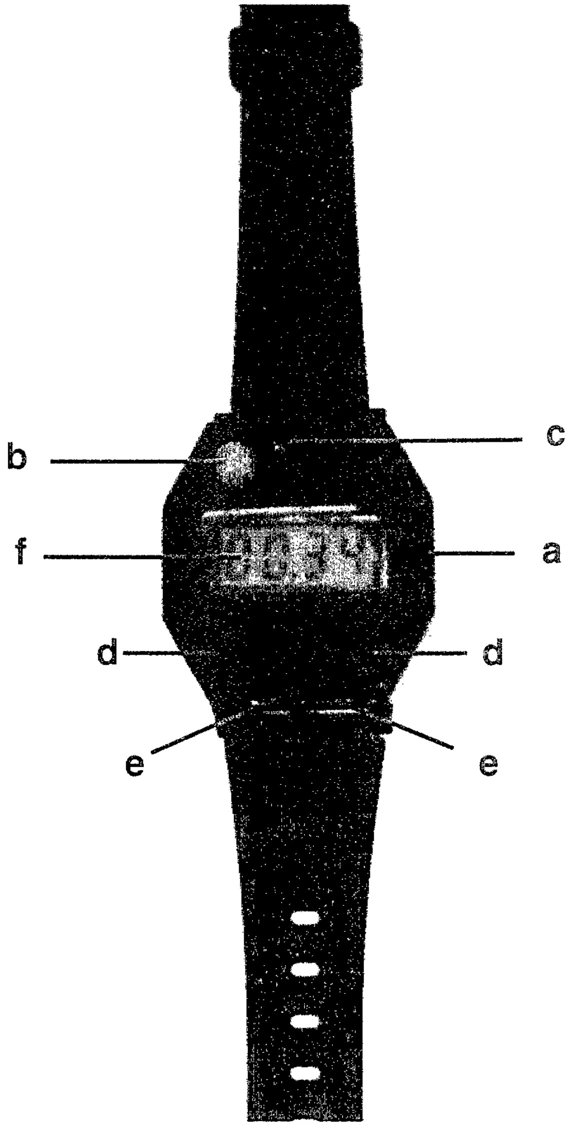


Figure 1. The actual size of the WAPEM prototype (a – ambient temperature sensor, b – humidity sensor, c – IR light sensor, d – set up buttons, e – computer interface pins, f – data display)

Technical testing requirements are formally defined in the Test and Evaluation Master Plan for the WAPEM (memo, 2000). This protocol and subsequent USARIEM efforts focused on test requirement issues that relate to the WAPEM sensor accuracy and reliability.

Sensor specifications: The performance requirements for the climatic sensors are shown in Table 2.

Table 2. The WAPEM's climatic sensors (ambient temperature [T_a], relative humidity [RH], and solar radiation [SR]) system performance specifications.

SENSOR SYSTEM PERFORMANCE AND SPECIFICATIONS			
Parameter	Sensor type	Accuracy	Range
Air Temperature	Thermistor	± 0.5°C	5° – 65°C
Relative Humidity	Capacitive	± 5% RH	0 – 100% RH
Solar Radiation	Light	$\pm 100\ W \cdot m^{-2}$	$0 - 1000\ W \cdot m^{-2}$

SENSOR SPECIFICATIONS

Air Temperature Sensor

The WAPEM thermometer sensor circuitry buffers the voltage in inverse proportion to its temperature in the ranges of -25°C to +65°C. The nonlinear thermistor signal is read by the 10-bit A/D module and processed via a lookup table with ±1°C resolution.

Relative Humidity Sensor

The WAPEM humidity sensor circuitry function is a timing circuit. The Microprocessor U5 port bit RD0 shorts out the humidity sensor (Panametrics version MCZ) when not in use. To start the measurement, the short is released. The amount of time required to charge the capacitance of the thin-film capacitive humidity sensor is measured by the microprocessor. This bit can generate an interrupt signal in order to provide precision timing. Since the time constant is proportional to %RH, the amount of time measured is also proportional to %RH in a reasonably linear fashion. The circuit provides a 4- 5 %RH resolution over a range of 0%-100%RH in a few milliseconds measurement interval. The erasible/programable (EEPROM) registers in the microprocessor store the unique calibration constants of each humidity sensor.

Infrared Light Sensor

The IR light sensor (Centro Vision, model CD-1705) is located on the top panel of the WAPEM and has a peak sensitivity of 800-920 nm. The accuracy of this IR sensor is ±5% and the effects of temperature are negligible.

The WAPEM IR light sensor circuitry provides a transconductance amplifier function and converter circuit. The current that is proportional to 850 nm infrared light intensity generated is converted to a voltage that is proportional to light intensity. The scaling of the conversion is adjustable over a wide range. The linear voltage proportional to light intensity output is measured by the 10 bit A/D converter, providing resolution over the determined range. The measurements are calibrated in W/m^2 (approximate) under microprocessor control.

Statistical Analysis

Statistical analyses including 2-tail, paired T-test and Pearson correlation factor (R) were done. The T-test was used to find significant differences between readings from pairs of instruments. Pearson correlation factor (R) was calculated to analyze the correlation between the instruments. All statistical contrasts were accepted at the $P<0.05$ or higher level of significance.

RESULTS

Ambient Temperature Sensor

In general, the WAPEM's measurements at the different ambient temperatures (15°,25°,30°,35°,40°, and 50°C) revealed no significant differences between the 3 WAPEM's sensors at each of these exposures. However, the T_a measurements in the climatic chamber were significantly different ($P<0.05$) from the WAPEM's sensors, as depicted in Table 3.

Table 3. Mean±SD of ambient temperature (T_a) measured by 3 WAPEM sensors and by climatic chamber sensors.

$T_{a,setpoint}$ (°C)	$T_{a,chamber}$ (°C)	$T_{a,WAPEM}$ (°C)	$T_{a,chamber}-T_{a,WAPEM}$ (°C)
15	14.98±0.21	21.68±5.78 17.81±0.04 18.05±0.02	-6.70 -2.83 -3.07
25	24.99±0.21	21.06±0.11 20.51±0.11 20.76±0.06	3.39 4.48 4.23
30-I	30.36±0.62	22.24±0.11 21.96±0.10 22.19±0.10	8.12 8.40 8.17
30-II	30.18±0.86	22.27±0.15 21.97±0.13 22.23±0.13	7.91 8.21 7.95
35-I	35.05±0.18	23.61±0.14 23.32±0.12 23.57±0.12	11.44 11.73 11.48
35-II	35.11±0.10	23.60±0.04 23.35±0.05 23.58±0.05	11.51 11.76 11.53
40-I	40.11±0.15	24.92±0.97 24.72±0.96 24.85±0.97	15.19 15.39 15.26
40-II	40.38±0.88	24.66±0.20 24.37±0.21 24.64±0.21	15.72 16.01 15.74
50	49.09±2.75	27.62±0.89 27.34±0.87	21.47 21.75

These results confirm a positive correlation between $T_{a,chamber}$ and the difference $T_{a,chamber}$-$T_{a,WAPEM}$, whereas the higher the $T_{a,chamber}$, the higher the $T_{a,chamber}$-$T_{a,WAPEM}$. Thus, in two tests, when the $T_{a,chamber}$ was 50°C, the mean T_{aWAPEM} was lower by 21.47° and 21.75°C, with mean values of 27.62°±0.89 and 27.34±0.87°C, respectively (Table 3).

Relative Humidity

In general, measurements made from the 3 RH WAPEMs were not significantly different from each other, and typical sensor measurements did not differ by more than 10%. Analysis of the comparison between $RH_{chamber}$ and RH_{WAPEM} showed no significant differences in all but a few exposures as depicted in Figures 2-9, or differences that were slightly higher than the expected tolerance of 5%. However, in the exposures at 35°C/70% RH, 50°C/50% RH, and 40°C/65% RH, the RH sensor at WAPEM II (W_2) measured significantly ($P<0.05$) lower values than $RH_{chamber}$ (Figures 2-4). The RH sensor in WAPEM I (W_1) measured 100%, instead of 70% and 75% RH in 3 exposures as found by using a General Eastern dew point system located in the climatic chamber.

Global Radiation

There were no significant differences between the P sensor values and the 3 IR light sensors. However, P sensor values were higher by 100-150 $W \cdot m^{-2}$ between 11:00h-15:00h at the 6 different locations (Figures 10-15).

Figure 2. The WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements in a climatic chamber (USARIEM) at T_a of 15°C and RH of 50%, 80% and 90%.

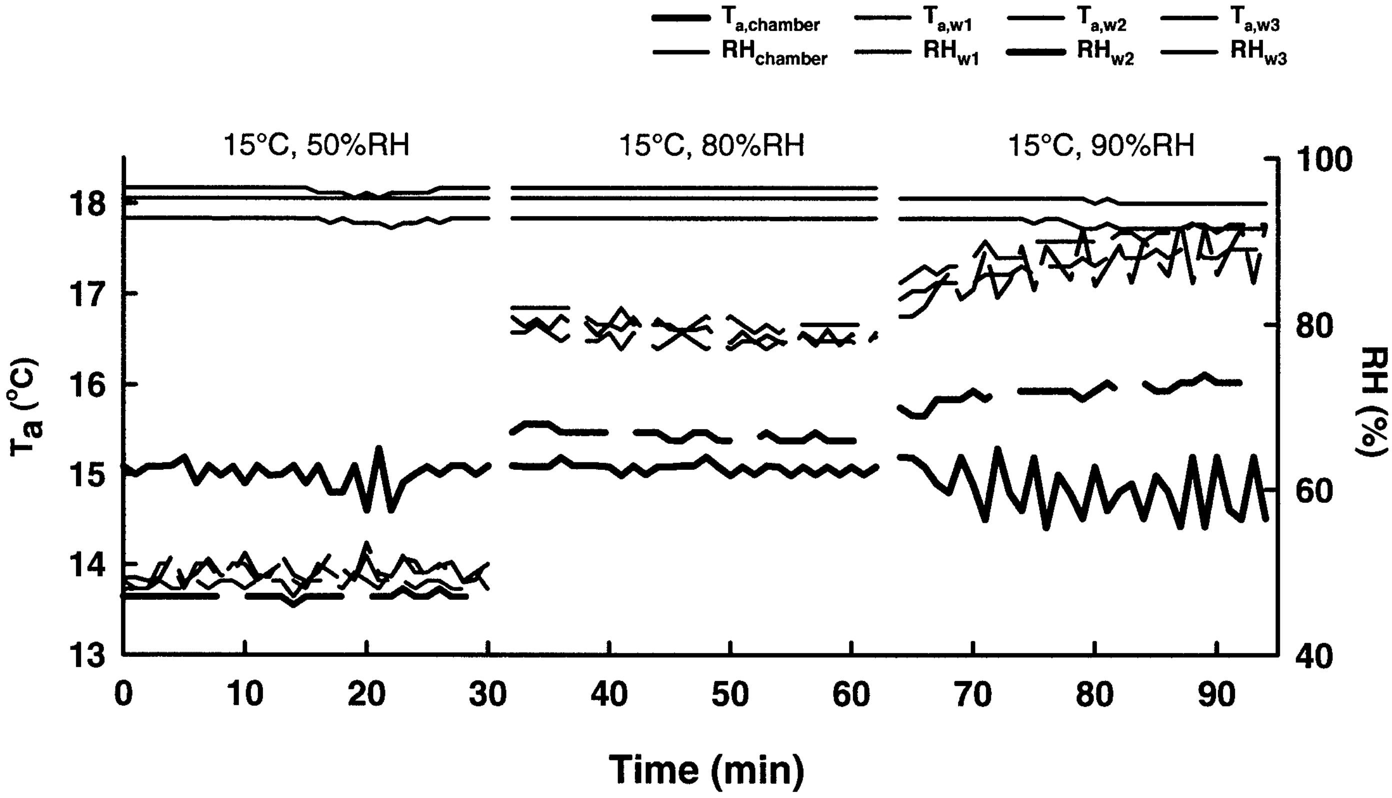


Figure 3. The WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements in a climatic chamber (USARIEM) at T_a of 25°C and RH of 20%, 50% and 80%.

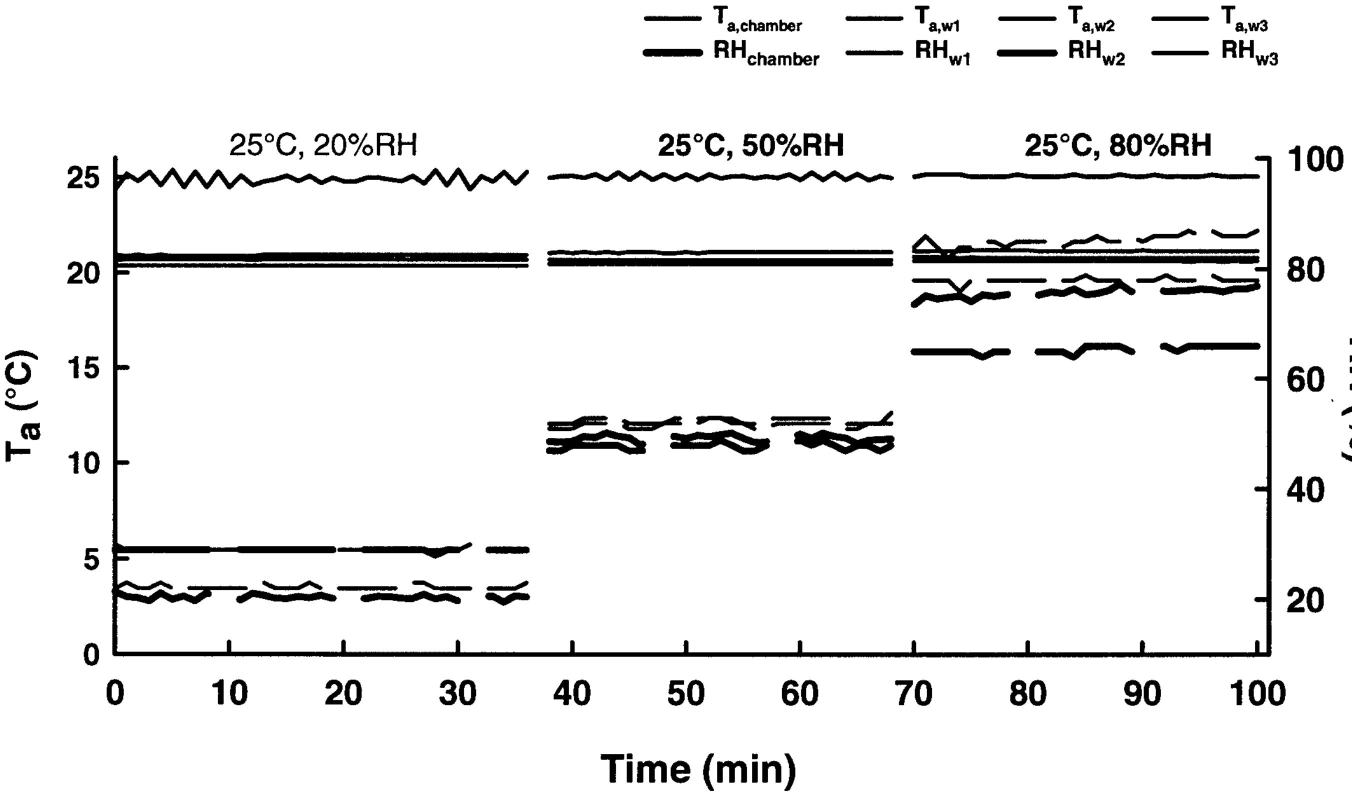


Figure 4. The WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements in a climatic chamber (USARIEM) at T_a of 30°C and RH of 20%, 30%, 50% and 75%.

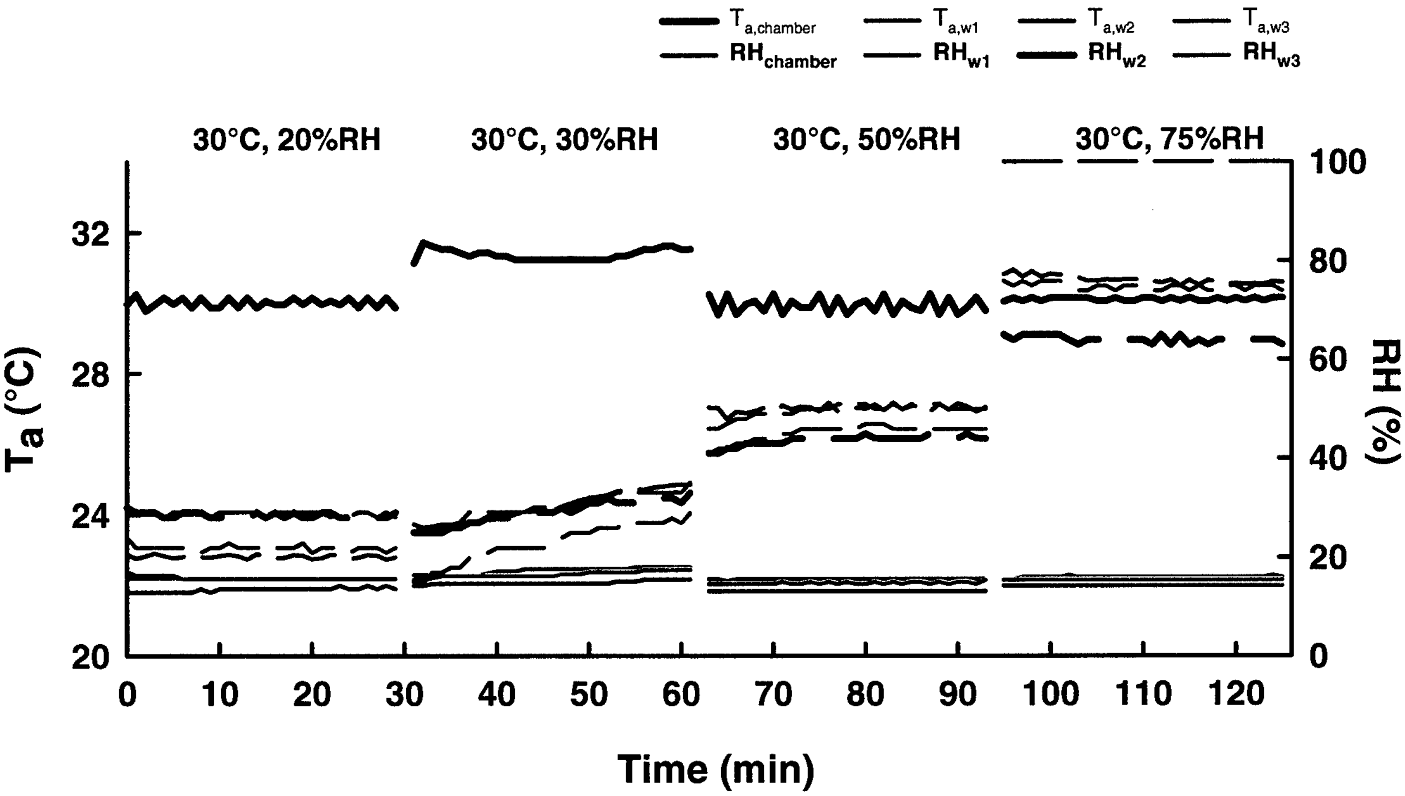


Figure 5. The WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements in a climatic chamber (USARIEM) at T_a of 35°C and RH of 10%, 20%, 50% and 80%.

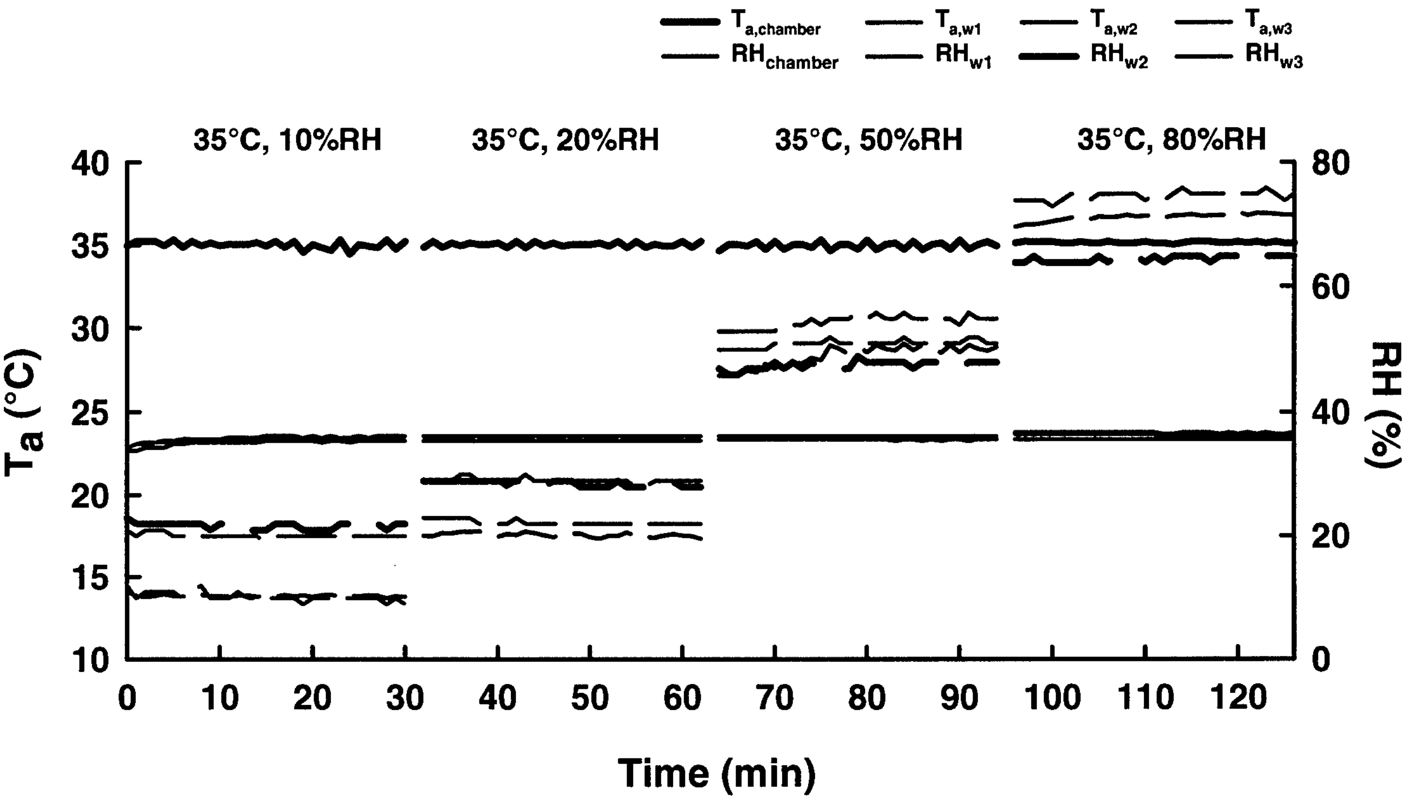


Figure 6. The WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements in a climatic chamber (USARIEM) at T_a of 40°C and RH of 10%, 20%, 50% and 65%.

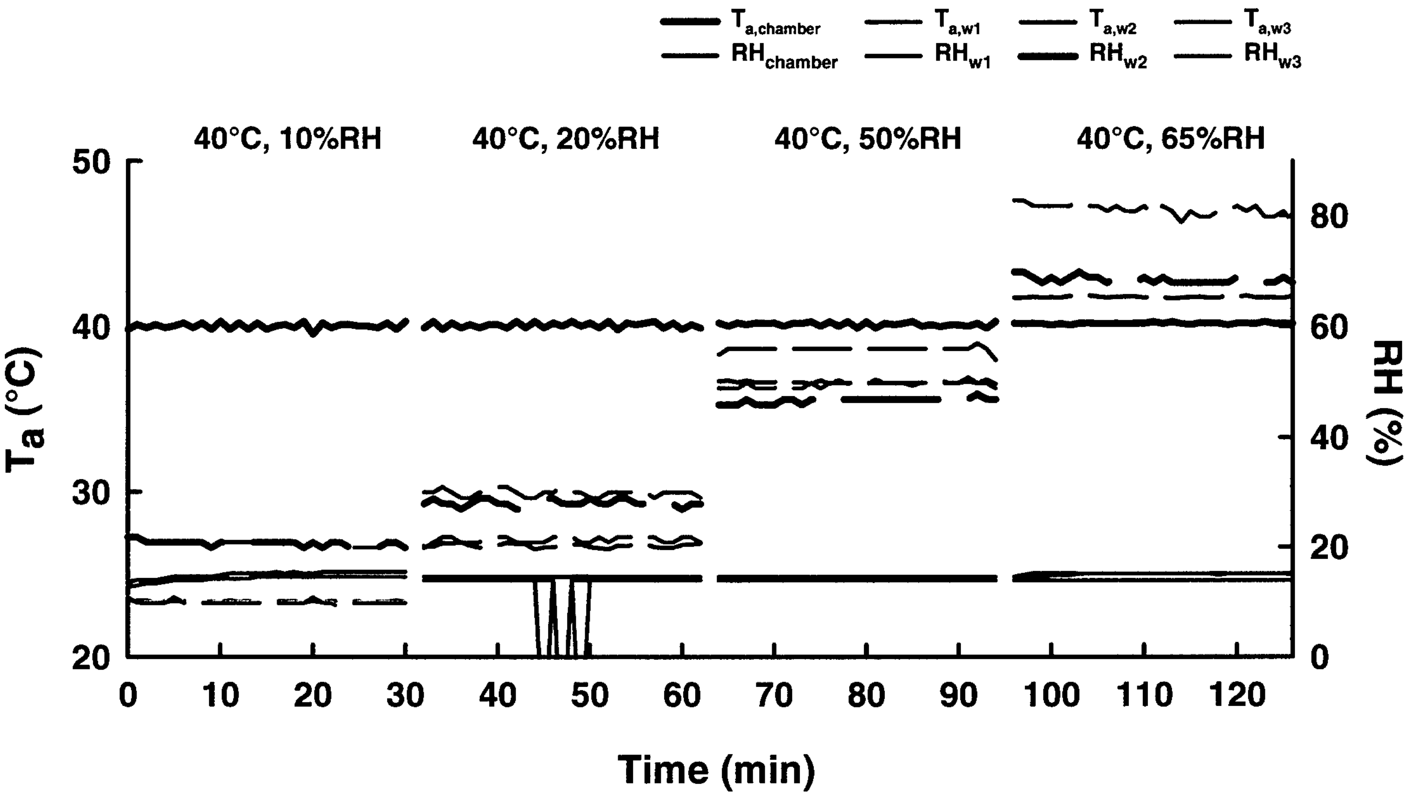


Figure 7. The WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements in a climatic chamber (USARIEM) at T_a of 50°C and RH of 10%, 20% and 50%.

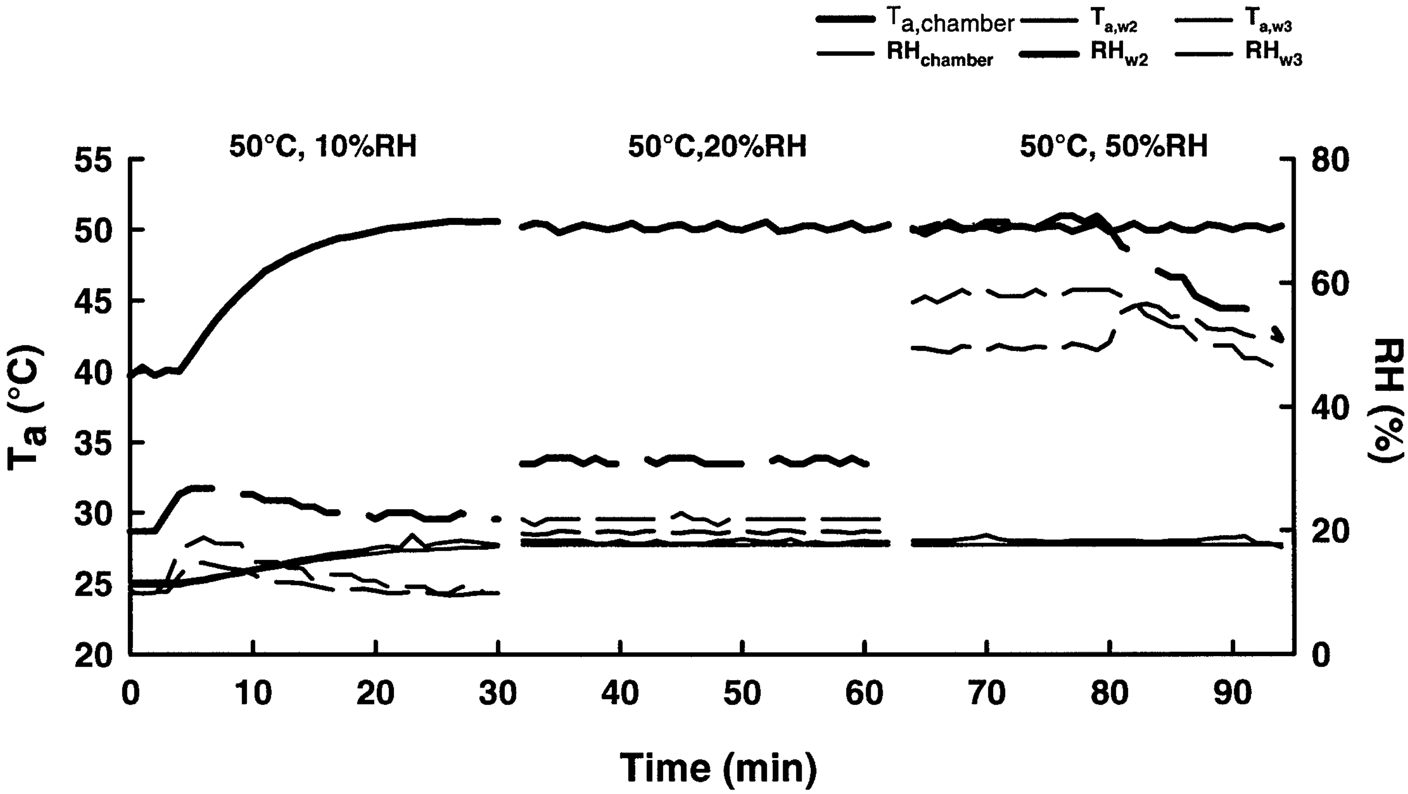


Figure 8. The WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements in a climatic chamber (Heller Institute) at T_a of 30°C and 35°C and RH of 50%, 45% and 70%.

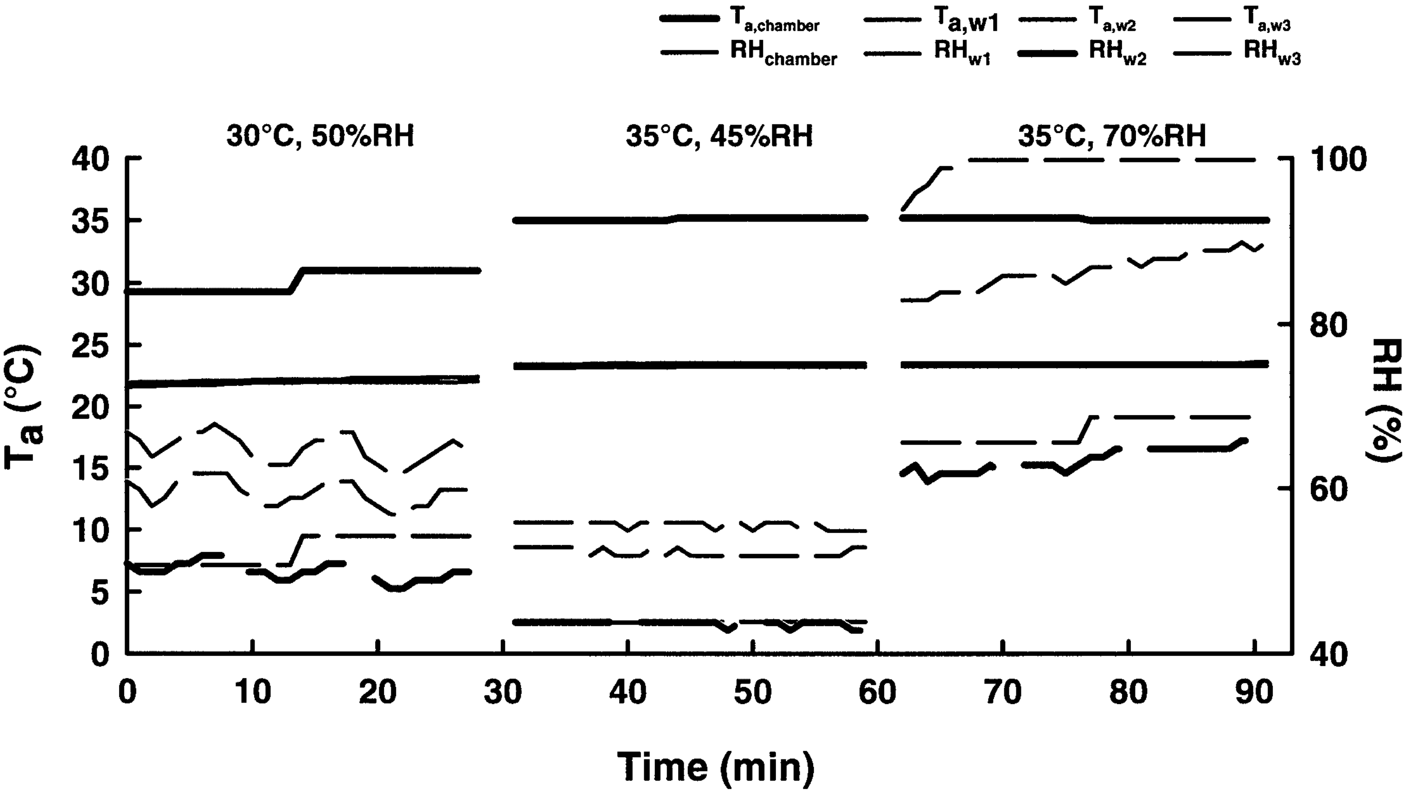


Figure 9. The WAPEM's ambient temperature (T_a) and relative humidity (RH) measurements in a climatic chamber (Heller Institute) at T_a of 40°C and RH of 40%, 50% and 60%.

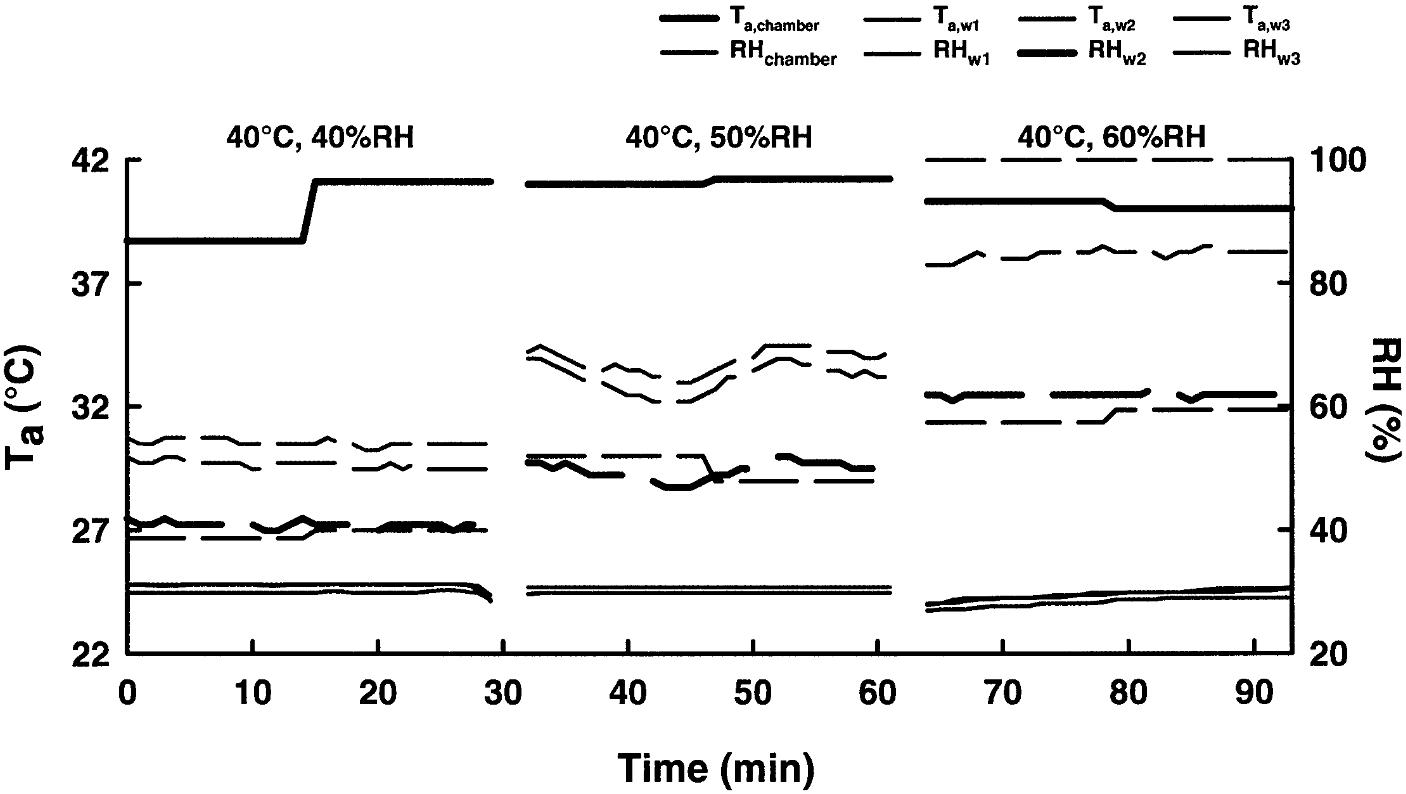


Figure 10. Global radiation (GR) measured by pyranometer (P), and 3 infra-red (IR) light sensors at -400 m below sea level.

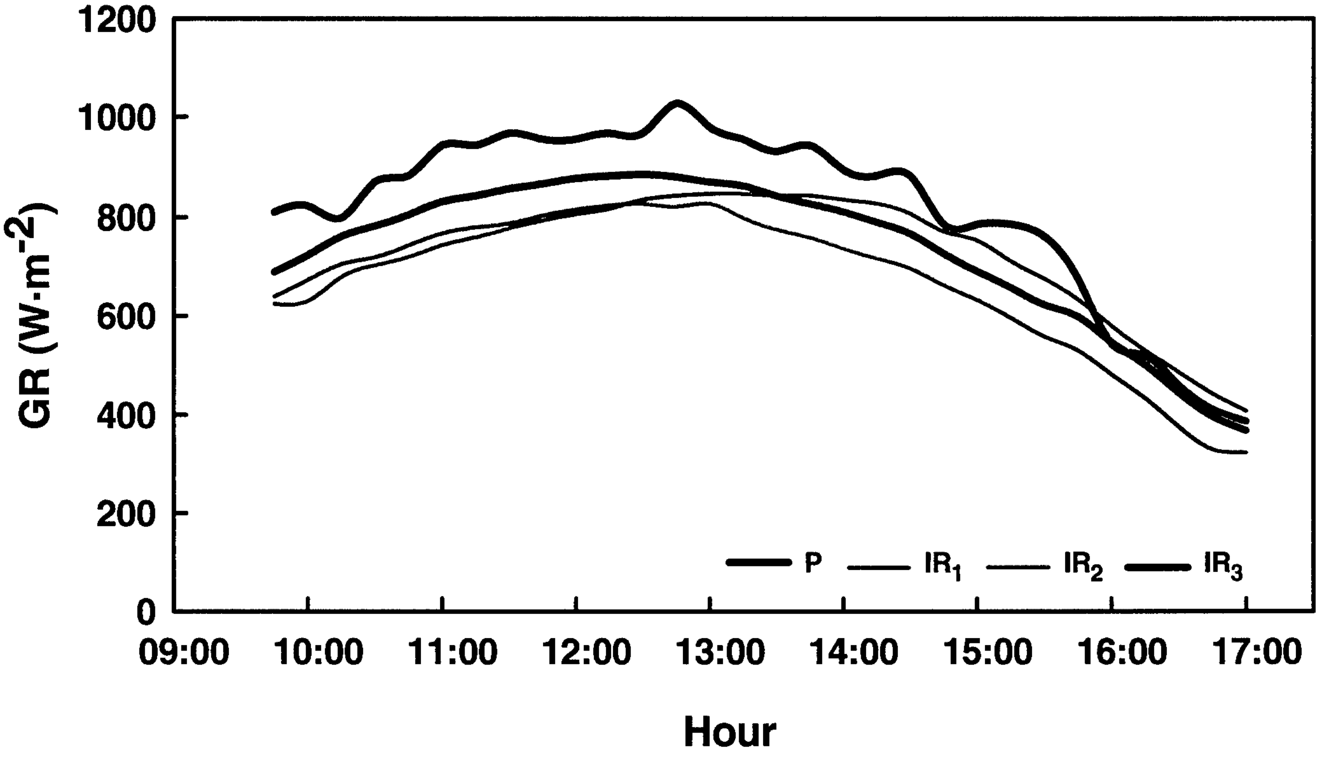


Figure 11. Global radiation (GR) measured by pyranometer (P), and 3 infra-red (IR) light sensors at -200 m below sea level.

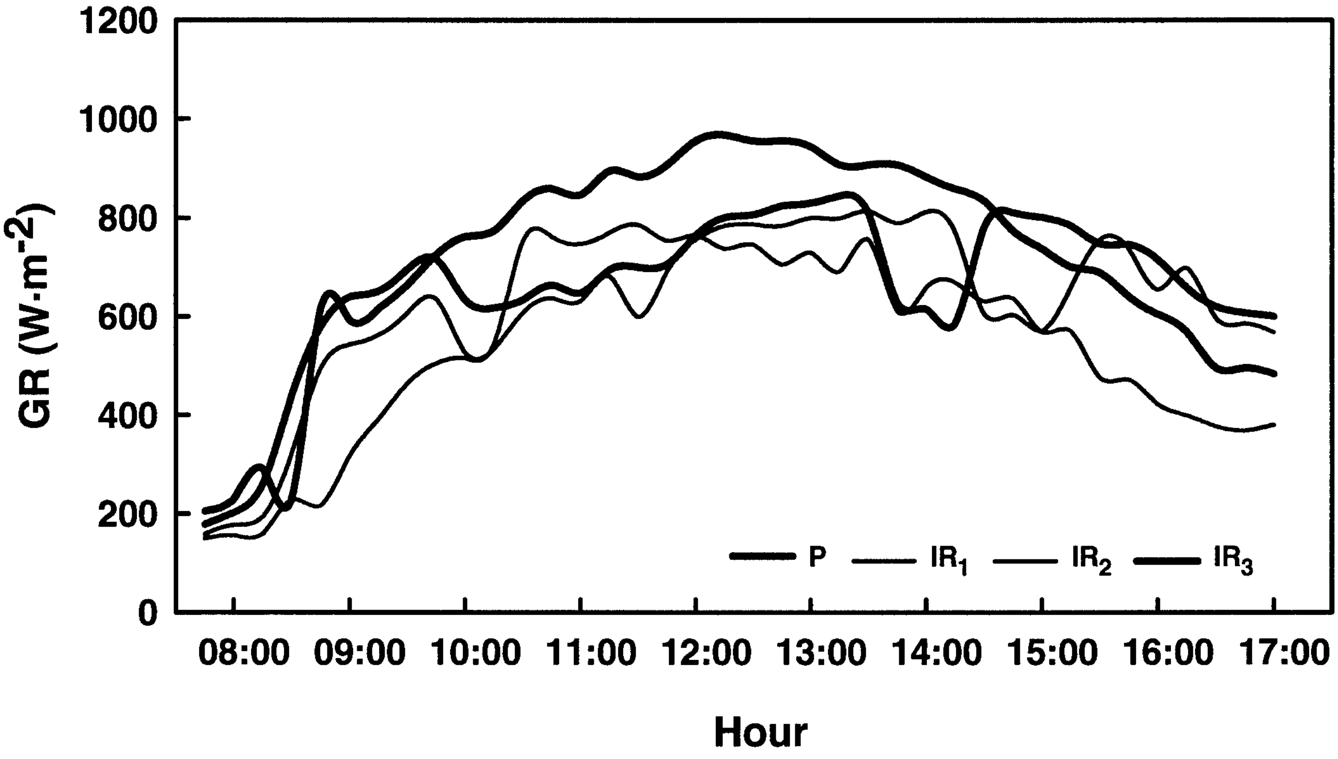


Figure 12. Global radiation (GR) measured by pyranometer (P), and 3 infrared (IR) light sensors at 30 m above sea level.

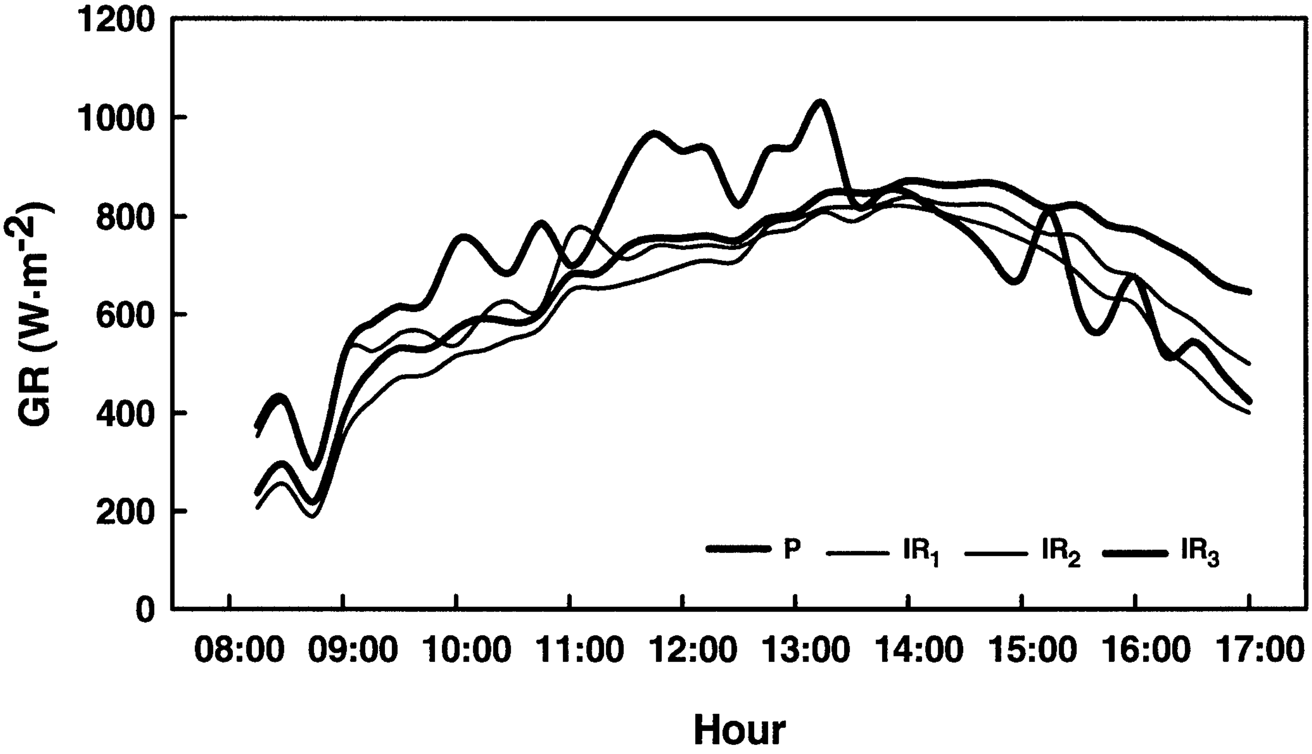


Figure 13. Global radiation (GR) measured by pyranometer (P), and infrared (IR) light sensor at 400 m above sea level.

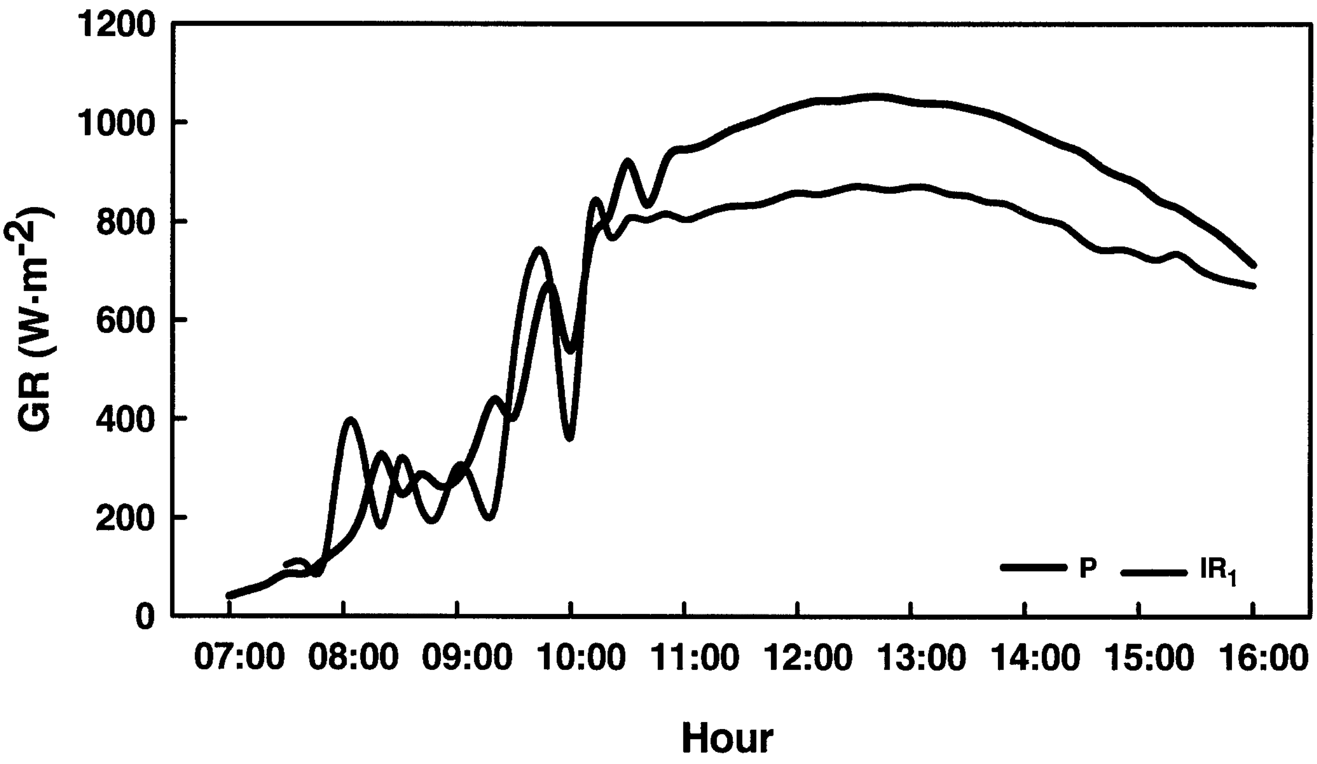


Figure 14. Global radiation (GR) measured by pyranometer (P), and 2 infrared (IR) light sensors at 900 m above sea level.

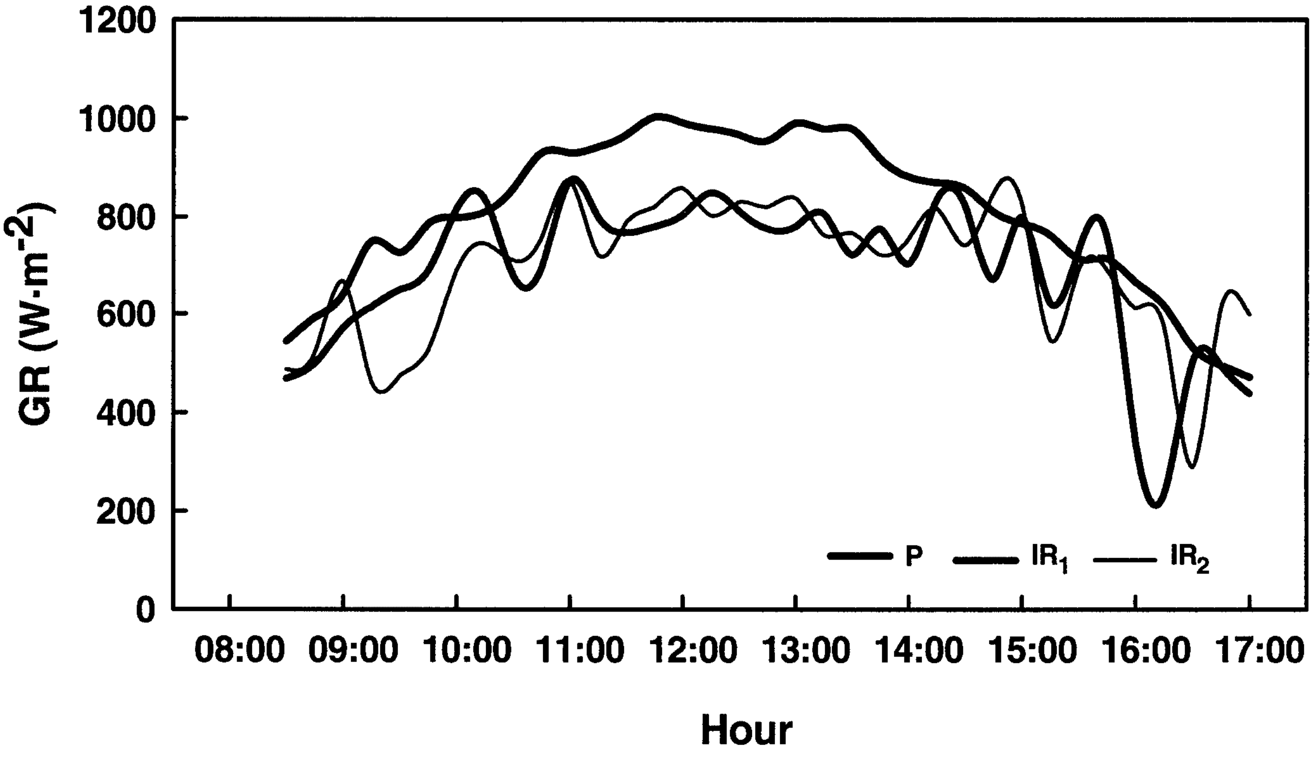
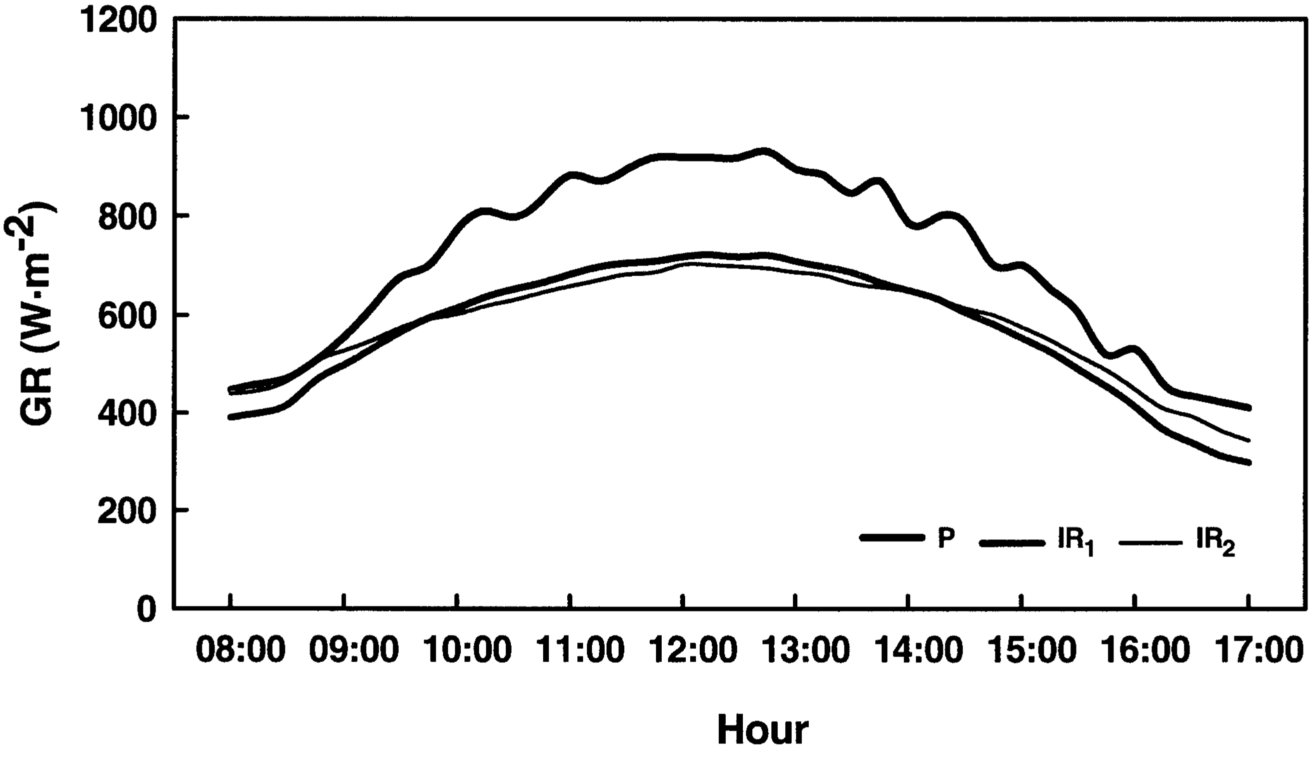


Figure 15. Global radiation (GR) measured by pyranometer (P), and 2 infrared (IR) light sensors at 1600 m above sea level.



Before 11:00h and after 15:00h, there were no differences between P and IRs, and/or differences were within the accepted tolerance (Table 4).

Table 4. Measurements of global radiation at different heights from sea level by pyranometer (P) and 3 infra-red (IR) light sensors.

	Height (m)	P ($W \cdot m^{-2}$)	IR_1 ($W \cdot m^{-2}$)	IR_2 ($W \cdot m^{-2}$)	IR_3 ($W \cdot m^{-2}$)
Extremely hot/dry˜	-400	817±180 387-1028	721±127 410-849	672±152 325-828	735±152 370-887
Hot/wet˜	-200	748±214 205-967	581±204 151-821	637±161 160-814	674±150 179-844
Hot/wet˜	30	707±183 290-1028	645±165 296-819	628±181 192-840	683±179 220-871
˜Hot/dry	400	709±348 40-1053	652±253 105-871	694±139 292-876	----------
Hot	900	806±159 471-1003	688±155 237-875	694±139 292-876	----------
Hot	1600	708±177 411-931	----------	572±133 301-724	579±105 346-704

DISCUSSION

In this study we evaluated commercial T_a and RH sensors built into 3 WAPEM prototypes in 27 temperature/humidity exposures at 2 different climatic chambers: USARIEM and at the Heller Institute. In addition, the SR sensor was evaluated at 6 different field locations in Israel at different distances above and below sea level.

$T_{a,WAPEM}$ measurements differed significantly ($P<0.05$) from $T_{a,chamber}$, and deviated by 3°-27°C from actual chamber dry bulb measurements. With elevated dry bulb temperatures, the residuals were also higher between $T_{a,chamber}$ and $T_{a,WAPEM}$. Therefore, it was concluded that $T_{a,WAPEM}$ is far from being accurate, and measurement values are not totally reliable in the current prototype configurations. Future investigation and analysis should consider the relocation of the T_a sensor (possibly as a separate deployable unit), recalibration of the algorithms from actual experimentally measured °C values, and replacing this particular sensor with a different brand, type, or model (Analog Devices, for example.

Analysis of the measurement 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 $RH_{chamber}$. However, in a few exposures, RH_{WAPEM} differed significantly from values measured by $RH_{chamber}$. In addition, RH_{WAPEM} values of 100% were measured when actual measurements were only 70%. Therefore, we believe that further evaluation and testing of the prototype WAPEM units is required before entering into phase II fabrication. A separate sensor location is another requirement. The present unit is located on the watch front panel near the IR light sensor, which is inadvertently exposed to direct solar load. An inconsistency between SR and RH measurements also appears because the SR sensor must be exposed to the sun, whereas the RH sensor should be measured in the shade. Therefore these 2 sensors should not be located near each other.

There were limitations to the (GR) measurements with the IR light sensor over various terrains and locations above and below sea level. This can only be forthcoming using a large database containing annual GR measurements at the same time at the 6 locations, which differ in their height from sea level. However, mean GR values were generally higher at –395 m than -208 m. The latter might be explained by other factors that influence the GR, apart from the topographical height from sea level (e.g., cloudiness, atmospheric transparency, and reflective radiation). In general, the range of the measurements for each day was wide, as shown in Table 4. In analyzing the data from the 3 IR light sensors and the P, we can draw 2 conclusions. First, there were no significant differences between these 3 sensors, which strengthens the reliability and validity of the IR light sensor to measure GR. The second conclusion relates to a comparison between the P measurements and the IR light sensors. Higher values for P were measured in all 6 locations. Although differences were not statistically significant in all the locations, for better accuracy, refinement of the model that predicts global radiation (PGR) from the IR light sensor should be considered.

In this study, we exposed the 3 WAPEM prototypes to continuous measurements ranging from 8-12 hours in the testing chambers and field conditions outdoors. However, assuming that these sensors have fast-reading responses, there is no need to expose them to such extreme conditions. In fact, by continuously exposing the sensors to excessive high temperatures, we also caused the WAPEM, in its current form, to store heat. Thus, a unit that can be deployed when needed is essential to the configuration of the WAPEM. Appropriate environmental scenario specifications for deploying the WAPEM sensors should be determined to prevent excess heat buildup in the field.

CONCLUSIONS

Additional consideration should be given towards modifying the T_a sensor in the current WAPEM prototypes. This study showed that the current sensor failed to measure T_a correctly and deviated substantially from actual measurements. It is recommended that the current T_a sensor be replaced with a more robust, accurate, and easily deployable sensor. A longer follow-up for the RH sensor is also recommended. Although the RH_{WAPEM} measurements were well correlated to $RH_{chamber}$ sensors, there were several exposures during which the values were unsatisfactory. For better accuracy of GR measured by the IR light sensor, additional refinement of the PGR model equations is required.

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