Development of BAS2 for determination of evaporative fluxes

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ABSTRACT

Accurate determination of evaporative flux from water surfaces and liquid containing porous media is critical for geotechnical and geoenvironmental applications. Laboratory simulations can isolate the various parameters influencing evaporative fluxes. However, most simulators capture selected surface and atmospheric conditions, and published literature generally provide limited information on the development and operation of the instruments. The new simulator adequately captures a wide range of relevant field parameters, maintains controlled conditions over the required testing time, utilizes readily available components for modular fabrication, and facilitates operational efficiency between individual modules.

- This paper presents the modified Bench-Scale Atmosphere Simulator (BAS2).
- This paper summarizes various atmosphere simulators developed over the last 25 years.
- This paper describes the design, fabrication, operation, calibration, and validation of BAS2.

ARTICLE INFO

Method name: BAS2 Instrument
Keywords: Bench-Scale Atmosphere Simulator, Evaporative fluxes
Article history: Received 21 December 2020; Accepted 17 June 2021; Available online 21 June 2021

Specifications table

| Subject Area:                      | Earth and Planetary Sciences |
|------------------------------------|-----------------------------|
| More specific subject area:        | Land-Atmosphere Interactions|
| Method name:                       | BAS2 Instrument             |
| Name and reference of original method: | BAS [27]                   |
| Resource availability:             | None                        |

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https://doi.org/10.1016/j.mex.2021.101424
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Introduction

Accurate determination of vapor flux from water surfaces and liquid containing porous media is critical for a variety of geotechnical and geoenvironmental applications [32]. Table 1 provides a state-of-the-art review of atmospheric simulators for measuring evaporative fluxes. The various simulators vary due to their intended purpose, that is, to determine potential evaporation from water surfaces or saturated soils, actual evaporation from unsaturated soils, and/or transpiration from plants. Laboratory-based simulators are designed to control artificially generated parameters over short time periods whereas field-based simulators have difficulty to ensure constant conditions albeit being capable of long-term experiments using natural atmospheric parameters. Furthermore, most simulators capture selected surface and atmospheric conditions and published literature generally provide limited information on equipment design, fabrication, and calibration. Therefore, there was a need to develop an atmospheric simulator that can adequately fulfill the following criteria: (i) capture a wide range of each relevant field parameter; (ii) maintain controlled conditions over the required testing time; (iii) utilize readily available components for modular fabrication; and (iv) facilitate operational efficiency between individual modules. Suchan and Azam [27] recently developed a bench-scale atmosphere simulator (BAS) that can effectively control the four meteorological variables related to evaporation, namely: air velocity, temperature, humidity, and solar irradiation, and can monitor surface-atmosphere variables such as air pressure and surface temperature. This paper presents the detailed design and the operational procedure of a thoroughly improved second version of the bench-scale atmosphere simulator (BAS2). The simulator performance was calibrated by comparing the null test and the water test in BAS2 and validated by comparing the water tests in BAS2 and the original simulator.

Detailed design

Table 2 provides detailed descriptions of the BAS2 components. The simulator comprises six independent modules, including climate chamber, solar irradiation, air supply, humidifier, heater, and cooler/dehumidifier. The system is designed for a thermally-regulated room with access to a building air intake that allows ambient conditions to be maintained despite the heat generated by the air cooler/dehumidifier, air heater, and solar irradiation modules.

Fig. 1 presents an overview of the system layout. The air supply module comprises a vacuum pump that ensures a smooth air through the system. The power controller was upgraded (to minimize voltage fluctuations thereby ensuring a consistent air velocity) by using a regulated bench power supply with a voltage regulation of 1 mV ± 0.03%. Similarly, the cooler/dehumidifier was improved by replacing the previous glycol chiller with a portable air conditioning unit outfitted with a 12,000 BTU compressor that supports long test durations. Furthermore, a three-port manifold was installed with one port connected to BAS2 while the other two were connected to an inline fan via an insulated line to push surplus cold air into the building intake. This arrangement prevented icing on the condenser coils by ensuring a constant air intake flowrate of 0.19 m$^3$/s into the air conditioner. A separate insulated line and inline fan were connected to the air conditioner for hot air exhaust.

Fig. 2 presents a schematic of the climate chamber and the solar irradiance module. The climate chamber was designed to host the sample and the sensors. To preclude inconsistent air temperature due to heat conduction from the surrounding walls, the insulation was improved by using foam boards cut to fit the interior of the chamber. This resulted in improved thermal energy gradients around the sample, such that temperature variation between thermometers decreased to 1 °C. Likewise, a silicon-fiberglass heating pad was placed between the pan and beam arrest of the analytical balance. The sample temperature is managed with a regulated power supply to the heating pad. Furthermore, the solar module was externally mounted on top of the chamber and was separated by a tempered glass lens. This isolated shortwave radiation from the intense infrared heat generated by the quartz-tungsten-halogen (QTH) lightbulb. The lightbulb was upgraded to a 400 W thereby nearly doubling the shortwave radiation capability up to 580 W/m$^2$. 


Table 1
Review of capabilities of atmospheric simulators for determination of evaporative fluxes.

| Reference                          | Conditions | Location | Energy | Mass | Solid | Momentum |
|------------------------------------|------------|----------|--------|------|-------|----------|
|                                    |            |          | Radiant| Vapour| Sample| Air      |
|                                    | Shortwave | Longwave | Shortwave | Longwave | Air | Surface | Area | Velocity | Pressure |
| BASZ                               | PA         | L        | Y      | Q     | Y     | Y       | Y      | E        | Y        | R        | Y       | Y       | Y        | Y        | Y        | Y        |
| Wilkinson et al. [33]              | PT         | F        | N      | N     | N     | N       | N      | N       | -        | Y       | N       | N       | N        | -        | N        | Y        | W        | N        |
| Qubaja et al. [20]                 | AT         | F        | N      | N     | N     | N       | N      | N       | N       | N       | N       | N       | N        | Y        | N        | N        | -        | N        |
| Schulz et al. [23]                 | P          | L        | N      | N     | N     | N       | N      | N       | -        | N       | N       | N       | N        | -        | Y        | Y        | W        | N        |
| Lozaza et al. [13]                 | PA         | L        | N      | -     | N     | Y       | Y      | N       | Y       | E       | Y       | H       | Y        | N       | N       | Y        | Y       | R        | Y       |
| Tran et al. [31]                   | A          | L        | N      | N     | Y     | I       | N      | N       | N       | N       | N       | Y       | N        | -        | N        | -        | N        | -        | Y       |
| Pöös et al. [18] [2019]            | P          | L        | N      | N     | N     | N       | N      | N       | N       | -        | Y       | N       | N        | Y        | N        | N        | N        | -        | N        |
| Lakshminantha et al. [11]          | A          | L        | N      | N     | Y     | I       | N      | N       | N       | -        | Y       | R       | Y        | Y        | Y        | W        | Y        | N        |
| Trautz et al. [32]                 | AT         | L        | N      | -     | N     | E       | N      | N       | -       | Y       | E       | Y       | O       | Y       | N       | Y        | S        | Y       | B        | Y       |
| Inan and Özgür [7]                 | P          | L        | N      | -     | N     | Y       | N       | Y       | /       | Y       | /       | Y       | /       | Y       | Y        | Y        | N        | -        | N        |
| Shokri-Kheneini et al. [24]        | P          | L        | N      | N     | Y     | /       | N       | N       | Y       | /       | Y       | N       | Y       | /       | Y        | Y        | N        | -        | N        |
| Tollenaar et al. [30]              | A          | L        | N      | N     | Y     | /       | N       | N       | Y       | /       | Y       | N       | Y        | W        | N        | N        | Y        | W        | Y        |
| Teng et al. [29]                   | A          | L        | N      | N     | Y     | E       | N       | N       | N       | Y       | H       | Y       | N       | -        | Y        | U        | Y       | R        | Y       |
| Liu et al. [12]                    | A          | L        | N      | N     | N     | N       | N       | N       | -       | N       | -       | Y       | E       | N       | N       | N       | -        | N        | Y        | N        |
| Song et al. [26]                   | A          | L        | N      | N     | Y     | E       | N       | N       | Y       | E       | N       | N       | N       | Y       | N       | Y        | K        | Y        | N        |
| Castilbano et al. [5]              | A          | L        | N      | N     | Y     | I       | N       | N       | N       | -        | Y       | N       | -        | Y       | Y        | E       | N        | Y       | Y        | Y        |
| Trautz et al.                       | A          | L        | N      | N     | Y     | /       | N       | N       | Y       | /       | Y       | Y       | Y       | Y        | Y        | Y        | Y        | Y        | Y        |
| Nelson et al. [17]                 | A          | F        | N      | N     | N     | N       | N       | N       | N       | N       | N       | Y       | Y       | N       | N       | N       | N        | N        | N        |
| Raimundo et al. [21]               | P          | L        | N      | N     | N     | N       | N       | N       | N       | N       | Y       | N       | -       | Y       | -       | Y        | Y        | N        | /        | Y        |
| Hermández-López et al. [6]         | A          | L        | N      | N     | Y     | I       | Y       | N       | N       | Y       | N       | N       | -        | Y       | Y        | N       | K        | N        | N        | N        |
| Ahmad et al. [1]                   | P          | L        | N      | N     | Y     | G       | N       | N       | N       | Y       | Y       | Y       | N       | Y       | E       | B       | Y        | Y        | N        | Y       |
| Bond-Lamberty et al. [3]           | T          | L        | Y      | Y     | Y     | /       | N       | Y       | N       | -        | Y       | Y       | /       | Y       | Y        | Y        | N       | N        | N        | N        |
| Kim and Lee [9]                    | P          | L        | N      | N     | N     | Y       | N       | N       | N       | Y       | Y       | Y       | N       | Y       | /       | Y       | Y        | Y        | N       | N        |
| Smits et al. [25]                  | A          | L        | N      | N     | Y     | I       | Y       | N       | Y       | I       | N       | Y       | N       | N       | N       | N       | Y       | N       | N       |
| Qiu and Ben-Asher [19]              | A          | L        | /      | /     | /     | /       | N       | Y       | Y       | /       | Y       | /       | Y       | /       | Y        | Y        | N       | /        | Y        |
| Caicedo et al. [4]                 | A          | L        | N      | N     | Y     | H       | N       | N       | Y       | H       | Y       | N       | Y       | Y       | R       | Y        | N       | Y        | W        | Y        |
| Kamai et al. [8]                   | PA         | L        | N      | N     | Y     | E       | N       | N       | Y       | E       | Y       | R       | Y       | N       | N       | -        | N        | N        | -        | Y        |
| Tang et al. [28]                   | PA         | L        | N      | N     | Y     | /       | N       | Y       | /       | Y       | N       | Y       | Y       | N       | N       | Y        | /        | N        | /        | Y        |
| Aydin et al. [37]                  | A          | L        | N      | N     | Y     | /       | N       | Y       | /       | Y       | Y       | N       | Y       | /       | Y        | Y        | Y        |
| Schneider et al. [22]              | PA         | L        | N      | N     | N     | N       | N       | N       | N       | Y       | H       | Y       | N       | N       | -        | Y       | R       | Y       | N        |
| Medhurst et al. [14]               | T          | F        | N      | Y     | N     | N       | N       | N       | N       | Y       | O       | Y       | N       | N       | Y       | R       | Y        | N        | Y        | /        | Y       |
| Meng et al. [15]                   | T          | F        | N      | N     | Y     | N       | N       | N       | N       | Y       | O       | Y       | N       | N       | Y       | R       | Y        | N        | Y        | /        | Y       |
| Yuge et al. [37]                   | A          | L        | N      | N     | N     | N       | N       | N       | N       | /       | /       | /       | Y       | /       | /        | /       | /       | /        | /       | /       |
| Komatsu [10]                       | A          | L        | N      | N     | N     | Y       | N       | N       | N       | Y       | H       | Y       | N       | N       | Y       | R       | Y       |
| Mohamed et al. [16]                | A          | L        | N      | N     | N     | N       | N       | N       | N       | N       | N       | N       | N       | N       | Y       | J        | Y        | N        | Y        |
| Yamazaki et al. [35]               | A          | L        | Y      | Q     | Y     | Y       | Y       | Y       | Y       | Y       | /       | Y       | Y       | Y       | Y       | Y       | Y       | Y       | Y        | W        | N        |
| Yanful and Choo [36]                | PA         | L        | N      | N     | Y     | /       | N       | N       | N       | Y       | Y       | Y       | Y       | Y       | N       | Y       | W        | N        | Y        |
| Wilson et al. [34]                 | PA         | L        | N      | N     | N     | Y       | N       | N       | N       | N       | Y       | Y       | N       | N       | Y       | N       | N        | N        | N        |

Abbreviation List. A: actual evaporation, B: desiccant, C: parameter controlled, D: data recorded, E: electric element, F: field, G: gas burner, H: thermoelectric, I: infrared bulb, J: sucking air, K: pushing air, L: laboratory, M: method used, N: no, O: glycol chiller, P: potential evaporation, Q: quartz-tungsten-halogen bulb, R: refrigerant, S: steam, T: transpiration, U: ultrasonic, V: evaporative, W: closed-return, Y: yes, -: not applicable, /: not given
Table 2
Detailed description of the modular components of BAS2.

| Component, Make and Model (when required) | Dimensions (mm), Specifications (variable unit), Materials (when required) | Purpose | Comments and Limitations |
|------------------------------------------|---------------------------------------------------------------------------|--------|--------------------------|
| **a. Climate Chamber**                   |                                                                           |        |                          |
| 1. Housing                               | L: 500; W: 345; H: 260; T: 14.7; IPD: 102; EPD: 102; M: Oriented Strand Board |        | The climate chamber casing, built to contain the test sample and data collection sensors. Poor insulation properties resulted in thermal gradients in the air profile above the sample. |
| 2. External Sealant                       | M: Polyurethane Liquid Adhesive                                           |        | Prevents air leaks past housing board joints. Caulking in the joints and on the internal sealant between the housing boards. |
| 3. Internal Sealant                       | M: Polyurethane Expanding Foam Adhesive                                   |        | Prevents air leaks past housing board joints. Provides a bonding surface for the external sealant. |
| 4. Corner Brace Everbilt 859-755          | L: 50.8; H: 50.8; M: Steel                                                |        | Supports the housing walls. Connects to the housing walls in the bottom corners. |
| 5. Lid Seal M-D Building WS31185          | W: 19.0; T:12.7; M: Foam                                                 |        | Prevents air leaks past the lid. Attaches to the lid. |
| 6. Box Seal W-D Building WS31525          | W: 10.0; T: 5.4; M: Foam                                                 |        | Prevents air leaks past the lid. Attaches to the top of the housing boards. |
| 7. Corner Brace Everbilt 859-704          | L: 38; M: Steel                                                           |        | Supports the housing walls. Connects to the housing walls in the top corners. |
| 8. Latch Brace HDG 173732                 | L: 152; W: 50.8; H: 50.8; M: Spruce Pine                                 |        | Mount for the closing latches. Connects to the lid. |
| 9. Closing Latch Everbilt 859-446         | L: 82.6; M: Brass Plated Steel                                          |        | Closes and seals the lid. Connects to the latch brace and the housing wall side. Panels are placed against each vertical wall above the draft shield, the lid, and on either side of the sample. The compound is used to fill in ports after cables have been passed through. |
| 10. Insulation                           | T: 26.9                                                                  |        | Insulates the space above the sample, reducing thermal gradients in the air profile above the sample. |
| 11. Cable Port Seal Elmer E1531           | M: Synthetic Rubber Compound                                             |        | Prevents air leaks past data and power cable ports. |
| 12. Shield Hinge Everbilt 859-432         | L: 38; M: Brass Plated Steel                                             |        | Allows the draft shield access hatch to open. Attaches to both sides of the draft shield. |
| 13. Cable Holder Gardener Bender PPC-1525 | L: 10; ID: 6                                                             |        | Supports the power cables going to sample warmer, reducing disturbance to the analytical balance. Mounted to the underside of the draft shield. |
| 14. Sensor Brace Everbilt 859-709         | L: 152; H: 152; M: Steel                                                 |        | Holds the thermometer and hygrometer sensors. Mounted to the draft shield. |
| 15. Sensor Brace Everbilt 859-710         | L: 152; H: 152; M: Steel                                                 |        | Holds the pyrometer sensor. Mounted to the draft shield. |
| 16. Sensor Adapter Everbilt 859-727       | L: 38.1; M: Steel                                                        |        | Allows the pyrometer to be adjusted. Cut to fit under the insulation panels. The pyrometer is adjusted using the calibration laser. Larger diameter to reduce turbulence as air supply passes through chamber. Connects the 76 mm air supply lines to the 102 mm air flanges. Individual tubes bundled inside the air flange. |
| 17. Air Flange Lesso RLN800-040           | L: 179; W: 51; ID: 101.6; M: Acrylonitrile Butadiene Styrene              |        | Connects the air supply to the chamber. |
| 18. Air Reducer Lesso RLN800-040          | L: 124.6; W: 102; ID: 101.6 to 76.2                                      |        | Gradually increases the air flow diameter. Connects the 76 mm air supply lines to the 102 mm air flanges. Individual tubes bundled inside the air flange. |
| 19. Flow Straightener Sip’n’Joy 42319-88271 | L: 50 " ; ID: 10 " per individual tube                                  |        | Reduces airflow turbulence in the chamber housing. |
| 20. Glass Pane Bayco SL-1006L             | L: 100; W: 80; T: 5; M: Tempered glass                                   |        | Prevents air entry and transmits radiant energy into the chamber. Mounted inside the chamber opposite to the aperture plate. |

(continued on next page)
### Table 2 (continued)

| Component, Make and Model (when required) | Dimensions (mm), Specifications (variable unit), Materials (when required) | Purpose | Comments and Limitations |
|------------------------------------------|-----------------------------------------------------------------------------|---------|--------------------------|
| 21. Draft Shield                         | L: 498; W: 343; H: 101; M: Oriented Strand Board                           | Reduces airflow turbulence in the chamber housing. | Provides a smooth surface leading to and from the sample container. |
| 22. Sample Container Humboldt H-4256    | Top ID: 45.0; Bottom ID: 40.0; H: 13.5; T: 1.0; V: 19,217 mm$^3$; C: 14.3 W m$^{-1}$ K$^{-1}$; M: Monel Nickel-Copper Alloy 400 Steel | Hosts sample material. | Material thermal conductivity can cause heat transfer to or from the sample. |
| 23. Sample Warmer Omega SRFA-3/10       | OD: 76.2; T: 1; OTR: -56 – 232°C; M: Silicone Rubber Fiberglass            | Warms the sample from below, controlling the surface temperature. | The power cables connecting to the warmer need to be managed, to preclude any disturbance to the analytical balance. |
| 24. Power Controller Sky Toppower STP6005D(US) | L: 140; W: 84; H: 226; IV: DC 105 - 115 V; OV: DC 0 - 60; OP: 0 - 300 W | Controls and regulates the power supply to the sample warmer. | Precise voltage control is required to warm the sample to the exact temperature required. |
| 25. Analytical Balance Sartorius Enris 124-1S | L: 303; W: 230; H: 85; Pan D: 90; DTS: 0; IV: AC 110-120 V; P: 0.1 mg: A: ± 0.2 mg; CR: 0 - 120 g; OTR: 5 - +40°C; LI: 10 s | Measures the sample mass. | The scale is sensitive to air turbulence in the housing. |
| 26. Thermometer Elite GSP-6             | DTS: 55; IV: DC 3.6 V; CR: -40 - 85°C; P: 0.1°C; A: ± 0.5°C; OTR: -40 - +85°C; LI: 10 s | Measures air temperature around the sample surface. | Four thermometers mounted on top of the draft shield, off-set in front and behind the sample container. |
| 27. Hygrometer Elite GSP-6              | DTS: 65; IV: DC 3.6 V; CR: -40 - 99%; P: 0.1°C; A: ± 3°C; CR: -40 - +85°C; LI: 10 s | Measures relative humidity around the sample surface. | Four hygrometers are mounted on custom brackets on top of the draft shield, off-set in front and behind the sample container. |
| 28. Data Logger Elite GSP-6             | IV: DC 3.6 V | Logs data from the thermometer and hygrometer. | Attached to a metal strip outside the chamber for easy viewing. |
| 29. Anemometer Holdpeak 86GB-APP        | Propeller OD: 85; DTS: 100; IV: DC 3 V; P: 0.1 m/s; A: ± 5%; CR: 0.3 to 30 m/s; LI: 10 s; OTR -10 - +45°C | Measures wind speed around the sample surface. | Anemometer mounted on top of the draft shield behind the sample container to avoid air turbulence. |
| 30. Barometer Tekcoplus TEK-204         | DTS: 255; IV: DC 1.5 V; P: 1 hPa; A: ± 3 hPa; CR: 300 to 1,100 hPa; LI: 30 s; OTR -30 - +70°C | Measures pressure around the sample surface. | Barometer mounted on chamber wall, behind and to the side of sample container. |
| 31. Pyrometer Omega IR-USB               | DTS: 95; IV: DC 5 V; P: 1°C; A: ± 2%; CR: -18 to +538°C; LI: 30 s; OTR: 0 - 70°C; E: 0.1 to 1; FOV: 6:1; SR: 5 to 14 μm | Measures temperature of the sample surface. | Pyrometer mounted on top of the draft shield above and to the side of the sample container. |
| 32. Pyranometer Hukseflux LP02-LI19     | DTS: 0; IV: DC 3 V; P: 1 W/m$^2$; A: ± 3%; CR: 0 to 1,600 W/m$^2$; LI: 30 s; FOV: 180°; SR: 0.285 to 3.00 μm | Measures incoming shortwave radiation on sample surface. | Pyranometer mounted in place of sample container before and after tests. |
| 33. Albedometer Hukseflux LP02-LI19     | DTS: 0; IV: DC 3 V; P: 1 W/m$^2$; A: ± 3%; CR: 0 to 1,600 W/m$^2$; LI: 30 s; FOV: 180°; SR: 0.285 to 3.00 μm | Measures outgoing shortwave radiation from sample surface. | Albedometer mounted on top of the roof above and to the side of the sample container. |
| 34. Sensor Adapter Paulin 174-652       | L: 76; OD: 4 | Holds the thermometer and hygrometer sensors. | Fixed in-place using a nut. |
| 35. Lid Hinge Everbilt 859-421          | L: 89; M: Nickel Plated Steel | Allows the lid to open. | Attaches to lid and housing wall. |

(continued on next page)
### b. Solar Irradiation

| Component                        | Dimensions (mm), Specifications (variable unit), Materials (when required) | Purpose                                                                 | Comments and Limitations                                                   |
|----------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Light Bulb                       | DTS: 223; L: 55; OD: 13.5; BP: s90; B: G6.35; IV: 0 - 36 V; OP: 0 - 400 W; NLF: 12,800 lm; M: Quartz-Tungsten-Halogen | Generates radiant energy.                                                | Solar irradiance in the chamber ranges from 0 - 585 W m⁻².                |
| Bi-Pin Base Leviton DROK 60054   | L: 8; W: 2; H: 7; M: Ceramic                                            | Socket for the light bulb.                                              |                                                                           |
| Inline Fan Vivosun Duct Fan      | L: 185; W: 170; H: 178; OP: 64; EPD: 102; IV: AC 110-120 V; CR: 0.09 m³·s⁻¹ | Draws through the solar irradiance housing.                            | Removes warm air generated by the light bulb to prevent heat transfer to the climate chamber. |
| Solar Exhaust Rigid VT2522       | L: 6,000; IPD: 64; EPD: 64                                              | Directs inline fan exhaust towards building air return vent.           |                                                                           |
| Insulation Dundas JaLine FPW5    | T: 5; M: Foam and Aluminum                                              | Protects the housing from the heat of the light bulb.                  | Put on all surfaces in the housing. Reflects heat away and is composed of fire-retardant material to prevent combustion. |
| Light Bracket Everbilt 859-704   | L: 38; M: Steel                                                          | Holds the Bi-Pin Base for the light bulb.                               | Two small holes are drilled in the Bi-Pin Base end to allow the wires to pass through. |

### c. Air Supply

| Component                        | Dimensions (mm), Specifications (variable unit), Materials (when required) | Purpose                                                                 | Comments and Limitations                                                   |
|----------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Building Air Intake              | L: 400; W: 300; CR: 3 - 4 m³·s⁻¹                                        | Removes air from chamber and solar housing exhaust.                     | Ensures constant laboratory temperature and humidity. 30 mm separation to prevent unwanted suction by the air return. |
| Chamber Exhaust Rigid VT7220     | L: 2,100; IPD: 64; EPD: 64                                               | Directs vacuum pump exhaust to building air intake.                     | Wind speed in the chamber ranges from 0.10 - 3.00 m/s. Required wind conditions may exceed the upper limit. |
| Vacuum Pump Rigid WD4052         | L: 482; W: 432; H: 419; IPD: 48; EPD: 64; IV: AC 0 - 120 V; OP: 0 - 3,728 W; CR: 0 - 0.05 m³·s⁻¹ | Draws air into the system.                                              | An improvement over the original power controller, the regulation function minimizes wind speed fluctuations. |
| Power Controller Sky Toppower STP6005D(US) | L: 140; W: 84; H: 226; OP: 105 - 115 V; OP: 0 - 300 W                      | Controls and regulates the power supply to the vacuum pump.            | (continued on next page)
### Table 2 (continued)

| Component, Make and Model (when required) | Dimensions (mm), Specifications (variable unit), Materials (when required) | Purpose | Comments and Limitations |
|------------------------------------------|-------------------------------------------------------------------------------|---------|-------------------------|
| 51. Vacuum Coupler Lesso 455247          | L: 25; ID: 48; M: Acrylonitrile Butadiene Styrene                           | Connects the air supply to the vacuum. | Fits directly into the vacuum pump intake, connects to an air coupler. |
| 52. Air Coupler IPEX 079416              | L: 50; ID: 38; OD: 48; M: Acrylonitrile Butadiene Styrene                   | Connects air flow pieces.             | Cut to size from larger piece. |
| 53. Air Reducer Lesso RL102-338           | L: 101; ID 60 - 89; M: Acrylonitrile Butadiene Styrene                      | Gradually increases the air flow diameter. | Connection joints sealed with foil tape. |
| 54. Air Coupler Lesso 079434             | L: 50; ID: 76; OD: 89; M: Acrylonitrile Butadiene Styrene                   | Connects air flow pieces.             | Cut to size from larger piece. |

**d. Humidifier**

| Component, Make and Model (when required) | Dimensions (mm), Specifications (variable unit), Materials (when required) | Purpose | Comments and Limitations |
|------------------------------------------|-------------------------------------------------------------------------------|---------|-------------------------|
| 55. Air Flange Lesso RLN800-040           | L: 179; W: 51; ID: 101.6; M: Acrylonitrile Butadiene Styrene                 | Connects the air supply to the chamber. | Larger diameter to reduce turbulence as air supply passes through chamber. |
| 56. Air Reducer Lesso RLN800-040          | L: 125; W: 102; ID: 102 to 76                                              | Increases the air supply diameter.    | Connects the 76 mm air supply lines to the 102 mm air flanges. Panels are placed against all exterior housing panels. |
| 57. Insulation Panels Durospan 1624701    | T: 27                                                                       | Insulates the space above the sample, reducing thermal gradients in the air profile above the sample. | |
| 58. Door Brace HDG 173732                 | L: 180 - 430; W: 51; H: 51; M: Spruce Pine                                 | Provides rigidity for the acrylic window and a mount for the closing latches. | Frames the acrylic door window. |
| 59. Closing Latch Everbilt 859-446        | L: 83; M: Brass Plated Steel                                               | Closes and seals the door.            | Connects to the door brace and the housing wall side. |
| 60. Lid Hinge Everbilt 859-421            | L: 89; M: Nickel Plated Steel                                              | Allows the lid to open.              | Attaches to door brace and housing wall. |
| 61. Humidifier Loviver Ultrasonic         | L: 190; W: 190; H: 350; IPD: 102; EPD: 38; IV: AC 110 - 120 V; C: 3,000 ml; CR: 0 - 380 m³/h⁻¹ | Adds water vapor, removes heat.       | Humidity in the chamber ranges from 4 - 10 g m⁻³. Required humid conditions may exceed these limits. The smaller end fits directly into the top of the humidifier. |
| 62. Spout Lesso RLN302-0155               | L: 56; W: 75; H: 56; ID: 38 - 48; OD: 48 - 58; M: Acrylonitrile Butadiene Styrene | Directs the humidifier vapor.        | The wing nut connected to the humidifier dial is attached using super glue. |
| 63. Adjustment Knob Precision 5701-014    | ID: 6; M: Nylon                                                             | Controls the humidifier adjustment rod. | |
| 64. Rod Gasket Paulin 163-142             | ID: 6; OD: 10; M: Nylon                                                     | Seals the humidifier adjustment rod as it passes through the acrylic door. | Poor insulation, requires an insulation panel to be fitted within the door braces when adjustments occurring. |
| 65. Door Panel Optix 11G0670A             | L: 430; W: 250; T: 2; M: Acrylic                                            | Allows the humidifier to be observed while making adjustments the rate of humidification. | |
| 66. Lock Nut Everbilt 814698              | ID: 6                                                                       | Locks the wing nuts into place on the adjustment rod. | Three columns of two pads stick to the bottom of the humidifier. |
| 67. Adjustment Rod Precision 5715-318     | L: 64; OD: 6                                                                | Turns the adjustment dial on the humidifier. | Connects to the housing walls in the corners. |
| 68. Humidifier Raisers Everbilt 98820     | D: 25; T: 6; M: Felt                                                        | Lifts the humidifier to align the air intake with the housing intake port. | Caulking in the joints between the housing boards. |
| 69. Corner Brace Everbilt 859-755         | L: 51; H: 51; M: Steel                                                      | Supports the housing walls.           | Poorly insulated, requiring additional insulation pads. |
| 70. Sealant Gorilla 8110003               | M: Polyurethane Liquid Adhesive                                             | Prevents air leaks past housing board joints. | |
| 71. Housing                               | L: 230; W: 220; H: 400; IPD: 102; EPD: 102; M: Oriented strand board        | Hosts the humidifier.                | |

(continued on next page)
### Table 2 (continued)

| Component, Make and Model (when required) | Dimensions (mm), Specifications (variable unit), Materials (when required) | Purpose | Comments and Limitations |
|------------------------------------------|--------------------------------------------------------------------------|---------|--------------------------|
| 72. Lid Seal M-D Building WS31185       | W: 19; T: 13; M: Foam                                                    | Prevents air leaks past the lid. | Attaches to the door. |
| 73. Box Seal W-D Building WS31525       | W: 10; T: 5; M: Foam                                                    | Prevents air leaks past the lid. | Attaches to the housing boards. |
| 74. Air Coupler Lesso 079434            | L: 50; ID: 76; OD: 89; M: Acrylonitrile Butadiene Styrene                | Connects air flow pieces.         | Cut to size from a larger piece. |
| 75. Air Tee Lesso RLN400-030             | L: 167; W: 99; H: 203; ID: 89; M: Acrylonitrile Butadiene Styrene         | Traps condensation in the bottom of the tee, preventing water from entering climate chamber. | Connection joints sealed with foil tape. |
| 76. Air Elbow Lesso RLN302-0305          | L: 142; W: 99; H: 140; ID: 76 - 89; M: Acrylonitrile Butadiene Styrene    | Bends the air flow 90°.           | Connection joints sealed with foil tape. |
| 77. Air Reducer Lesso RLN107-337         | D: 89; W: 43; ID: 48; OD: 89; M: Acrylonitrile Butadiene Styrene          | Reduces the pipe size so that the drain adapter can be connected. | Connection joints sealed with foil tape. |
| 78. Air-Drain Adapter Lesso RLN108-210   | D: 46; ID: 13; M: Acrylonitrile Butadiene Styrene                        | Bends the drain 90°.              | The tee connects to two valves on either side. |
| 79. Drain Elbow Lesso R408-007           | D: 46; W: 33; ID: 13; M: Polyvinyl chloride                             | Diverts the drain water down.     | Clear tubing allows operator to determine when the line needs to be emptied. |
| 80. Drain Tee Lesso R405-007             | D: 46; W: 70; ID: 13; M: Polyvinyl chloride                             | Connects the drain pipes to drain hose. | Collect water; left open, right and bottom closed. Empty water; left closed, right and bottom open. |
| 81. Drain Hose Adapter Sioux Chief 903-402001 | L: 150; ID: 13; OD: 16; M: Vinyl                                        | Holds drain water until released by drain valves. | |
| 82. Drain Valve Aqua-Dynamic 1107-133    | L: 79; ID: 13; OD: 37; M: Polyvinyl chloride                            | Three valves work to collect water in the drain hose and allow it to be emptied when full. | |

#### e. Heater

| 83. Housing Imperial GVH004              | L: 550 mm; ID: 127 mm; M: Steel                                       | Hosts the heating element.        | Despite measures to insulate the housing, warming may occur during warm-air tests. Manually controlled and lags in time. |
| 84. Heating Element Podoy 3387747        | L: 280 mm; W: 125 mm; H: 25 mm; IV: AC 0 - 240; OP: 0 - 5,200 W       | Adds heat.                        | |
| 85. Insulation Reflectix SPV04025        | L: 1,000; W: 102; T: 5; M: Aluminum Foil                            | Prevents the heater from warming the air in the lab. | |
| 86. Power Controller Sky Toppower STP6005D(US) | L: 140; W: 84; H: 226; IV: DC 105 - 115 V; OV: DC 0 - 60; OP: 0 - 300 W | Controls and regulates the power supply to the heating element. | Precise voltage control is required to warm the air to the exact temperature required. |
| 87. Air Coupler Lesso 079434             | L: 50; ID: 76; OD: 89; M: Acrylonitrile Butadiene Styrene             | Connects air flow pieces.         | Cut to size from a larger piece. |
| 88. Air Elbow Lesso RLN302-030S          | L: 142; W: 99; H: 140; ID: 76 - 89; M: Acrylonitrile Butadiene Styrene | Bends the air flow 90°.           | Connection joints sealed with foil tape. |
| 89. Air Reducer Lesso RLN800-040          | L: 125; W: 102; ID: 102 to 76; M: Acrylonitrile Butadiene Styrene    | Increases the air supply diameter. | Connects the 76 mm air supply lines to the 102 mm air flanges. |
| 90. Air Reducer Lesso RLN102-338         | L: 101; ID 60 - 89; M: Acrylonitrile Butadiene Styrene                | Gradually increases the air flow diameter. | Connection joints sealed with foil tape. |

(continued on next page)
The data loggers are turned on. If solar irradiance is to be included, the inline fan is started, followed by a gradual engagement of the light bulb: a sudden delivery of power to the QTH bulb can damage the filament. For air supply, the power is turned on and the voltage adjusted until the target air velocity is registered on the anemometer output. If ambient conditions satisfy the selected parameters, no other modules are needed and the system enters the 60 min stabilization period. In contrast, the following steps are required when modifications to ambient laboratory conditions are

### Table 2 (continued)

| Component, Make and Model (when required) | Dimensions (mm), Specifications (variable unit), Materials (when required) | Purpose | Comments and Limitations |
|------------------------------------------|--------------------------------------------------------------------------|--------|--------------------------|
| f. Cooler/Dehumidifier                   |                                                                          |        |                          |
| 91. Air Conditioner Dandy DPAC11012BL    | L: 900; ID: 76; IPD: 76; EPD: 76                                         | Removes heat and water vapour. | Requires a calculated amount of air to be drawn through using the inline fans to prevent the cooling coils from freezing. Cut to size from larger piece. |
| 92. Air Coupler IPEX 079416              | L: 50; ID: 38; OD: 48; M: Acrylonitrile Butadiene Styrene                | Connects air flow pieces.      | Connection joints sealed with foil tape. Attached with screws and seal with liquid adhesive. Fabricated to replace the factory cold-air exhaust vent on the air conditioner. Connects the 76 mm air supply lines to the 127 mm air tee. Attached with screws and seal with liquid adhesive. Connects the air tee to the inline fan, and the inline fan to the lab intake. Connects the air conditioner hot exhaust to the inline fan, and the inline fan to the lab intake. |
| 93. Air Elbow Lesso RLN300-015S          | L: 76; W: 56; H: 79; ID: 38                                                | Bends the air flow 90 °.       | |
| 94. Manifold Port Lesso RLN111-015       | L: 25; ID: 38; OD: 42                                                     | Connects the air flow pipe to the air conditioner manifold. Connects the air conditioner to the air flow pipes. | |
| 95. Manifold                             | L: 330; W: 130; T: 7; M: Medium-Density Fibreboard                      |        |                          |
| 96. Air Reducer Imperial GVH0037         | L: 191; W: 127; ID: 127 to 76; M: Galvanized Steel                      | Increases the air supply diameter. Connects the air flow pipe to the air conditioner manifold. Moves cold air without affecting the ambient lab conditions. Moves hot air without affecting the ambient lab conditions. | Connects the 76 mm air supply lines to the 127 mm air tee. Attached with screws and seal with liquid adhesive. Connects the air tee to the inline fan, and the inline fan to the lab intake. Connects the air conditioner hot exhaust to the inline fan, and the inline fan to the lab intake. |
| 97. Air Tee Imperial GVH0051              | L: 305; W: 216; ID: 125; M: Galvanized Steel                            |        |                          |
| 98. Insulated Line Dundas Jafine BPC525  | L: 5,000; ID: 127; OD: 200; M: Fiberglass                               |        |                          |
| 99. Insulated Line Dundas Jafine BPC625  | L: 5,000; ID: 153; OD: 229; M: Fiberglass                               |        |                          |
| 100. Inline Fan AC Infinity Cloudline S6 | L: 320; W: 129; H: 200; IPD: 150; EPD: 150; IV: AC 0 - 120 V; OP: 0 - 3.728 W; CR: 0 - 0.19 m³/s⁻¹ | Equalizes cold air intake from air conditioner, and boosts hot air exhaust. | |

**Abbreviation List.** L: length, W: width, H: height, V: volume; IPD: intake diameter, EPD: exhaust diameter, IV: input voltage, OV: output voltage, OP: output power, D: diameter, ID: inner diameter, OD: outer diameter, C: conductivity, T: Thickness, V: Volume, DTS: distance to sample, CR: capability range, A: accuracy, P: precision, OTR: operating temperature range, TF: top-front; BF: bottom-front, TR: top-rear, BR: bottom-rear, LI: logging interval, E: emissivity, FOV: field of view, SR: spectral response, BP: burning position, B: base, NLF: nominal luminous flux; C: capacity, M: material

a Sensor not positioned directly above the sample surface to avoid obstruction of the incoming solar radiation

b Not displayed in figure.

**Figs. 3 and 4** present schematics of the humidifier and heater, respectively. The humidifier is primarily comprised of an ultrasonic vaporizer. Heat transfer is reduced by the insulation foam boards around the housing and shortened length of connecting pipes. The regulated power supply heater ensured consistent air temperature.

## Operational procedure

**Fig. 5** presents a stepwise guide for operating BAS2. The required surface-atmosphere parameters are selected and most do not require further adjustment. To simulate air velocity, the wind profile logarithmic law is used to downscale field data (typically recorded at 2 m above the surface) to the BAS2 measurements at 30 mm above the sample.

The data loggers are turned on. If solar irradiance is to be included, the inline fan is started, followed by a gradual engagement of the light bulb: a sudden delivery of power to the QTH bulb can damage the filament. For air supply, the power is turned on and the voltage adjusted until the target air velocity is registered on the anemometer output. If ambient conditions satisfy the selected parameters, no other modules are needed and the system enters the 60 min stabilization period. In contrast, the following steps are required when modifications to ambient laboratory conditions are
required. For cooling and/or dehumidification, the inline fans and the air conditioner are sequentially turned on. For humidification, the humidifier is turned on and the output dial adjusted until the selected humidity is displayed on the hygrometer data logger. For heating, the heater is turned on and the voltage adjusted until the target air temperature is reported on the thermometer data logger. When the required modules are engaged, the system is allowed to stabilize for 60 min.

Once steady state atmospheric conditions are achieved, the chamber lid is opened and the sample along with the cup is placed on the weight scale. The lid is closed and the system is allowed to re-stabilize for about 5 minutes prior to beginning the test. The sample surface cools off due to evaporation and requires heating from the underlying pad to ensure a constant sample temperature, as reported on the pyrometer data logger. Minor adjustments to the various power supplies and dials may be required during testing. Once the test is complete, the modules are turned off in the reverse order to prevent damage to the equipment. The data loggers are all turned off and the data exported to a computer file.

**Calibration and validation**

**Fig. 6** and Table 3 presents the atmospheric and surface measurements. To simulate a typical spring day in the Canadian Prairies, the target air velocity was 1.7 m/s, humidity was 5 g/m$^3$, air temperature was 10 °C, solar irradiance was 325 W/m$^2$, and surface temperature was 12 °C. Shortwave flux (incoming and outgoing) was calibrated ahead of time, and sensor measurements were collected
every 10 s, except for air pressure which was every 30 s. The null test was conducted for about 90 min with 564 data points (BAS2) whereas the water tests were carried out over 180 min with 1054 data points (BAS) and 1103 data points (BAS2). The standard error \( SE = SD/\sqrt{n} \) remained below zero for all measurements, except for air pressure which ranged between 2 Pa to 3 Pa.
Calibration was achieved by comparing the results of the null test (baseline reference) with the water test in BAS2. The humidity ranged between 5.0 g/m$^3$ to 5.2 g/m$^3$ in all four sensors for both tests whereas air temperature ranged from 9.9 °C to 10.8 °C. Only negligible differences were observed between the null test and the water test parameters. Surface temperature in the null test (measuring the empty sample cup) was uncontrolled and reached 9 °C whereas that in the water test was controlled and increased to the target value of 12 °C.
Validation of the BAS2 improvements was accomplished by comparing the water test results with those of the previous simulator. Air velocity in the BAS frequently fluctuated and often required readjustment. Humidity and temperature sensor readings in the BAS varied by 0.6 g/m³ and 7.0 °C around the sample, as compared to 0.2 g/m³ and 0.9 °C in the BAS2, while evaporative flux increased by 21% in the BAS2. Surface temperature in the BAS was uncontrolled and naturally reached 15 °C, whereas the BAS2 consistently maintained the target temperature.
Fig. 6. Comparison of atmospheric and surface measurements: (a) null in BAS2, (b) water in BAS; and (c) water in BAS2.
Table 3  
Summary of average experimental atmospheric and water surface parameter measurements.

| Parameter          | Unit | Symbol | Calibration BAS2 | Validation BAS2 | BAS      |
|--------------------|------|--------|------------------|-----------------|----------|
| Measurements       |      |        |                  |                 |          |
| Momentum           |      |        |                  |                 |          |
| Velocity           | m·s⁻¹ | v      | 1.7 ± 0.0        | 1.7 ± 0.0       | 1.7 ± 0.0 |
| Mass               | g·m⁻³ |        |                  |                 |          |
| Air Pressure       | Pa    | e_a    | 94307 ± 3        | 94298 ± 2       | 93606 ± 2 |
| Absolute Humidity  |       |        |                  |                 |          |
| Upwind, Low        | g·m⁻³ | h_{UL} | 5.0 ± 0.0        | 5.0 ± 0.0       | 4.9 ± 0.0 |
| Downwind, Low      | g·m⁻³ | h_{DL} | 5.2 ± 0.0        | 5.2 ± 0.0       | 5.3 ± 0.0 |
| Upwind, High       | g·m⁻³ | h_{ULH}| 5.1 ± 0.0        | 5.0 ± 0.0       | 4.7 ± 0.0 |
| Downwind, High     | g·m⁻³ | h_{DLH}| 5.2 ± 0.0        | 5.1 ± 0.0       | 4.9 ± 0.0 |
| Energy             |       |        |                  |                 |          |
| Temperature        | °C    | T_{DLH}| 10.1 ± 0.0       | 10.1 ± 0.0      | 11.4 ± 0.0 |
| Upwind, Low        | °C    | T_{DLH}| 9.9 ± 0.0        | 9.9 ± 0.0       | 9.3 ± 0.0 |
| Upwind, High       | °C    | T_{DLH}| 10.8 ± 0.0       | 10.8 ± 0.0      | 16.3 ± 0.0 |
| Downwind, High     | °C    | T_{DLH}| 10.2 ± 0.0       | 10.4 ± 0.0      | 13.4 ± 0.0 |
| Shortwave Flux (↓) | W·m⁻² | S_L   | 325 ± 0.0        | 325 ± 0.0       | 325 ± 0.0 |
| Surface            |       |        |                  |                 |          |
| Mass               | g·s⁻¹·m⁻² | Φ    | 0.147 ± 0.000    | 0.116 ± 0.000   |          |
| Energy             |       |        |                  |                 |          |
| Shortwave Flux (↑) | W·m⁻² | S_0   | 2 ± 0            | 2 ± 0           |          |
| Temperature        | °C    | T_c   | 12 ± 0           | 15 ± 0          |          |

Note. ± indicates the standard error (SE).

² obtained from sub-sampling 2.836 to 5.028 h.

Declaration of Competing Interest

The Authors confirm that there are no conflicts of interest.

Acknowledgments

Natural Sciences and Engineering Research Council of Canada for providing financial support.

References

[1] A. Ahmad, S. Rehman, LM Al-Hadhrami, Performance evaluation of an indirect evaporative cooler under controlled environmental conditions, Energy Build. 62 (1) (2013) 278–285.
[2] M. Aydin, M. Aydin, T. Yano, T. Yano, F. Evrendilek, F. Evrendilek, Implications of climate change for evaporation from bare soils in a Mediterranean environment, Environ. Monit. Assessm. 140 (1) (2008) 123–130.
[3] B. Bond-Lambrick, S.T. Gower, B. Amiro, B.E. Ewers, Measurement and modelling of bryophyte evaporation in a boreal forest chronosequence, Ecolhydrology 4 (1) (2011) 26–35.
[4] B. Caicedo, J. Tristancho, L. Thorèl, Centrifuge modeling of soil atmosphere interaction using climatic chamber, in: Physical Modelling in Geotechnics, Zürich, Switzerland, 2010, pp. 299–305.
[5] P.M. Castiblanco, C. Lozada, B. Caicedo, L. Thorèl, A new climatic chamber adapted to the mini-centrifuge for simulating soil drying, in: EUROFUGE 2016, Nantes, France, 2016, pp. 111–115.
[6] M.F. Hernández-López, J. Gironás, I. Braud, F. Suárez, J.F. Muñoz, Assessment of evaporation and water fluxes in a column of dry saline soil subject to different water table levels, Hydrol. Process. 28 (10) (2014) 3655–3669.
[7] M. Inan, S. Öğüz Atayilmaz, Experimental investigation of evaporation from a horizontal free water surface, Sigma J. Eng. Nat. Sci. 35 (1) (2017) 119–131.
[8] T. Kamal, N. Weisbrod, M.I. Dragila, Impact of ambient temperature on evaporation from surface-exposed fractures, Water Res. Res. 45 (2) (2009) W02417.
[9] K. Kim, X. Lee, Isotopic enrichment of liquid water during evaporation from water surfaces, J. Hydrol. 399 (3) (2011) 364–375.
[10] T.S. Komatsu, Toward a robust phenomenological expression of evaporation efficiency for unsaturated soil surfaces, J. Appl. Meteorol. 42 (9) (2003) 1330–1334.
[11] M.R. Lakshmikantha, P.C. Prat, A. Ledesma, Boundary effects in the desiccation of soil layers with controlled environmental conditions, Geotech. Test. J. 41 (4) (2018) 675–697.
[12] X. Liu, W. Xu, L. Zhan, Y. Chen, Laboratory and numerical study on an enhanced evaporation process in a loess soil column subjected to heating, J. Zhejiang Univ. A. Sci. 17 (7) (2016) 553–564.
[13] C. Lozada, B. Caicedo, L. Thorel, A new climatic chamber for studying soil-atmosphere interaction in physical models, Int. J. Phys. Model. Geotech. 19 (6) (2019) 286–304.
[14] J. Medhurst, J. Parsby, S. Linder, G. Wallin, E. Ceschia, M. Slaney, A whole-tree chamber system for examining tree-level physiological responses of field-grown trees to environmental variation and climate change, Plant, Cell Environ. 29 (9) (2006) 1853–1869.
[15] Q. Meng, Y. Zhang, L. Zhang, Measurement of the equivalent thermal resistance of rooftop lawns in a hot-climate wind tunnel, in: Envelope Technologies for Building Energy Efficiency, Shenzhen, China, 2006, p. 54, ESL.
[16] A.A. Mohamed, T. Sasaki, K. Watanabe, Solute transport through unsaturated soil due to evaporation, J. Environ. Eng. 126 (9) (2000) 842–848.
[17] K. Nelson, S.A. Kurc, G. John, R. Minor, G.A. Barron-Gafford, Influence of snow cover duration on soil evaporation and respiration flux in mixed-conifer ecosystems, Ecolohylogy 7 (2) (2014) 869–880.
[18] T. Pois, E. Varju, Review for prediction of evaporation rate at natural convection, Heat Mass Transf. 55 (6) (2019) 1651–1660.
[19] G.Y. Qiu, J. Ben-Asher, Experimental determination of soil evaporation stages with soil surface temperature, Soil Sci. Soc. Am. J. 74 (1) (2009) 13–22.
[20] R. Qubaja, M. Amer, F. Tatarinov, E. Rotenberg, Y. Preisler, M. Sprintsin, Partitioning evapotranspiration and its long-term evolution in a dry pine forest using measurement-based estimates of soil evaporation, Agric. For. Meteorol. 281 (1) (2020) 107831.
[21] A. Raimundo, A. Gaspar, A. Oliveira, Q. Divo, Wind tunnel measurements and numerical simulations of water evaporation in forced convection airflow, Int. J. Thermal Sci. 86 (1) (2014) 28–40.
[22] I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Reineke, I. Re