

Article

Sensor actuator network for in situ studies of antarctic plants physiology†

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Abstract: The article documents a custom sensor-actuator network designed and implemented as a part of experimental setup, where a long term phenological response of antarctic plants is studied. The first part of our work presents the context of the study, reports experimental methods used in antarctic plant field studies, characterize the environmental conditions and logistics facilities available on the measurement spot. After contextualization of the research we present, in details, booth: the network itself and some results obtained during antarctic summer seasons between 2019 and 2022 on the King George Island, South Shetlands. The results collected with our network and correlated with some data registered with a reference meteorological station reveal the plants response to the daytime temperature change caused by heat conduction and radiation and nighttime response, where some individual were actively warmed using thermal actuators.

Keywords: sensor networks; thermal actuators; antarctic plans; IoT

1. Introduction

The ongoing climate change is a fact however, it is not uniform across the planet, and it depends on the geographical latitudes, revealing that the extremes are situated on the poles of the planet. According to the long term meteorological data reported in the paper [1], the region of Antarctic Peninsula has warmed around 3.7°C during the last 100 years and this rate of change, 0.03° C/year, has been 4 times faster than the warming rate of the rest of the globe. Each day the "breaking" news, such as reported in the New York Times on Feb 6-th [2] "... a new air temperature record was registered in the Argentinean station *Esperanza* in Antarctic", thrill less the public. A few days later, some other research stations have confirmed the high value of the air temperature in the region of the Antarctic Peninsula. The above-mentioned facts cause that the polar and subpolar regions of Arctic and Antarctic are a research subject for many scientists investigating the climate change and its direct and indirect impacts on environment. Since the climate affects both: biotic and abiotic parameters of ecosystems, not only direct climate related physical variables are being studied, but also a variety of indicators and phenomena related to the fauna, flora, ice-cape, marine ecosystem, geology, geomorphology, atmosphere and many more. The presence of plants and its ability to withstand the extreme environmental conditions in these remote areas has been investigated by various research groups. The region of Arctic is much more rich and diverse in terms of vascular native plants comparing it to the Antarctic remote areas, where only

29 two vascular plants species were able to colonize some of the most southern regions of the planet. The
30 vascular plants in Antarctic are represented by the following ones: the Antarctic hair grass *Deschampsia*
31 *antarctica* DA and the Antarctic pearlwort *Colobantus quitensis* CQ, which have been studied for more
32 than century as it was reported in the article [3]. There are plenty of articles [4], [5], [6] that reveal, how
33 the temperature changes take an effect on the plants, its growth, reproduction capabilities and internal
34 processes such metabolism and photosynthesis. In 1994, in the article [7], the plants were recognized
35 as bioindicators (more precisely its expansion rate) of the climate change due to:(1) relatively rapid
36 response to the climatic changes in comparison to most other terrestrial macro-organisms, (2) the strong
37 correlation between the increase in number of individuals and populations, and a warming trend in
38 summer air temperatures. The as reported in the articles [8] and [9] the major environmental factors,
39 which impact the plant's physiology, and therefore its presence in a particular zone, are the following:
40 low summer temperature, water availability, length of the growing seasons and soil availability. Due
41 to the climate change, temperature changes, retreating glaciers and others propitious factors increases
42 in the surface covered by flowering plants, the number of populations and the increase in plant size
43 have been observed during the last 20 years.

44 In situ measurements, biological samples collection and analysis represent retrospective methods
45 of reasoning, where conclusions are based on historical data outcomes and predictions are made using
46 models developed using the same data. What if we could alter the growth conditions of the plants and
47 measure its response? If the global trend of warming will continue, what would be the response of the
48 plant? Those are valid questions. There are plenty of studies, where the Antarctic plants were grown
49 in a laboratory under strictly controlled conditions, however performing the same in situ, especially in
50 Antarctic sounds challenging. One of the methods used in order to increase locally the environmental
51 temperature, thus the plant's temperature, is a passive method of OTC *Open Top Chamber*. The OTC,
52 visualized in the Fig. (1), is a hexagonal prism made of transparent acrylic, where the base of the prism
is around 1 sq meter. The ventilation perforations ensure that the inside temperature does not exceed a

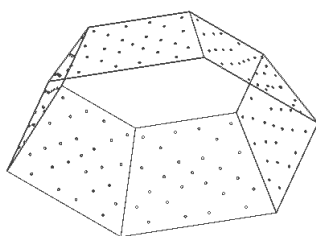


Figure 1. Visualization of an OTC chamber used in the experiments in order to simulate the day time warming and a photograph of a measurement spot (King George Island, South Shetlands), with OTC installed.

53
54 few grades of Celsius in reference to the outside temperature. One of the principal issues related to the
55 OTC is that it alters the temperature only during the daytime and the supposition of the continuity
56 of the future warming trend is based on daily mean temperature understood as 24 h period. Finally,
57 the rest of the article describes a solution, which address this particular problem by means of sensor
58 actuator network for nocturnal warming in a context of antarctic plants physiology in situ studies.

59 1.1. Review of methods used in the field studies of antarctic plants

60 In general, the biological studies in antarctic are based on sampling and sample analysis, however
61 the physical conditions related for example with the local meteorological conditions can be and in fact
62 are measured using automatic methods such as automatic weather stations or data loggers. In our
63 particular case, the principal problem to solve is a heat transfer towards the biological tissue of the
64 antarctic plants in its natural habitat in order to maintain plant's leaves temperature higher than the
65 ambient temperature. The constant temperature difference can be obtained thorough a sensor-actuator

66 network together with a dedicated control system. Since the heat transfer process depends on the
67 source-medium-object characteristics, it is necessary to identify the system thermal parameters in
68 order to correctly design the whole system. Although there are some studies, that reveal thermal
69 properties of some common plants described in the article [10] and methods to estimate it reported in
70 the following study [11], there are no records of similar data in the case of the antarctic plants. There are
71 two, supposed reasons, for that: (1) antarctic plants are not in the mainstream of the plant's biology in
72 opposition to the agriculture and food processing, (2) antarctic plants because of its small dimensions
73 present serious problems during measurements (the instrumentation equipment is sized to measure
74 bigger objects). An overview of methods for leaves temperature measurements was presented in the
75 paper [12] however all the measured objects (leaves) were sized, at least, order of magnitude higher
76 in surface in comparison to the antarctic plants. In the field studies, the most common method of
77 measuring the antarctic plants temperature is application of small thermocouples and IR sensors. Until
78 the moment, there is only one article published, which reports active heat transfer in field experiments
79 using IR radiators [13].

80 The presented system was designed to be applied in field experiments in order to study the
81 antarctic plants and to validate a biological hypothesis: *Antarctic vascular plant morpho-physiological*
82 *traits are more responsive to the increase in minimal nocturnal temperatures rather than the increase in daylight*
83 *average temperature*, where a methodology based of statistical methods was proposed. The methods
84 involve variance comparison between groups known as ANOVA test, where the experimental data,
85 associated with the groups being compared, are processed. In terms of the proposed system, the groups
86 are represented by different measurement spots, where the plant's leaves temperature is monitored.
87 The experiment assumes three different groups: (1) active warming group, where heating elements
88 are installed inside the OTC's (denominated as Nocturnal Warming by IR radiation on the figure (2),
89 (2) groups with OTC's without heat actuators (denominated as Control OTC on the figure (2)), (3)
90 groups without OTC often called a control group (denominated as Open Space on the figure (2)). The
91 ANOVA method is founded on Gaussian distribution of the measured variables, where a condition
92 of sufficient number of samples have to be satisfied. The above constrains set up each group to be
93 represented by various measurement points, under the assumption of homogeneous measurement
94 conditions within these groups. In our particular case, the measurement methodology has considered
95 measurements of three individuals per spot per species. In other words, we had to scale prepare the
96 system to be able to monitor 6 individual plants per OTC (or open space). In total, we had to manage
97 measurements of the leaves temperatures of 90 individual plants and actively heat 30 of them. Due
98 to the spatial distribution of the plants in the field and temperature measurements methods (local
sensing) the system should be distributed conforming a scalable sensor network.

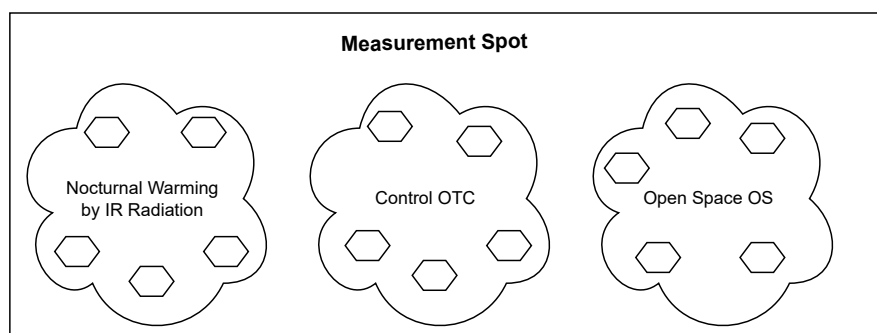


Figure 2. The main diagram of the experimental setup organized by three main groups. Each group contains five OTC, where six plants are monitored (three DA and three CQ).

100 1.2. Detailed characterization of the measurement spot

101 The field measurement campaign was carried during the Antarctic summer periods in the years
 102 2019–2022 in the vicinity of the Polish Antarctic Station "Arctowski" ($62^{\circ}09'34''S$ $58^{\circ}28'1''W$), King
 103 George Island. The station is operating all year round and provides access to the 220 [V] power
 104 grid and low speed internet satellite connection up to 1 [Mbit/s]. The measurement spot is situated
 105 approximately 500 [m] away from the station and elevated around 60 m above the sea level (a.s.l),
 with a clear line of sight between the spot and the station shown on the Fig. (3). As mentioned in the

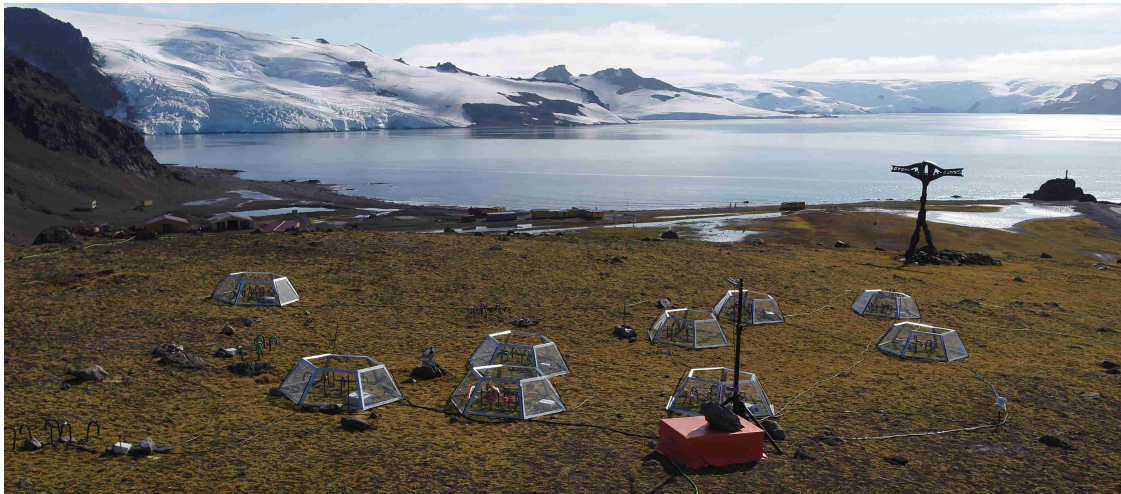


Figure 3. The aerial view of the measurement spot. In the background H. Arctowski Polish Antarctic Station and the Admiralty Bay.

106 article [14] on the spot the respective densities of *C. quitensis* CQ and *D. antarctica* DA are in the range
 107 of 70–200 and 20–150 individuals m^{-2} . The plants in size are small, the average values of the surface
 108 area and the height for *C. quitensis* are 2 cm^{-2} and 2.5 cm respectively and the corresponding values
 109 for *D. Antarctica* are 10 cm^{-2} and 4 cm.

110 According to the recent meteorological data from investigated area for the period 2013–2017 [15]
 111 the summer (Dec - March) mean monthly air temperature varies between $0,3\text{ }^{\circ}\text{C}$ in December (the
 112 coldest summer month) and $1,6\text{ }^{\circ}\text{C}$ in February (the warmest summer month). During summer mean
 113 daily air temperature is predominantly higher than $0\text{ }^{\circ}\text{C}$ (on average form 58% of days in December to
 114 76% of days in February). The annual mean relative humidity was 78.1% [15]. The Antarctic region is
 115 famous for its strong winds. The mean monthly wind speed at Arctowski Station during the period
 116 2013–2017 in summer was from 4.6 m/s (Dec.) to 5.5 m/s (Mar.), and the mean number of days where
 117 the maximum wind speed exceed 20 m/s was reported from 3.0 (Dec.) to 11.6 (Mar). The predominant
 118 wind direction was SW (31%). The monthly sum of precipitation in the summer period (2016–2017) was
 119 reported to be in the range of 14.6 – 170.1 mm [15]. Continuous snow cover occurred rarely during
 120 summer. During summer in 2016–2017 there was 0 – 5 number of days with snow cover per month
 121 [15] and during investigated period (summer 2019/20 and 2020/21) only 0 – 2 days with snow cover
 122 per month [personal observations].
 123

124 1.3. Selected recent advances in sensors and sensors technology in the regions of Arctic and Antarctic

125 Although the title of the subsection could be a title of a separate article, in this paragraph we
 126 would like to present some reviews of sensors and technological solutions, which were applied in
 127 various research studies in the polar regions during the last decade, in fact during the last 5 years. Since
 128 the polar regions are the main reservoir of a freshwater in a form of snow and ice, there are plenty of
 129 studies related to this matter, where new technological solutions are emerging. The standard methods
 130 based on image processing and matching [16] are being constantly modified due to a proliferation of
 131 image capture techniques (satellite imaging, multispectral cameras, stereoscopy, UAV HD imaging).

132 Apart the snow (ice) cover area, some more parameters are measured in order to estimate for example
133 glacier mass balance and its impact on the local weather conditions. Those are: snow depth and snow
134 water equivalent (SWE). Some new methods, of these parameter's evaluation, were recently reported:
135 (1) a microwave resonator tested in Concordia station and described in [17], (2) the article [18] reports
136 a 24 GHz radar for snow depth, ice thickness and SWE evaluation, (3) ground based snow depth and
137 density estimation methods using ultrasonic waves tested on King George Island and reported in [19].
138 It is rather straightforward that the snow and ice properties depend on the meteorological conditions,
139 which are being measured using various technologies, each day more automated and autonomous.
140 Automatic weather stations and data loggers commonly used in the polar regions, however, due to
141 absence of power sources and limited availability of telecommunications services some alternative
142 technologies have emerged. Some wireless sensor networks, based on Wi-Fi [20] and LoRa [21]
143 are proposed in order to: (1) acquire information about spatial distribution of measured physical
144 variables (mostly meteorological data), (2) minimize the data delivery time, (3) provide feedback
145 about the sensor failure. Apart to the Iridium based satellite service there were some attempts in
146 order to provide reliable data transmission from the sensors or sensor networks to an online database,
147 among them a long haul radio link from the Greenwich Island to Spain [22] [23]. Nevertheless, at the
148 moment the article was being written (Sep 2022), SpaceX together with Nantional Science Foundation
149 have announced [24], that the Starlink service at McMurdo station was successfully launched Some
150 advanced algorithms, discrimination [25] and machine learning [26], were recently reported, what
151 supports the global tendency related to so called smart sensors, which process the raw data on site and
152 a deliverable in the information about process being monitored, for example the local weather forecast.

153 2. Nocturnal warming system — detailed description

154 In order to fulfil the requirements commented in the previous sections, the experimental setup
155 have to be organized as a distributed sensor actuator network, mainly due to the spatial plant
156 distribution and methodology used. The system is going to be exposed to the harsh condition because
157 of the high value of the relative humidity, possible precipitation (rain and snow) and wind blasts.
158 Apparently, near 0 °C temperatures does not cause problems itself, however, in conjunction with
159 the high humidity and freezing - defreezing cycles it can affect the system mechanical components,
160 especially sealing elements. Since the detailed description of the control methods applied for this
161 project is reported in [?] this part will not be mentioned in this section. The overall system diagram
162 is presented on the fig. (4). The three spots shown on the figure (2) represent three groups to be
163 compared. Each group consists of five OTC, where plant's leaves temperature, air temperature and air
164 relative humidity are monitored periodically. The system is able to: (1) monitor of leaves temperature
165 of 90 plants, (2) measure air and air humidity at each node, (3) measure status information such as
166 supply voltage level, error status, core temperature at each node, (4) backup and report the collected
167 information, (5) perform active plants heating during the nighttime. Since the experiments involve
168 actuation using heat sources, the 220 [V] power line was delivered to the spot. Availability of the
169 AC power gave the opportunity to supply power to all modules using locally installed DC sources.
170 Moreover, all the modules were connected using a copper wire in order to: (1) power up all the
171 modules, (2) implement a reliable communication system. The three groups were distributed spatially
172 within the radii of $< 50 m$, what constrains the communication system, which have to collect the data
173 from each node and forward it to the gateway and then to the cloud. The data forwarding can be done
174 using the two methods: (1) satellite data transfer via "Arctowski" and station local LAN or (2) using
175 GSM data link available an provided by Brazilian station. The above scenario suggested incorporation
176 of some additional nodes being able to maintain the communication, sensor data transfers and other
177 services such local backup, time synchronization, network monitoring, node management, event
178 scheduling.

179 During the design stage, we have considered that the cable network on the spot should be able
180 to transfer data at relatively low bit rate, and the network reliability should be the principal factor to

181 evaluate. There are a plenty of variation of Ethernet based LAN however the high throughput and
 182 additional hardware needed (switches, cables, interfaces) seems to be not adequate for our network
 183 considering them as possible single points of failure (SPOF). Some industry standard like CAN (*Control*
 184 *Area Network*) and MODBUS were revised and finally the CAN protocol [?] was selected and applied.
 185 The CAN network offers a complete protocol solution beginning from the electrical level up to the
 186 data encapsulation within frame with CRC correction and error reporting. Moreover, CAN bus offers
 187 differential signaling together with a hardware based negotiation what gives possibility to organize
 network in a single bus topology, what reduces the number of connections. On the fig. (5) the spatial

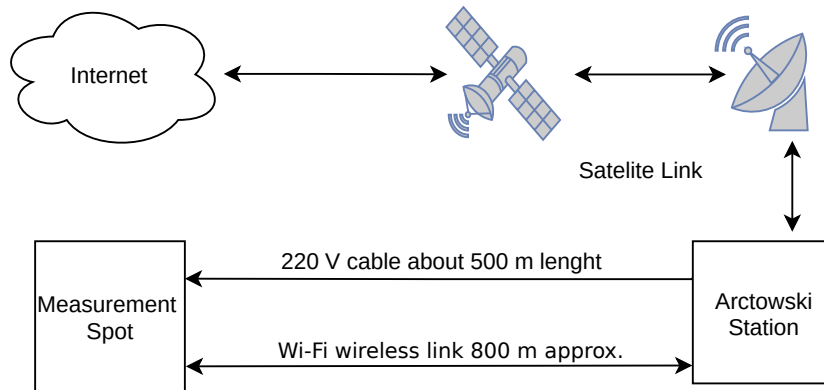


Figure 4. A global diagram of the custom network insertion into the Arctowski station infrastructure.

188 distribution of the nodes is shown. In fact, the diagram was prepared using an aerial photo taken
 189 by an UAV. The figure, apart the nodes aggregated in groups, shows respective interconnections and

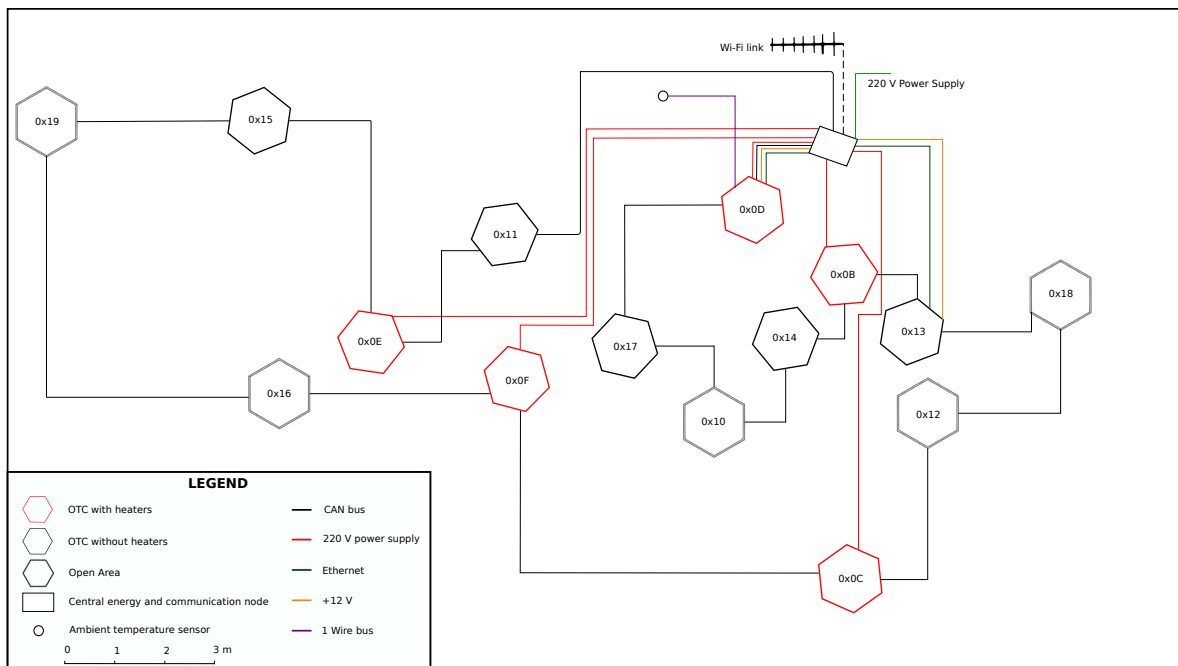


Figure 5. A schematic view of the measurement setup installed in Antarctica

190 the center rectangular point, where: (1) 220 power is divided and distributed to the heating nodes,
 191 (2) security devices are installed (fuses, local ground point), (3) DC power supply, DC backup power
 192 supply and 12 batteries are installed in order to provide 12 V system voltage to each node, (4) wireless
 193 is installed in order to communicate gateways with the Arctowski station and thus, with internet.

195 The basic network unit, designed to handle the data acquisition and temperature control, was
 196 a module named ARM-Node (after the ARM Cortex M processor being the center of the unit). The

197 mentioned ARM Cortex M3 processor was selected due to the rich communications peripherals such
 198 as CAN, I2C (SMBus), SPI, UART; advanced timers with PWM channels; embedded RTC clock with
 199 backup domain and a variety of low power consumption modes. As it is shown on the Fig. (6)
 200 the ARM-node is powered by 12 volt power supply line voltage distributed together with the CAN
 201 network using ethernet cat6 cable. The processor was clocked using two crystals 8 MHz and 32 kHz
 202 respectively, what permits to switch between low /high power modes and to preserve (together with
 the backup battery) the backup domain registers thus the time, date and critical data during reset. The

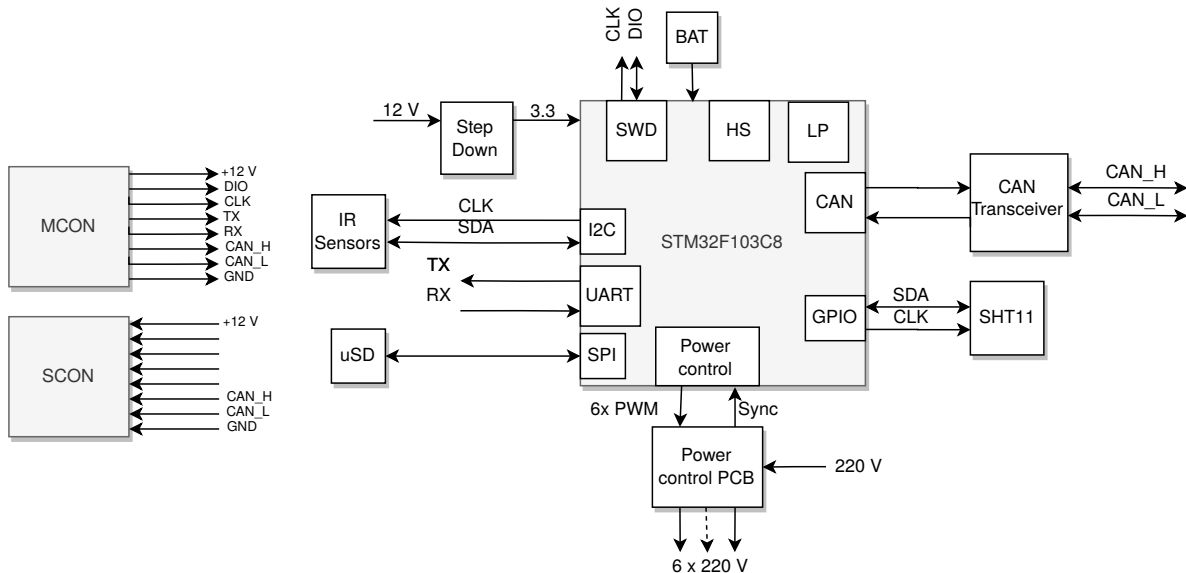


Figure 6. A schematic diagram of the ARM-Node. Description in text.

203 node has its own local data backup implemented using a micro SD card interfaced via SPI module
 204 what, in the case of the network failure, provide a mechanism of local data backup and continuity of
 205 operation. The device can be accessed via CAN network and throughout the UART interface in a debug
 206 mode. The nodes with thermal actuators uses six PWM independent channels in synchronized to the
 207 power line voltage zero crossing in order to generate trigger pulses for independent, optocoupled
 208 triacs. The node was encapsulated in a plastic enclosure with IP67 protection grade. The network
 209 connection was realized using two rugged RJ45 connectors while the sensors were connected using 4
 210 wire cable and silicon sealed cable glands. The power supply for the ARM node network was designed
 211 to be 12 [V] stepped down by node converter to be 3.3 V at the node. This solution permits to distribute
 212 the power supply and implement CAN bus using CAT 5,6, AWG 26 cable and guarantees protection
 213 against the voltage IR drops at the end of the bus. The basic feature of the network node was to perform
 214 the plants leaves temperature measurements and to implement the control mechanism in order to drive
 215 heat sources on the plants, where the nocturnal warming was required. The contact less, automotive
 216 grade, temperature sensor MLX90614 were chosen to monitor the plant temperature. Six MLX sensors,
 217 organized in a daisy chain, are connected to the node, where the sensors-node communication was
 218 implemented using SMBus protocol. The control of the heat transferred to each of the six plants within
 219 one OTC was implemented using PWM modulation, where the heat sources (25 W ceramic heaters)
 220 were controlled independently, thus each plant temperature was controlled separately.

222 In our case, the network consisted of 15 ARM-Nodes, which collected data from over 120 sensors
 223 and heat up 30 plants individually. In order to manage the local CAN based sensor network and
 224 make a bridge between CAN and the station's LAN network, two single board computer modules
 225 were incorporated. The Beagle Bone Black based on AM335x ARM Cortex-A8 Sitara processor were
 226 utilized as hardware platforms. The computer's hardware involves 100 MBit Ethernet connection,
 227 CAN 2.0 module, GPIO, UART, RTC, 1-Wire, USB 2.0. In opposition to the ARM-Node, where all the
 228 application is a bare metal, interrupt driven application, the Beagle Bone node runs Linux Debian OS,



Figure 7. The ARM-Node inside IP67 enclosure. The rugged RJ45 connectors and cable glands are show.

229 what permits to exploit the mechanisms of the OS. The principal goals of the Beagle Bone are: (1) to
 230 schedule the measurements, (2) to collect and store the biological and system data, (3) to manage a
 231 local database, (4) to synchronize the database with the cloud, (4) to manage the sensor network via
 232 remote connection, (5) to report system status, (6) to measure a reference temperature using a DS18B20
 233 temperature sensor and distribute it to the local controllers. Although the Beagle Bone Black does
 234 have the CAN 2.0 support, the CAN level transceiver had to be installed together with additional
 235 5 V voltage regulators to source current to the GSM module. The above was realized in a form of a
 cape for the BBB module, see Fig. (8). Two Beagle Bone Black modules were connected via wireless

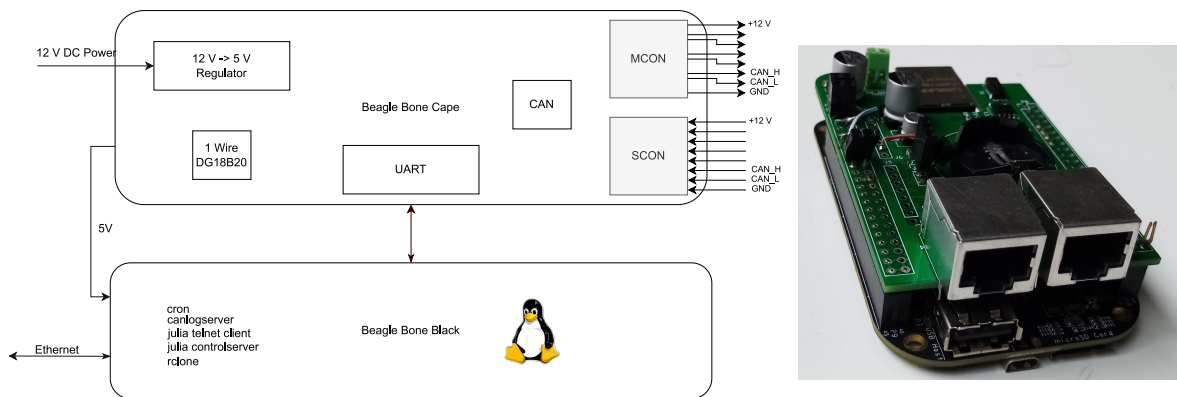


Figure 8. The block diagram of a system gateway based on the Beagle Bone Black with the custom cape.

236
 237 router to the station Wi-Fi in order to get access to the satellite link. In the get remote access to the BBB
 238 module, a Zerotier [27] network client was installed, thus one can access the remote module using for
 239 example the SSH protocol. The measurement automation operates in the linux user space, taking the
 240 advantage of linux builtin applications. The CAN network is managed by the can-utils package [28],
 241 where one can send and register the CAN frames. To perform the periodical tasks, cron mechanism
 242 was extensively used especially to implement the main application, which was based on Julia language.
 243 We have implemented an asynchronous control server that receives cron scheduled commands related
 244 with particular tasks. Once received, it takes corresponding action in order to perform an action. In
 245 a case of an error, an exception is thrown and reported in the system log. The reception of the CAN
 246 frames is based on client - server application as well. We have used the canlogserver from the can-utils

247 package, which exposes the incoming CAN frames as a plain text on a particular TCP port. We have
 248 developed a telnet client using Julia language, where the data not only are captured but also parsed
 249 and categorized, due to the fact that the data in the CAN frame are sent in a binary form (not string)
 250 using a custom frame format described in [29]. The custom telnet client uses a database based on
 251 Julia DataFrames, which dumps the data in a form of CSV files. Once per day the local data backup
 252 was performed and synchronization with a Google Drive was made using rclone tool. In order to
 253 explain the network operation, it has to be divided into 2 parts: ARM-Node operation and Beagle
 254 Board operation. The ARM-Node after booting recovers its fixed ID from the code, day, and time
 255 from the backup domain and, if it corresponds, PID (proportional, integral, differentiate) coefficients
 256 of the controller, it also sends a frame over the network that it is ready to operate. Since then, the
 257 node is ready to be managed using commands send over the network. If timeout has occurred, (no
 258 command arrives) the node perform measurement and stores results in the local backup (SD card). In
 259 case of a node with active heating, the node perform heating if the corresponding flag (set by Beagle
 260 Bone) was set and recovered from the backup domain. The unit measurement contained: timestamp,
 261 successive measurement iterator, power supply voltage, core temperature, six MLX sensors readings
 262 (corresponding to six plants), air temperature, air humidity.

263 Because of possible failure, we have had two Beagle Bone nodes in the can network, where one
 264 was manually set as a master node. During boot, the service of canlogserver was activated. Since
 265 then, the julia custom control server and telnet client could booth: monitor the network and control
 266 the network operation. Each minute, cron used to send a control command to the control server in
 267 order to trigger a local reference temperature measurement and distribute a call for measurements
 268 to each ARM-Node. Once distributed, the ARM nodes have responded to the call with four frames
 269 that contained the measured data. The frames were captured by booth Beagle Bones individually by
 270 respective custom telnet clients and stored in respective data frames. At the end of the day, typically at
 271 20:00 h the call for warming was distributed along the network, what in result switched on heating on
 272 the active ARM nodes, since that moment the reference temperature measured by the master Beagle
 273 Bone was broadcasted along the network in order to feed PID controllers with a reference values. The
 274 nocturnal warming usually was switched off at 6 am. Additionally, once per hour the data from data
 275 frame structure were saved to a respective CSV file, and once per day an update of RTC clock was
 276 performed in a whole network.

277 3. Results

278 The measurement campaigns took place during the summer seasons, 2019 – 2022. The network
 279 was deployed on the spot only for the summer and uninstalled and kept safe during the winter time.
 280 The data were collected not only using our sensor network, but also using a reference automatic
 weather station, AWS, with the sensor presented in the table (1). In order to render the principal

Table 1. Reference weather station sensors

Equipment function	Type
Air temperature sensor at 2 m	Vaisala HMP155
Air temperature sensor at 0 m	Campbell 107
Solar radiation sensor	Apogee CS300
Data logger	Campbell CR1000

281 functionality of the system, a daytime fig. (9) and nighttime fig. (10) average temperature of the air
 282 of each group is presented. The data show the substantial difference between the groups. During
 283 the daytime, there exists a systematic gap between the open space and nodes inside the OTC's, what
 284 supports the greenhouse effect of the OTC. Correspondingly, during the nighttime the temperature of
 285 the open space and control OTC are almost perfectly aligned, what supports the lack of the greenhouse
 286 effect inside OTC during the nighttime, and it validates our study.
 287

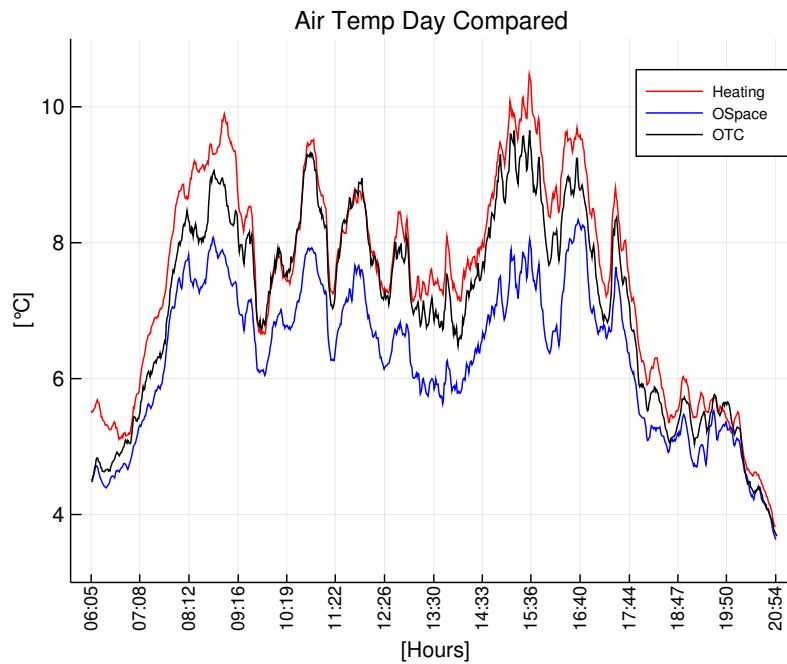


Figure 9. Daytime temperature at nodes of each group.

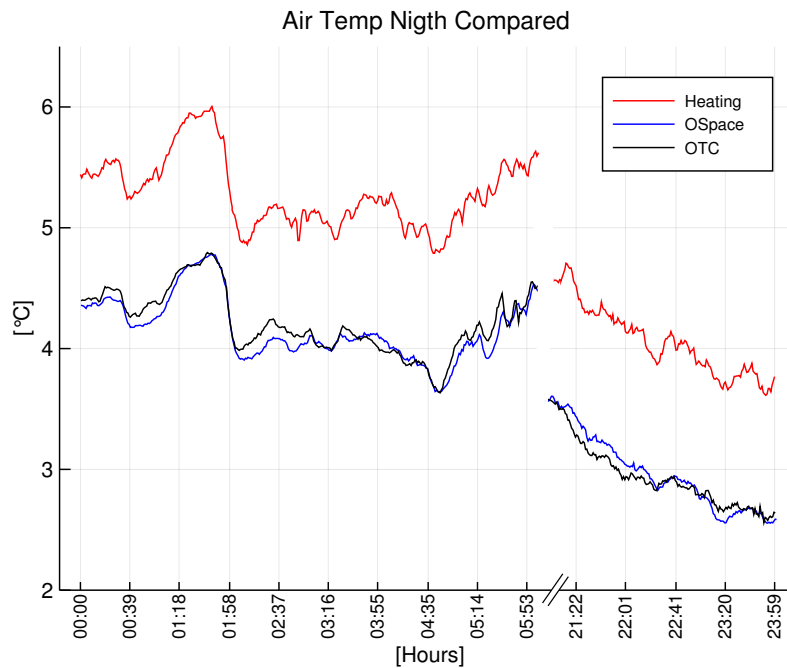


Figure 10. Nighttime temperature at nodes of each group.

288 On the fig. (11) the mean and standard deviation of the plant's temperature, local temperature
 289 and reference temperature are shown.

290 On the fig. (12) a customized histogram of the temperature is shown. The data were rendered by
 291 segments in order to represent the number of "events" such as very cold nights or very warm days,
 292 what is useful when correlating with the physiological response of the plants.

293 In order to investigate a dependence between leaves temperature, solar radiation and ambient
 294 temperature some selected data related to sunny days were shown on the fig. (13). Additionally
 295 correlation plots shown on fig. (14) compare the data presented previously on the figure (13) taken
 296 during the first days of January with data taken during the whole month of January 2021.

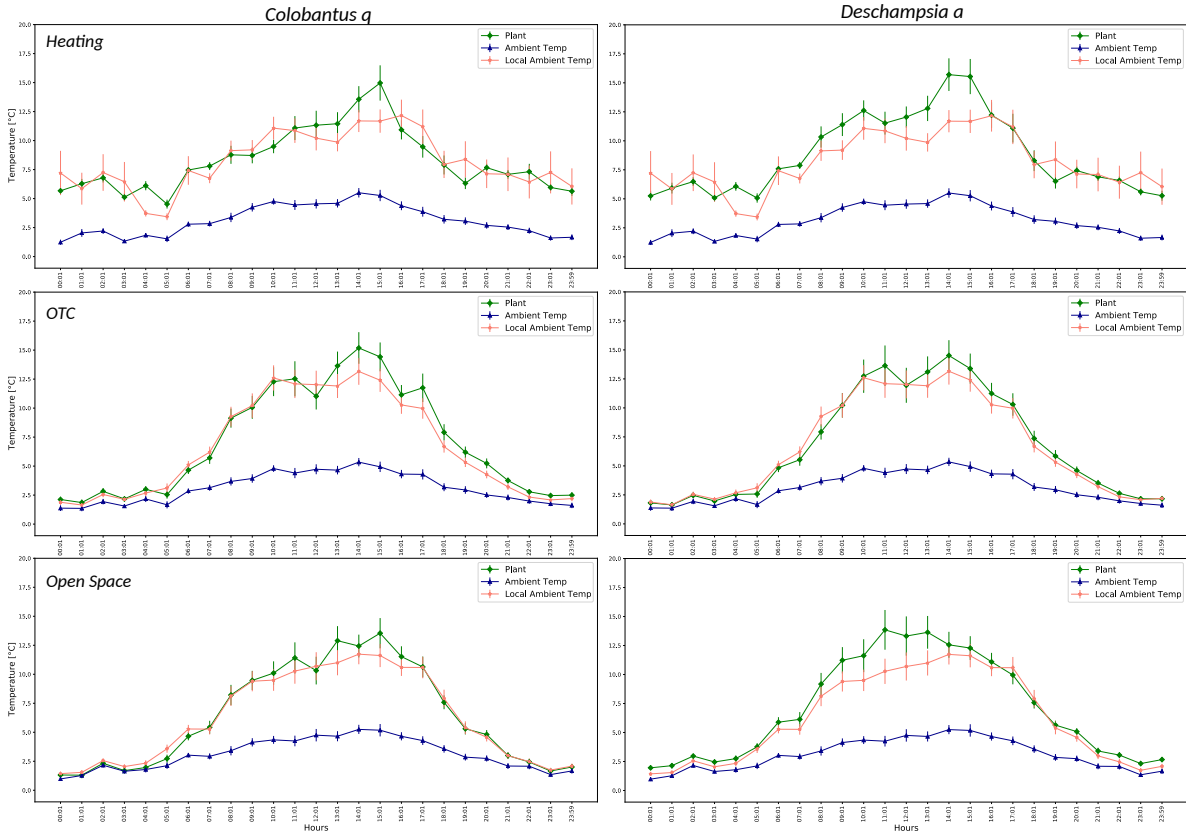


Figure 11. Leaves temperature, air local temperature and reference temperature segmented by plants and groups.

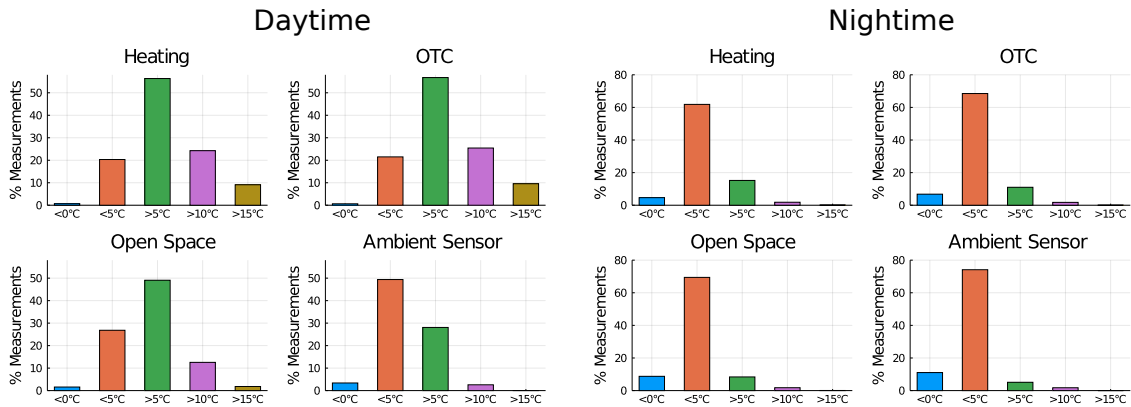


Figure 12. Customized temperature histograms segmented by groups and period (daytime or nighttime).

297 **4. Discussion**

298 The first point of discussion is that it is very difficult to compare our solution to anything, at
 299 least similar. The only one existing study carried out in the vicinity of the Palmer Station in the
 300 region of Antarctic Peninsula reported in the article [13], used fixed power IR heaters mounted over
 301 experimental traits of plants. Although, the experiment was carried out in antarctic the plants were
 302 transplanted into pots and finally the growth conditions were altered. Some interesting insights can
 303 be found analyzing data reported in the article [30], where some relationships between radiation,
 304 leaves temperature and air temperature were shown. Considering two methods of leaf temperature
 305 measurement: (1) direct on reported in [30] and (2) non-contact using infrared radiation we can argue
 306 if the first method is adequate in the case of measurements of such small objects as the leaves of the

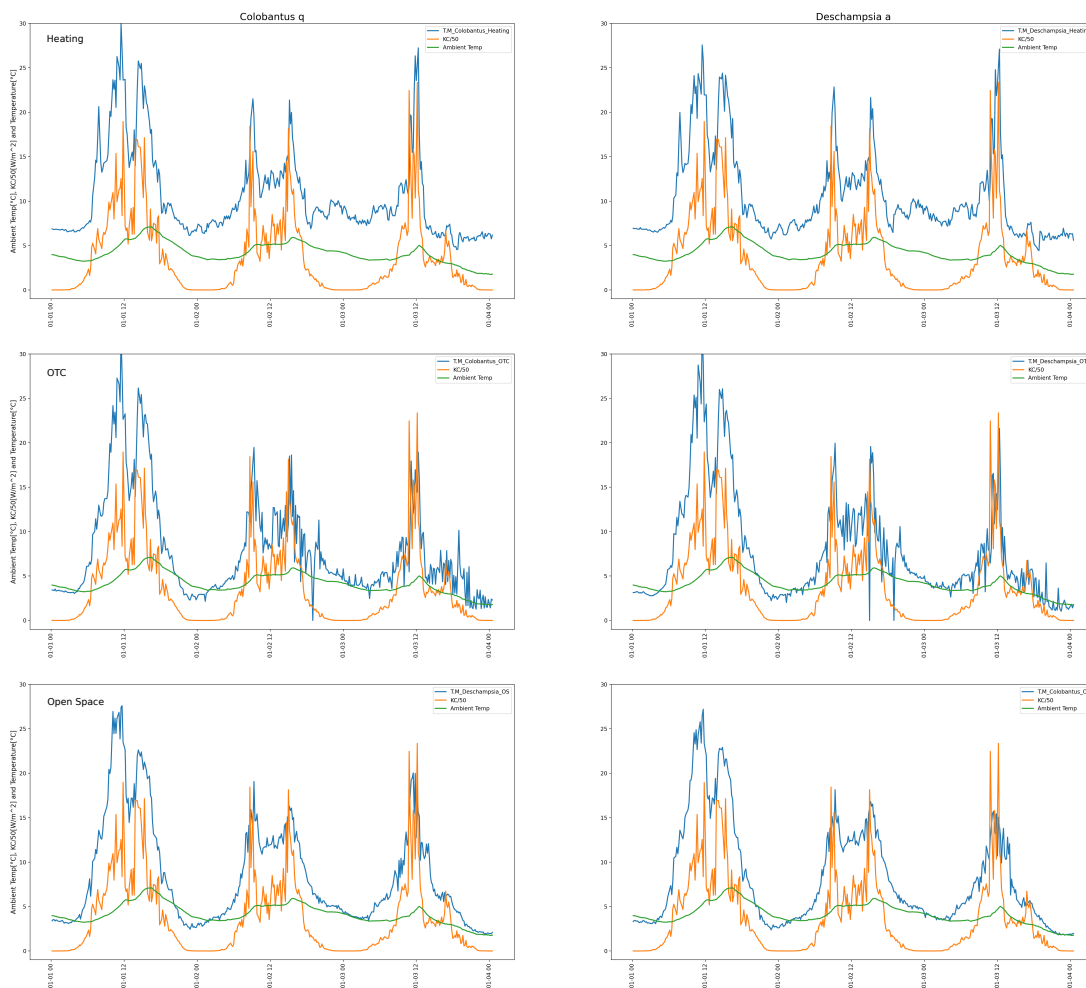


Figure 13. Time series of leaves temperature, segmented by specie and group, together with solar radiation and ambient temperature measured by automatic weather station in a period of 1-4 January 2021.

307 antarctic plants. The above can be justified using two arguments: (1) specific heat capacity of the
 308 thermocouple and the leaves, (2) thermal coupling between leaves and the thermocouple. A typical
 309 copper-nickel thermocouple wire has a specific heat of 393 J/kg/K^{-1} , while the same parameter of
 310 some leaves of plants reported in [10] can have a value in a range of $255 - 2267 \text{ J/kg/K}^{-1}$ for fresh
 311 leaves. Assuming ideal thermal coupling between the leaf surface and the thermocouple still there is
 312 a substantial systematic offset in the results of measurements introduced by the thermocouple. The
 313 method presented in our article estimates the leaves temperature using contact less method as a spatial
 314 integral of infrared radiation measured by the MLX90614 sensor. The sensor itself guarantees accuracy
 315 of $0.2 \text{ }^\circ\text{C}$

316 Analysing the results presented on the figures (9) - (12) it becomes clear that the OTC and the
 317 active warming system alternate the micro climatic conditions inside the OTC with the nocturnal
 318 warming system installed. However careful a distinction should be made between air temperature
 319 and leaves temperature. Since the infrared heaters radiate heat on individual plants the effect of
 320 heating and maintaining the $5 \text{ }^\circ\text{C}$ difference is evident (as a result of high performance of individual
 321 PID controller). Nevertheless the distinguishable difference in air temperature inside the OTC's with
 322 nocturnal warming system is also evident although is a side effect of dissipated heat.

323 The data from the weather station fig. (13) and correlation plots (14) provide us some interesting
 324 insights about the experiment. A strong correlation between plants leaves temperature and solar

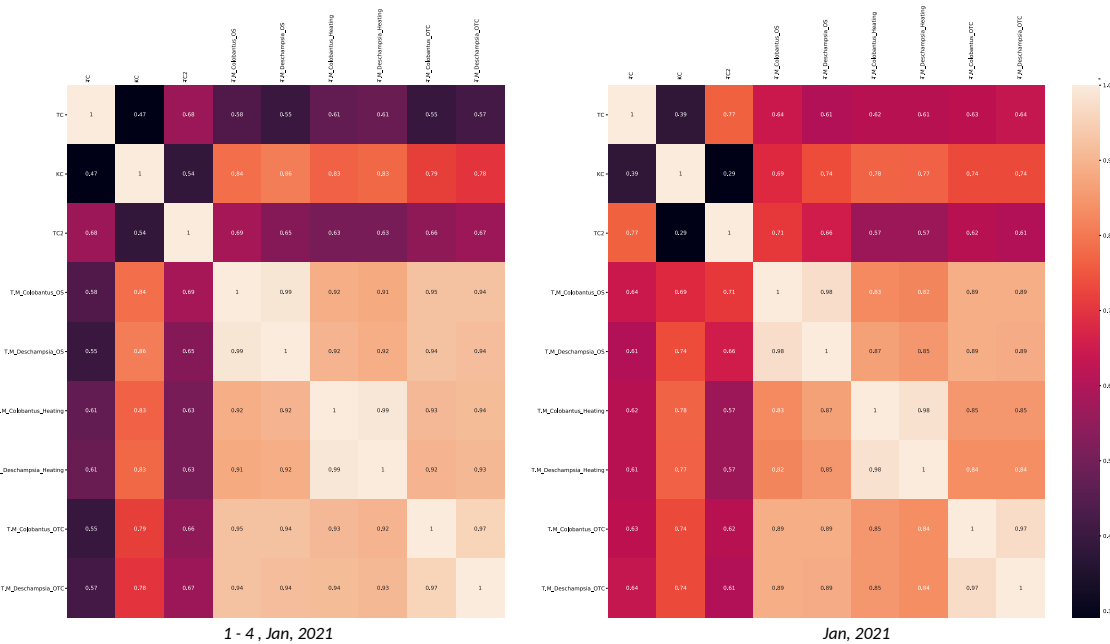


Figure 14. Correlation diagrams between data from weather station (TC - air temperature, TC2 - soil temperature, KC—radiation) and leaves of the plants in different groups in a period of 1-4 January 2021 and whole month Jan 2021.

325 radiation can be observed especially in the selected period of 1-4 January. The air temperature does
 326 not respond immediately and there exist a lag between peak of radiation a peak of temperature (in
 327 a simplified model would be related to the dynamics of a heat transfer). We can also observe a very
 328 strong correlation with corresponding groups (Heating, OTC and Open Space) and moderate
 329 correlation between air temperature and leaf temperature.

330 5. Conclusions

331 In the article, a sensor—actuator network for in situ studies of antarctic plants physiology was
 332 demonstrated. Although until the moment we can not provide any data related with plants physiology,
 333 we can state that our solution has accomplished its role by alternating local microclimatic conditions of
 334 the plant's growth. One of our final remark is that, the plants leaves temperature is strictly correlated
 335 with the solar radiation and can reach temperatures much higher than the ambient temperature. Also
 336 it seems that the introduced non contact method of temperature measurement is more confident in
 337 terms of systematic error introduced by the measurement method. The final remark, we would like
 338 to share is that, the presented study is unique and distinctive because it explores methods, where an
 339 active component is introduced into the local environment. Traditionally, and due to environmental
 340 restrictions, any introduction of biological or non-biological material is prohibited or limited in antarctic.
 341 From this point of view, the alteration of the microclimatic growth condition of the antarctic plants
 342 using state of an art technology surely opens new possibilities of investigation.

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 344 contributions must be provided. The following statements should be used “conceptualization, K.H. and L.B.;
 345 methodology, K.H. and L.B.; software, K.H. and M.M.; validation, K.H., M.M. and J.P.; data analysis, K.H., M.M.
 346 J.P.; investigation, K.H., L.B., M.M.; resources, L.B., K.H. and J.P.; data curation, M.M., J.P.; writing—original draft
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