Microclimate variability of Antarctic terrestrial ecosystems manipulated by open top chambers: Comparison of selected austral summer seasons within a decade

Miloš Barták[1*], Kamil Láska[2], Josef Hájek[1], Peter Váczi[1]

[1]*Department of Experimental Biology, Section of Plant Physiology and Anatomy, Laboratory of Extreme Environments Life, Masaryk University, Kamenice 5, 62500 Brno, Czech Republic*
[2]*Department of Geography, Masaryk University, Kotlářská 2, 61137 Brno, Czech Republic*

Abstract

Open top chambers (OTCs) were established in the northern part of the James Ross Island, Antarctic Peninsula, as a part of long-term program in January 2007. They were installed in two typical locations differing in vegetation cover. First group was set in a seashore ecosystem dominated by moss carpet supplemented with few lichen species. The other group was located on the top of a volcanic mesa (350 m a.s.l.) with irregular cover of lichens *Usnea antarctica* and *Umbilicaria decussata*. Temperature regimes inside and outside OTCs were continuously measured and related to year-round reference meteorological data. For majority of OTC installations, temperature increase caused by OTC was apparent in the period of September-March. Detailed analysis of chamber effect on the increase in air, surface, vegetation, and ground temperatures was done for late austral summer seasons of 2007 and 2008, and 10 years later, the seasons of 2017 and 2018. The OTC-induced temperature increase was more pronounced for mesa than seashore plot. For both locations, OTC-induced increase in temperature was highest for warm days with full sunshine and limited wind speed. On stormy days with overcast sky and high wind speed, the shift in temperature was smaller. Consequences of a long-term manipulation of Antarctic terrestrial ecosystems by OTCs for moss and lichen ecophysiology are discussed.

Key words: James Ross Island, microclimate, manipulated environment, chamber effect, austral summer, ground warming, ecophysiology, lichens, moss

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Introduction

Global climate change has been recently demonstrated as an increase in atmospheric CO_2 concentration and air temperature. These changes are apparent also in tundra and polar regions and affect functioning of local ecosystems. Potential warming and its effects on polar and Alpine biota have been studied lately (*e.g.* Hennion et al. 2006, Jägerbrand et al. 2006, Rai et al. 2010). In case of Antarctica, near surface air temperature increase has been reported in its coastal regions, the Antarctic Peninsula in particular (Turner et al. 2005, 2007) where both short and long-term responses to warming of the terrestrial ecosystems along the coasts have been observed and reported in the form of increased rate of glacier retreat (*e.g.* Skvarca and De Angelis 2003, Engel et al. 2012). Altered colonization of bare ground by terrestrial autotrophic vegetations has also been reported (Convey and Smith 2006).

It is well established that plants from polar biomes are sensitive to global warming (*e.g.* Aerts et al. 2006). Long-term prediction of changes induced by air temperature increase in biodiversity, primary production, and rate of plant colonization is, however, difficult. Recently, several field approaches have appeared to manipulate *in situ* air temperature in order to simulate future polar vegetation development. Among them, FATI system was used in Greenland on grassland tundra ecosystem (Nijs et al. 2000, Mertens et al. 2001). Open top chamber approach (OTC) has been used more frequently, *e.g.* in Canada within the ITEX tundra project (Hollister and Webber 2000, Hollister et al. 2005, 2006), in Svalbard (Dollery et al. 2006, Nybakken et al. 2004). In Antarctica, OTCs have been used only in several locations, *e.g.* Taylor Valley (USA program, see *e.g.* Nkem et al. 2006), Yukidori station (Japanese program), and along the longitudinal gradient consisting of the Falkland Islands, the South Orkneys, and Leoni Island (Bokhorst et al. 2007). The Dutch Program studies the effect of warming on soil biological activity and biodiversity (for details see *e.g.* Rinnan et al. 2009). It was found that significant increases happened in the abundance of fungi and bacteria and in the Alphaproteobacteria-to-Acidobacteria ratio, which could be a reason for an increase in soil respiration (Yergeau et al. 2012). Similarly, soil microbial community changes and humic substances degradation in OTCs was studied by Kim et al. (2018) on the King George Island. In Antarctica, the responses of vegetation components, vascular plants in particular (*Colobanthus quitensis* and *Deschampsia antarctica*), to simulated warming has been studied in last two decades (*e.g.* Sáez et al. 2018). Some studies focused particular plant responses to manipulated warming, such as *e.g.* their freezing resistance (Sierra-Almeida et al. 2018, King George Island). For mosses, the effects of OTC microclimate on sporophyte production has been studies on the King George Island (*see* e.g. Casanova-Katny et al. 2016). Cryptogamic vegetation components responses to manipulated warming have been studied much less frequently. For lichens, Rai et al. (2010) used OTC approach to evaluate changes in lichen-dominated habitats in the Indian Himalaya. Similarly, Casanova-Katny et al. (2019 - Czech Polar Reports, this issue) focused on the co-effects of OTC-induced changes in water regimen on primary photosynthetic processes in *Placopsis antarctica*.

It is reported that particular growth and productivity parameters of terrestrial autotrophs increased due to elevated air temperature and altered relative air humidity inside an OTC (Bokhorst et al. 2007). However, in case of Antarctic terrestrial ecosystems only limited knowledge exist on: 1) diurnal and seasonal variability of microclimatic parameters inside an OTC, and 2) dependence of temperature shift on actual weather conditions. Among the attempts to evaluate site, and local effects on OTC microclimatic parameters, the study of Bokhorst et al. (2013) should be mentioned. The authors provided documentation of the microclimatic influences of OTCs throughout the year, and analyzed temperature data from 20 studies distributed across polar and alpine regions. To add some site-specific analysis from James Ross Island, Antarctic Peninsula, we used microclimate data from OTCs and analyzed general trends as well as season-related differences. We hypothesized that the extent of OTC-induced temperature shift is dependent on actual weather and may alter air humidity. Therefore, we related the OTC-induced temperature shift to weather conditions of particular days, wind velocity, cloudiness, and snow fall accumulation in particular. We also addressed the question whether or not the OTC-induced increase in air and ground temperature represents a positive factor for mosses and lichens physiology, growth and productivity.

Material and Methods

Open top chambers

Open top chambers (OTCs) were established in the northern part of James Ross Island in a close vicinity of the Johann Gregor Mendel Czech Antarctic station (63° 48´ S, 57° 53´ W) in January 2007. They are a part of a Long term research plot (LTRP), *see* Fig. 1. The LTRP is located close to a coastal line at the altitude of 7 m. The LTRP is dominated by *Bryum pseudotriquetrum* that forms carpets. The area is rich in microbial mats formed by *Nostoc sp.* colonies, algal (*e.g. Zygnema* sp.) and cyanobacterial (*e.g. Microcoleus* sp.) species found in seepages. Dry and stony surfaces are covered patchilly by lichens, such as *e.g. Rhizoplaca melanophthalma*, *Xanthoria elegans*. The other OTCs were installed at the top of the Berry Hill volcanic mesa at 350 m a.s.l. The OTCs were installed over typical vegetation cover lichens: *Usnea antarctica* (reported by *e.g.* Bohuslavová et al. 2012) and *Umbilicaria decussata* located on basalt cobbles and boulders forming patterned ground (Davies et al. 2013). Dominating species is *Usnea antarctica* that forms dense clusters of blackish thalli (*see* Fig. 3).

The OTCs serve for evaluation of growth rate changes of vegetation components and biodiversity at long-term elevated temperature. Recently, they have also been used for monitoring of the physiologically-active time of mosses using chlorophyll fluorescence technique (Barták et al. 2009). Here, we present only data related exclusively to the effect of OTC-induced changes in microclimate.

Hexagonal OTCs are made of 6 plates of 5 mm thick extruded PMMA plexiglass. Transparency of the material for photosynthetically active radiation was 96%. Each plate was of trapezoid shape with the base/top/height dimensions of 70/50/50 cm. The contact line between two neighbouring plates was reinforced by an aluminum belt and fixed by 6 screws. The whole OTC construction was placed at an experimental plots and well fixed to the surface with iron ropes fitted to the top parts of the OTCs (*see* Fig. 2). Vegetation inside the OTCs (*see* Fig. 4) was photodocumented regularly.

Fig. 1. Geographic location of James Ross Island. Detailed map of the northern part of the Island with indicated open top chambers (OTCs) and the selected automatic weather stations [1].

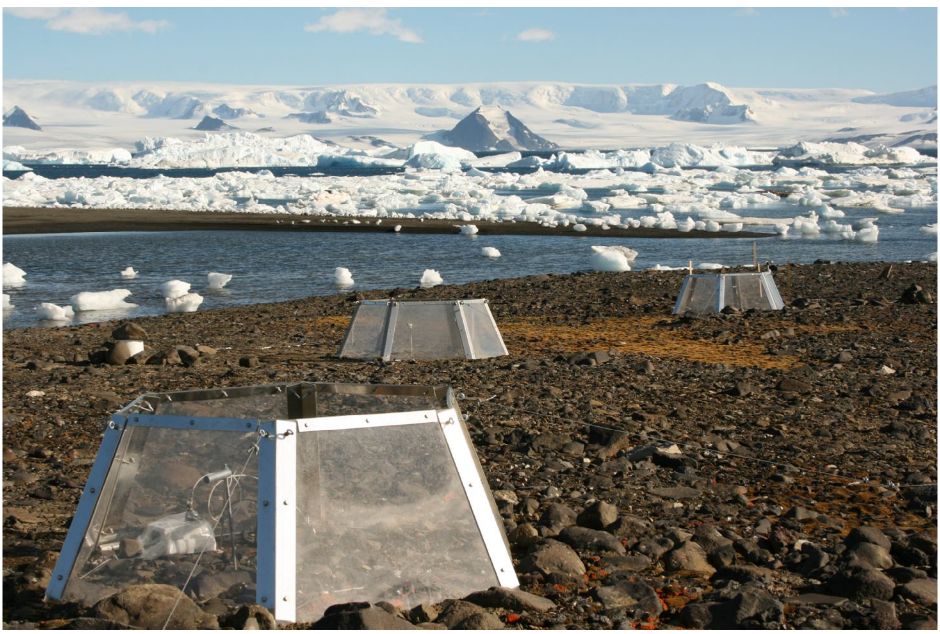

Fig. 2. OTCs located close to the seashore of the northern coast of James Ross Island close to the J. G. Mendel station. Vegetation is dominated by lichens and mosses. (Photo: M. Barták).

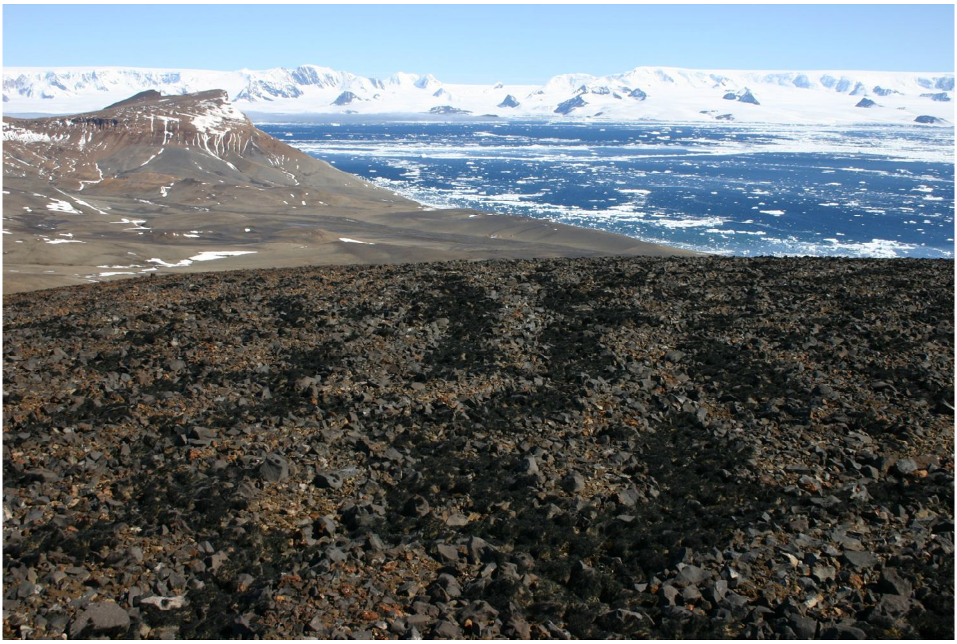

Fig. 3. Patterned ground of the Berry Hill mesa surface. Dark margins of the polygonal structure are formed by *Usnea antarctica* thalli grown in shallow depressions. (Photo: J. Gloser).

Subgroup Jan-Feb 2007	No. of days	Daily Mean Air Temperature (°C)	Daily Mean Global Radiation (W m^{-2})	Mean Wind Speed (m s^{-1})	General characteristic
A	13	1.0	255.7	4.0	Clear sky, warm with limited wind
B	14	- 0.9	151.7	6.1	Partly cloudy
C	10	- 1.6	78.4	9.0	Overcast sky, high wind speed
Mean	**37**	**- 0.4**	**168.4**	**6.1**	Whole period (Jan 25 – March 3, 2007)
Jan-Feb 2008					
A	13	2.3	256.6	4.8	Clear sky, warm with limited wind
B	13	1.9	181.9	6.7	Partly cloudy
C	6	1.2	100.2	5.6	Overcast sky, high wind speed
Mean	**32**	**1.9**	**197.0**	**5.7**	Whole period (Jan 21– Feb 21, 2008)

Table 1. Physical characteristics of the individual weather subgroups.

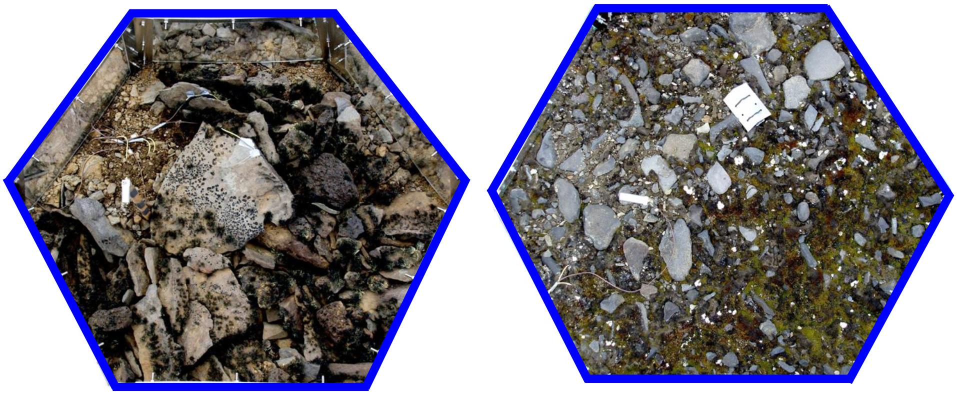

Fig. 4. Top view on the vegetation cover inside open top chambers (OTCs) located on the Berry Hill mesa (left) and seashore plot (right). The Berry Hill mesa OTC is dominated by *Usnea antarctica* and *Umbilicaria decussata* while the seashore-located OTC is dominated by moss cover.

Local climate and microclimate measurements

The climate of James Ross Island is characteristic by short summers (December - February) when the air temperature typically fluctuates between -10°C and +10°C. Mean annual air temperature is -7.0°C (2006-2015) (Ambrožová and Láska 2016, Hrbáček et al. 2016b). The warmest month is January with the mean temperature of 0.1°C while the coldest being August in the course of which the monthly mean temperature is -13.9°C. Minimum air temperatures may drop below -20°C (Fig. 5) during episodic short-term events when the south–southwest winds reach James Ross Island (Ambrožová et al. 2019). Similarly to air temperature, short-time fluctuations of relative air humidity are related to fast changes in patterns of atmospheric circulation; from the Antarctic continental (cold) to oceanic (warm) advections. Model rainfall estimates range between 300 to 500 mm water-equivalent per year (van Lipzig et al. 2004). The snow cover depth varies significantly due to the strong effect of wind, and being at the maximum of 30 cm at the flat coastal areas (Hrbáček et al. 2016a).

Within the OTC and neighbouring outside control plot of the same area (1.27 m^2), thermocouple temperature sensors (T type) were installed and connected to a multichannel data logger (Minicube VV/VX, EMS, Brno, Czech Republic). The sensors were placed (*a*) into the height of 30 cm above surface, into the ground to the depths of (*b*) 5 cm, (*c*) 10 cm, (*d*) 15 cm, and also (*e*) into the surface vegetation cover (moss or lichen). When the surface was not covered by vegetation, rock or stone surface temperature was measured. The temperature data were taken in 30-min. intervals throughout a year. For analysis of OTC effects on microclimate, austral summer periods of 37 d (Jan 25^{th} to March 3^{rd} 2007), 32 d (Jan 21^{st} to Feb 21^{st} 2008), 41 d in 2017 (Jan 21^{st} to March 3^{rd} 2017) and 2018 (Jan 21^{st} to March 3^{rd} 2018) were selected. Several temperature characteristics were evaluated (*see* Table 1). Starting from 2008, relative air humidity (RH) has been measured. RH probes (Minikin TH, EMS, Brno, Czech Republic) were placed both into the OTCs and at outside control plots to the ground level and shielded by an aluminium plate to avoid direct sunshine and induced warming of the probes. RH was recorded in 30-min. intervals. In a close vicinity of the coastal OTC location, an automatic meteorological station (Edge Box V12, EMS, Brno, Czech Republic) was located and a full set of microclimate parameters recorded: atmospheric pressure, 2-m air temperature and relative humidity, global solar radiation, surface temperature, ground temperature in different depths, and wind speed and direction (measured at the height of 10 m). Apart from that, incident solar radiation was measured closely: total UV radiation, erythemally effective UV-B radiation, photosynthetically active radiation (for instrumental setting and measurement details *see* Prošek et al. (2004), Láska et al. (2011b). Each day of the above-specified measuring periods was classified according to global radiation, air temperature, and wind speed. Subsequently, subgroups of days with typical prevailing weather were selected (*see* Table 1). Analysis of OTC effects on inside microclimate was then performed for the whole measuring period and the respective subgroups.

Results

Air and ground temperature

General climatic conditions of the periods of (1) Jan - Feb 2007 and 2008, and (2) Jan - Feb 2017, 2018 at the J. G. Mendel station are given in Fig. 6, and Fig. 7 respectively. Variation in global radiation intensity (GR) showed proportion between fully sunny and cloudy days within the investigated periods. The courses reflected cyclogenesis and related cloudiness typical for this particular region of Antarctica. In 2007, sunny and overcast periods regularly changed each of which lasted 3-4 d (Fig. 6). This was apparent in GR time series that exhibited low values of daily maximum (150-500 W m^{-2}) when atmospheric fronts were passing James Ross Island. High GR intensities (> 700 W m^{-2}) were recorded during anticyclogenesis. Occurrence of high amount of the clouds coincided with atmospheric front zones and reduced GR intensity. Reduction in GR was closely linked with air temperature decrease, especially during February 2007 (*see* Fig. 6). In 2008, such periodicity of GR and air temperature was much less apparent, particularly due to reduced number of cyclones. Generally, the late austral summer seasons of 2007 and 2008 differed to a great extent. Austral summer of 2008 was warmer with much less precipitation (only 1 day with a snowfall) than that of 2007 (13 d with a snowfall). Fluctuation in GR was found in 2017 and 2018 data to only limited extent. This was particularly true for the period of Feb 9th to Feb 21st 2017 and the period from Jan 26th to Feb 11th 2018.

In January-March 2007, there was an evident difference in OTC-induced air temperature shift measured at 30 cm height inside OTCs between seashore location and the Berry Hill mesa. While mean daily shift reached 0.9°C in coastal OTCs, it was apparently higher (1.7°C) at the mesa. The mean temperature difference at 30 cm height was much lower in 2008 (*cf.* 1.1°C for coastal site and 1.4°C for the Berry Hill mesa) than in 2007. For 2007 and 2008, the temperature shift was much higher (*see* Table 2) on calm sunny days (Subgroup A) and apparently lower for overcast windy days (Subgroup C).

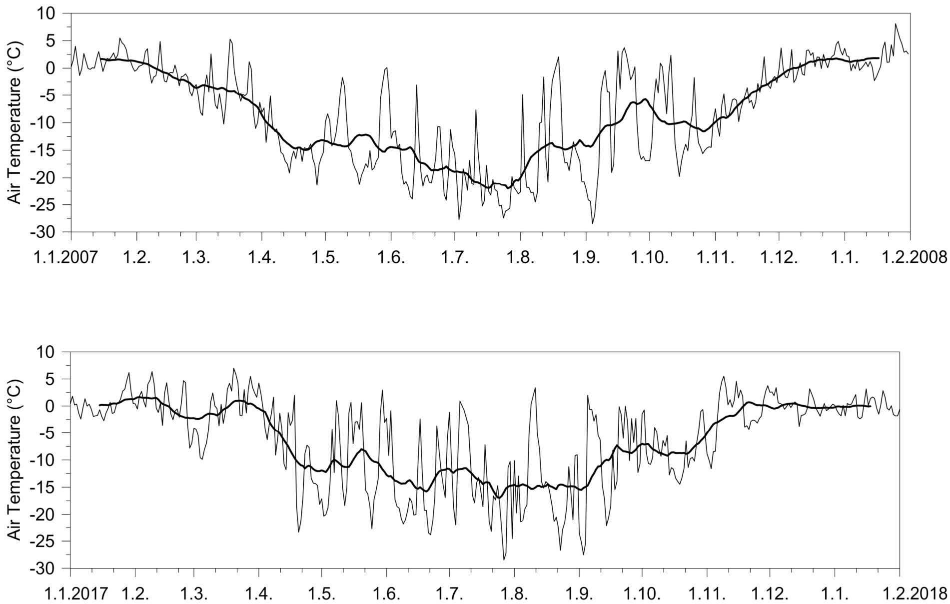

Fig. 5. Variability of mean daily air temperature at the J. G. Mendel station (James Ross Island) in the period of January 2007 to February 2008 (upper panel), and January 2017 to February 2018 (lower panel). Thick line represents values smoothed by the Gaussian filter for 30 days.

Weather Subgroup	DIFF air temperature 30 cm above surface	DIFF air temperature 30 cm above surface	DIFF ground temperature 2 cm below moss	DIFF ground temperature 10 cm below surface	DIFF ground temperature 10 cm below surface	DIFF *Usnea antarctica*	DIFF *stone surface with Umbilicaria decussata*
Jan-Feb 2007	Seashore Mendel station	Mesa Berry Hill	Seashore Mendel station	Seashore Mendel station	Mesa Berry Hill	Mesa Berry Hill	Mesa Berry Hill
A	1.6 ± 0.5	2.5 ± 1.1	1.9 ± 1.8	0.7 ± 1.1	1.6 ± 3.8	1.6 ± 1.3	3.0 ± 1.8
B	0.7 ± 0.4	1.5 ± 0.7	0.6 ± 1.2	0.1 ± 0.8	- 0.2 ± 1.9	1.2 ± 1.9	2.5 ± 2.4
C	0.4 ± 0.4	0.9 ± 0.4	- 0.1 ± 0.5	- 0.2 ± 0.5	- 1.6 ± 1.8	0.2 ± 1.0	0.3 ± 1.2
Whole period	**0.9 ± 0.7**	**1.6 ± 1.0**	**0.9 ± 1.5**	**0.2 ± 0.9**	**0.1 ± 2.9**	**1.1 ± 1.5**	**2.1 ± 2.1**
Jan-Feb 2008	Seashore Mendel station	Mesa Berry Hill	Seashore Mendel station	Seashore Mendel station	Mesa Berry Hill	Mesa Berry Hill	Mesa Berry Hill
A	1.6 ± 0.5	2.0 ± 0.9	1.3 ± 0.9	0.4 ± 0.4	2.8 ± 1.1	0.9 ± 0.5	2.8 ± 1.3
B	0.9 ± 0.4	1.1 ± 0.7	1.0 ± 0.3	0.3 ± 0.2	1.5 ± 1.1	0.8 ± 0.8	2.3 ± 1.3
C	0.5 ± 0.3	0.8 ± 0.8	0.5 ± 0.6	-0.1 ± 0.3	0.6 ± 0.8	1.1 ± 1.1	1.3 ± 0.5
Whole period	**1.1 ± 0.6**	**1.3 ± 0.9**	**1.0 ± 0.7**	**0.2 ± 0.3**	**1.9 ± 1.3**	**0.9 ± 0.7**	**2.3 ± 1.3**

Table 2. Daily mean temperature differences (DIFF) and their standard deviations between OTC-located temperature sensors and outside control for the seashore location close to the J. G. Mendel station and Berry Hill mesa.

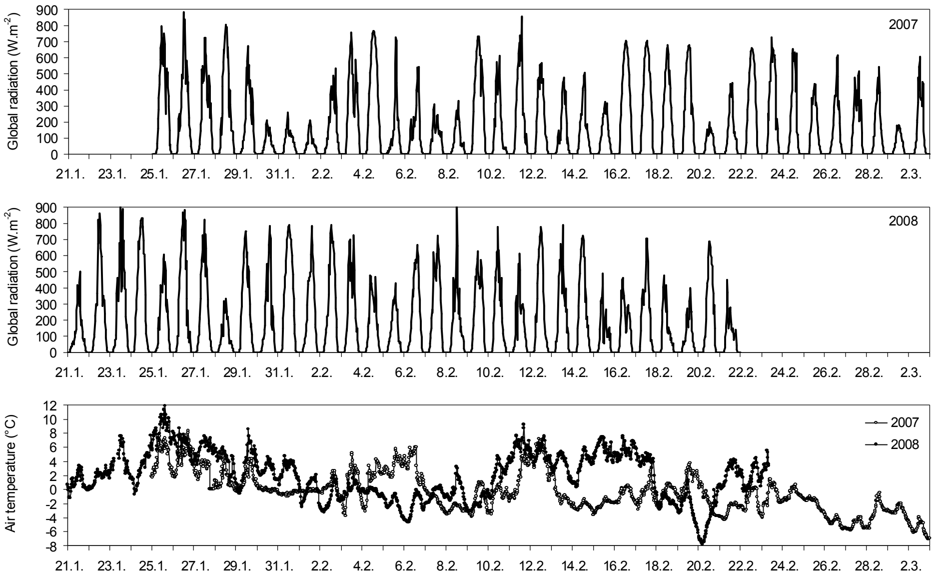

Fig. 6. Variability of global radiation intensity (upper two panels) and 30-min. air temperature (lower panel) observed during the austral summer months of 2007 and 2008 at the J. G. Mendel station.

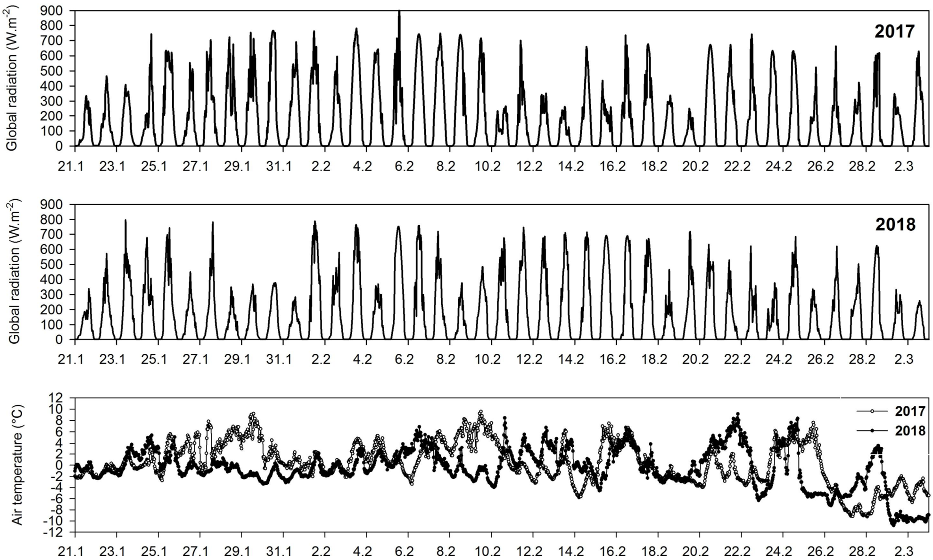

Fig. 7. Variability of global radiation intensity (upper two panels) and 30-min. air temperature (lower panel) observed during the austral summer months of 2017 and 2018 at the J. G. Mendel station.

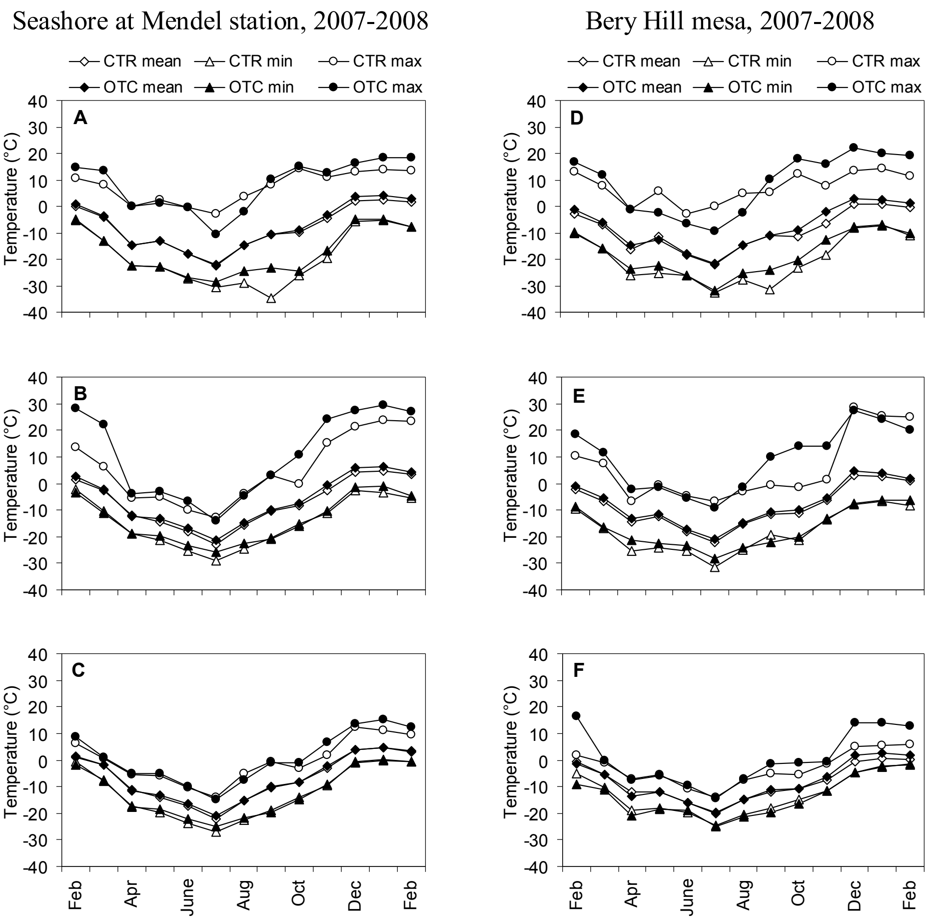

Fig. 8. Annual variations (Feb 2007 - Feb 2008) of monthly mean and extreme temperatures for the seashore location close to the J. G. Mendel station (A, B, C – left column) and Berry Hill mesa (D, E, F, – right column). *Key to the abbreviations:* CTR – control plot, OTC – inside open top chamber. Temperature was measured at the height of 30 cm above surface (A, D), in a moss carpet in the depth of 2 cm (B, E), in the ground at 10 cm depth (C, F), and in the clump of *Usnea antarctica* (E).

Seemingly large standard deviations (*see* Table 2) were due to the fact that 24 h means were taken for calculation. The means of temperature shift for the *A*, *B*, and *C* weather types were thus underestimated because they were lowered due to night temperatures. Temperature difference between OTCs and control was higher when day-light period was considered (data not shown).

Temperature measured inside OTCs at the surface and subsurface (the depth of 2 cm) levels of investigated lichens and mosses showed a shift, the extent of which differed between individual weather subgroups. Generally, mean daily difference between OTCs and their outside was the highest on the *A* days, medium on the *B* days, and close to zero on the days with prevailing *C* weather type. Extreme single values of temperature maxima were recorded on basalt stones bearing individual thalli of *Umbilicaria decussata* and *Usnea antarctica*.

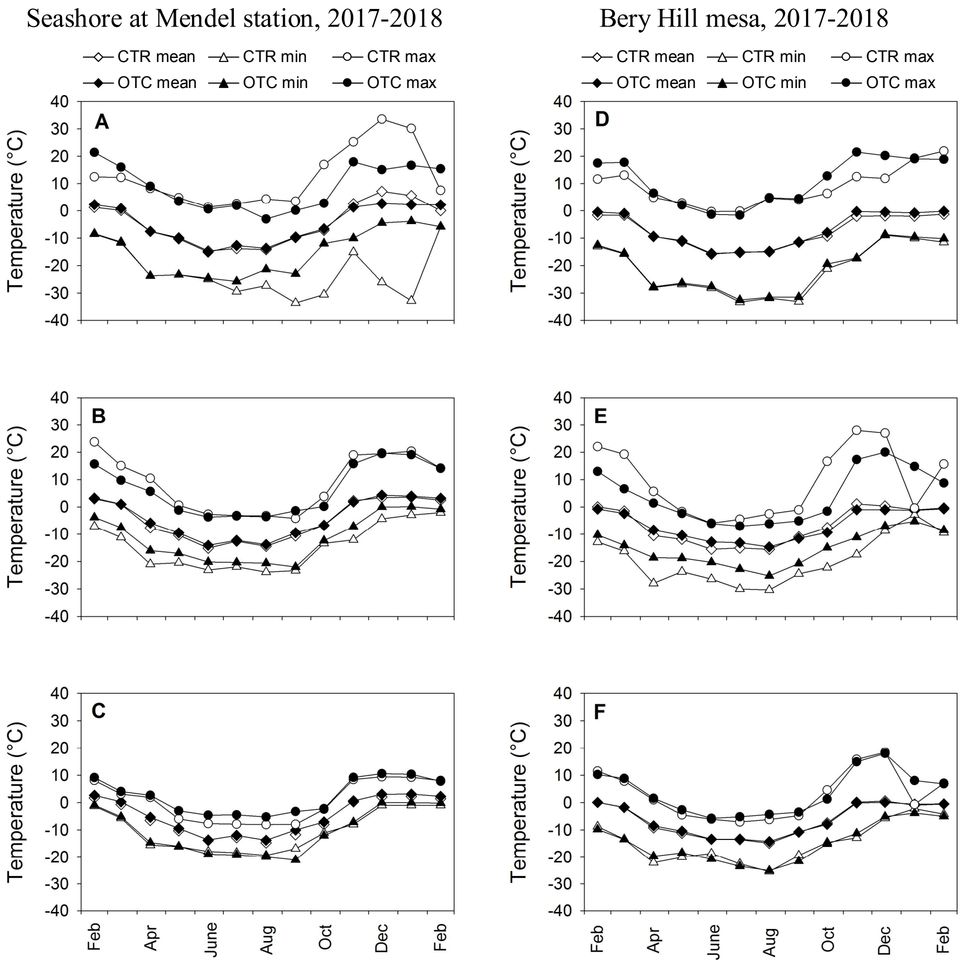

Fig. 9. Annual variations (Feb 2017 - Feb 2018) of monthly mean and extreme temperatures for the seashore location close to the J. G. Mendel station (A, B, C – left column) and Berry Hill mesa (D, E, F, – right column). *Key to the abbreviations*: CTR – control plot, OTC – inside open top chamber. Temperature was measured at the height of 30 cm above surface (A, D), in a moss carpet in the depth of 2 cm (B, E), in the ground at 10 cm depth (C, F), and in the clump of *Usnea antarctica* (E).

At midday hours on the *A* days, it reached actual maxima as high as 28.6°C and 24.2°C (2007, 2008), respectively. Such high values were accompanied by large mean differences between *U. decussata* sites inside and outside OTCs: 3.0°C and 2.8°C for the 2007 and 2008 summer subseasons, respectively (mesa, *see* Table 2, the last column).

For other mosses and lichens, the mean daily difference was less pronounced on *A* days. In contrast to the *A* weather type days, there were almost no temperature differences apparent between the inside and outside of OTCs on the *C* days. The ground temperature differences at 10 cm depth between OTCs and their outside plots were highest on the *A* weather type days. On such days, mean daily difference was higher at the mesa than at seashore. On the *C* days, the difference in ground temperature was even negative, indicating that there was a lower temperature below the OTCs than outside at the control plot. This effect was caused by snow accumulation inside OTCs during stormy days that lasted longer than outside (for detailed analysis, *see* Discussion). The yearly courses of the ground temperature in the depth at 10 cm (Fig. 8 - C) and were comparable between 2007 and 2017 seasons.

This was true for mean values, as well as minima/maxima both in control and OTCs at the seashore plot (close to Mendel station). At the Berry Hill mesa, however, the difference between mean and the extreme values was found much higher throughout the year. The difference was highest for August 2017 and January 2018 (between monthly mean and minimum values), and December 2017 (between monthly mean and maximum values). Similarly, ground temperature difference between monthly mean and maximum values was found much higher for the 2 cm depth in 2017 than 2007 at the Berry Hill mesa.

Annual variations in mean monthly temperatures (2007) showed that OTC-induced increases in air, vegetation, and ground temperature were apparent mainly during the spring (September-October) and the whole of the summer period (November-February), while only small or no difference was seen during the austral winter. More pronounced temperature difference between OTCs and control plots was found in extreme temperatures. The highest differences were recorded for surface temperatures (Fig. 8 – B, E). The lowest but still significant difference between OTCs and outside temperatures was found in ground temperature at 10 cm depth (*cf.* Fig. 8 – C, F). In 2017 observations (Fig. 9) the highest difference was found between minimal and maximal monthly means of air temperature at the seashore plot close to Mendel station in Dec 2017 and Jan 2018 (*see* Fig. 9 A) while the Berry Hill mesa site did not show such large difference.

Relative air humidity

Annual variation of relative air humidity (RH) were affected by OTC only to a minor extent. The differences in RH between the values recorded inside OTC and outside control were apparent only during the period from October to March, while within the rest of the year they were not seen. At the seashore plot, monthly mean difference of RH between OTCs and control plot reached -3.7% during austral summer. At Berry Hill mesa, an opposite phenomenon was observed. Monthly mean RH inside OTCs was slightly higher (by +2.7%) then at control during the same period of austral summer. Generally, OTCs decreased slightly RH at the seashore plot, while they increased RH at the Berry Hill mesa. The different effect of OTCs on RH at seashore plot and Berry Hill mesa was even more apparent when expressed in daily means. In austral summer, daily mean RH differences between OTC and control ranged from -14 to +3% (*i.e.* general decrease of RH inside an OTC) for the seashore plote, while it ranged from -10 to +18% at the Berry Hill mesa.

Discussion

The data analysis showed that daily mean air temperature inside OTCs increased more apparently in the OTCs located at the mesa than in those located close to the seashore. As expected, the largest temperature shift inside OTCs in comparison with the control plots was found during the *A* weather type days. Apart from direct solar radiation, wind speed was the main factor affecting the extent of temperature shift inside the OTCs, since during windy days at which wind speed Ws > 10 m s^{-1}, there was hardly any difference between inside and outside air temperature.

On the other hand, during sunny days with calm or limited wind (Ws < 5 m s^{-1}), surface temperature inside / outside the OTCs was absolutely higher at the Berry Hill mesa than at the seashore experimental plot. This was caused by basalt stones that got warmer than organic substrates at the seashore location. Therefore, *Usnea antarctica* and *Umbilicaria decussata*, dominant lichen species at the Berry Hill mesa (Bohuslavová et al. 2012), had to cope with a wider range of temperature than the seashore mosses and lichens within a single day. When considering only day-light period, typically 4 h to 22 h, the difference is even higher (data not shown). In some periods (*e.g.* Feb 1st - Feb 4th 2007), increased air temperature caused snow melting inside OTCs resulting in an uncovering of bare ground, while there was still snow cover at control plots for a few more days. Contrary to that, snow accumulation persisted longer inside than outside OTCs after snowstorms, which resulted in even lower temperature inside OTCs than those outside recorded for a couple of days with prevailing *C* weather type. It might be documented mainly for the Berry Hill mesa (*see* Table 2) for surface and ground temperatures. Such situations may have consequences for water regime inside OTCs (*see* the Discussion below) and negative effects on lichens, especially their physiologically-active time (Barták, personal observations at the Berry Hill mesa in the summer seasons of 2007-2017). Earlier study of Bokhorst et al. (2016) done in the Signy Island, Antarctica, revealed that *Usnea antarctica* is a species responding relatively sensitively to manipulated warming by OTC approach.

The authors found that the cover of *Usnea antarctica* declined by 71% in the OTCs following 10 years' of warming, while much less decline was apparent in control plots. Our long-term (10 years) data on the changes in cover of the lichen species in the OTC at the Berry Hill mesa are processed (not yet published, manuscript in prep.) and they address the problem.

We demonstrated the effect of OTCs on surface and ground warming, most apparent at the depth of 10 cm at seashore OTCs. This is consistent with the evidence from many OTC sites in Antarctica. Studies carried out within last decade(s) reported OTC-induced soil warming throughout a variety of substrates and vegetation cover (reviewed by van Gestel et al. 2019). Increase of ground temperature found in our study might be of significance for promoted microbial activity of substrates (c.f. *e.g.* Huiskes 2007) and altered respiration of soil biota (Barett, Wall, unpublished data). However, increase in N and P availability in substrates might not be expected due to extremely limited sources of nutrients in the Antarctic soils located far away from bird nesting sites and sea mammal colonies. Moreover, similar studies with experimental warming conducted in polar regions in the Northern hemisphere (Jonasson et al. 1993, Robinson et al. 1995) and in maritime Antarctica (Bokhorst et al. 2007) did not prove any effect of manipulated soil warming on N, P availability.

Apart from altered temperature regime inside OTCs, there is a question to be answered to what extent water regime differs between OTCs and outside control plots since the results available from recent long-term studies (Bokhorst et al. 2007) indicated that air humidity might be strongly affected within an OTC. Our data, however, showed that OTC-induced decrease in RH was very small and apparent only at seashore plot, which was generally warmer and more diverse in moss and lichen species than the other plots on the James Ross Island. At the Berry Hill mesa, there was slight increase in RH inside the OTCs, especially during austral summer. Such a difference between the seashore and mesa site might be associated with generally colder and humid climate (Láska et al. 2011a, Ambrožová et al. 2019) affected by much more frequent occurrence of low-level clouds (*i.e.* stratus) at the mesa than at the seashore plot. The clouds obviously have their base at the altitude of 250 to 300 m a.s.l. For poikilohydric lichens and mosses at the mesa, moisture from clouds represents an important source of water. Moisture could condensate on thalli surfaces forming drops of water that are sucked by thalli immediately and thus available for physiological processes (personal observations). Another factor affecting the same or slightly increased value of RH inside OTCs (compared to control plot) at the mesa, is an active layer depth, which is much lower than that at the seashore plot (Hrbáček et al. 2018). Therefore, active layer thawing caused by the temperature shift inside OTC may produce additional water accumulated in large-in-volume pores in patterned ground at the volcanic mesa. The melt water could be released as water vapour through the pores (gaps between individual irregularly -shaped stones) and thus enrich RH in the air close to the ground. Another important factor reducing differences in RH between inside OTC and outside control is a wind, which reaches higher velocities at the mesa than at the seashore (Bohuslavová et al. 2018). Thus, we may conclude that vegetation which grows inside OTC was not affected by any OTC-induced water limitation, since OTCs brought only very small change in RH both at seashore plot and at the Berry Hill mesa.

Availability of liquid water represents a key factor for moss and lichen survival in Antarctica (Gjessing and Øvstedal 1989) since especially lichens that due to co-action above-zero of thallus temperature and wind speed may loose water from their thalli very fast (in terms of hours). Generally, there are inter-specific and even intrathalline differences in the rate of dehydration in lichens (see *e.g.* Schlensog and Schroeter 2000, Lange et al. 2001, Barták et al. 2005, 2007). In our study, lichens may have dried faster in OTCs than those at the control plots during sunny days due to OTC-induced temperature shift. That may result in a lower water potential (Ψ) in lichen thalli inside OTCs than control plots for a short period of time. Such short-term periods, however probably do not bring hydration-dependent limitation of photosynthetic processes because lichens keep high photosynthetic rate under partial dehydration (0 to -15 MPa, Hájek et al. 2006), Barták (unpublished data). On the other hand, full dehydration of lichen thalli may come earlier in OTC-located lichens than control and thus shorten physiologically active time. Therefore, higher temperature-induced limitation of photosynthesis in OTCs than at outside control plots might be related to faster dehydration and reduction of time available for photosynthesis. In this concept, OTC-located lichens may suffer from limited CO_2 uptake and fixation which might have negative effects on biomass growth and stability of lichen thalli in long-term scale. For the mosses, increased air temperature did not bring any change in hydration status (compared to control plot) since mosses might exploit some water from lower strata of moss carpet or organic substrate. They might be considered rather stable autotrophic components (compared to lichens) of Antarctic terrestrial ecosystems exposed to manipulated warming by OTC approach

(Bokhorst et al. 2016).

OTC-induced warming may affect physiological responses of Antarctic mosses and lichens in a complex manner. Photosynthesis in such organisms increases with temperature rise before reaching optimal temperature which lies between 0-15°C (Barták et al. 2007, Friedmann and Sun 2005). It is, however, obviously accompanied by progressive thallus dehydration and concurrent loss of photosynthetic activity (see *e.g.* Barták et al. 2005). In some moss species, contrastingly, temperature increase is reported to have decreased net photosynthesis due to progressive respiration (Nakatsubo 2002). Solely positive effect of OTC-induced warming on moss and lichen photosynthesis and productivity is therefore questionable and still subject to discussion.

In conclusion, the OTCs induced the highest shift in air temperature during sunny days. On these days, air temperature increase was 1.6 and 2.0°C (mean value for the both summer seasons) for the seashore and Berry Hill plots, respectively. Occurrence of sunny days, however, was 38%, while the rest of summer seasons was typical either by intermediate weather or an overcast sky, high wind speed and frequent snowfall episodes (23% of days). Even at these weather conditions, there was still OTC-induced air temperature shift varying within the range of 0.4 to 0.9°C according to the type of vegetation cover. The temperature shift was more pronounced at surface or vegetation level. Therefore, we may conclude that the OTCs located at the James Ross Island induced the temperature shift at all weather situations and might be used for a long-term study of vegetation responses to manipulated warming (Barták et al., MS in prep.). Responses of vegetation to the OTCs environment is of crucial importance since lichens have been identified biomonitors of global change recently (Sancho et al. 2019). It is because lichens seem to offer possibilities for future research that could contribute considerably to our understanding of physical drivers of climate change. Although net photosynthetic rates of lichens are apparently both low and stable in Antarctic terrestrial ecosystems, there is evidence that allocation patterns of recently fixed carbon change from stress toleration to growth in the field (Sancho et al. 2019). Therefore, there is a challenge for follow-up studies to elucidate the biodiversity changes and growth patterns of lichens witnessed in the field by the ecophysiological data gathered in OTC-based *in-situ* experiments.

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