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Indoor air quality in an Antarctic Research Station: Fungi, particles and aldehyde concentrations associated with building materials and architectural design

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Abstract

Antarctic buildings are enclosed structures, which provide shelter and logistic support to researchers and personnel who remain indoors for long periods and can be affected by air pollution caused by construction materials and activities inside buildings. This study aims to investigate the indoor air quality at the Brazilian Comandante Ferraz Antarctic Station based on measurements of aldehydes, particulate matter and fungi conducted during the Antarctic summer in 2012. The sampling site was divided in conditioned (personnel living quarters) and unconditioned (service and utilities areas) compartments and outdoor sites. A field log book was used to record the activities in the station. Furniture and plywood coverings may have contributed to high average concentrations of formaldehyde. Cooking resulted in high average levels of acrolein and fine particles in most of the monitored environments. Other activities such as cleaning, use of personal and cosmetic products, waste incineration, building maintenance and movement of people and vehicles have also contributed to particles concentration increase. Dominance of the species *Aspergillus versicolor* and *Penicillium* sp. showed potential means of fungal proliferation. Considering that the functionality and operation are similar in many Antarctic buildings, some general recommendations were outlined.

Keywords

Indoor air quality, Building materials, Human activities, Aldehydes, Particles, Antarctic station

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Introduction

Antarctica is known as the continent of peace and science. Many governments maintain permanent research stations on the continent, which provide shelter and logistic support to researchers and civil and military personnel. Until the last century, technologies for designing and constructing these stations were similar to those used for buildings in other locations on the planet even though Antarctic is very distant from

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urban areas and has an inhospitable environment.[1] However, after the first heroic expeditions to the continent followed by concerns of housing safety for human settlements under extreme weather conditions in the region, aspects related to environmental impact caused by building construction and operation became relevant.[2]

Regardless of the research station nationality, the needs and uses of these buildings are similar. Furthermore, the Antarctic-Environmental Protocol[3] emphasizes the environmental protection of the continent and requires environmental assessment for all activities carried out in and outside all research stations. Therefore, a specific case study related to one single station can be useful as reference for all other stations.

Brazil inaugurated the Comandante Ferraz Antarctic Station (Estação Antártica Comandante Ferraz – EACF) in 1984. After successive expansion and improvements, on 25 February 2012, a major fire destroyed a significant part of the building constituting the Brazilian station.[4] Considering the need to reconstruct the destroyed building and the existing data and knowledge already gathered from the station operation[5] the Brazilian Antarctic Program[6] promoted an international contest to select the design and construction techniques and materials for the new EACF. The main criterion for the project selection was sustainability, which included indoor air quality (IAQ).[7]

IAQ is an important parameter for indoor environmental quality (IEQ), which must be taken into account in the design phase in order to guarantee building environmental performance.[8] The air quality inside a building has been associated with numerous health problems such as coughing, headaches, eye, nose and throat irritation, lethargy and exacerbation of pre-existent respiratory diseases such as asthma and rhinitis.[9] However, little importance has been given to the inherent aspects of IAQ, as focus is very often on energy efficiency, primarily energy consumption and thermal comfort.[10] Nevertheless, a growing number of studies on IEQ highlight IAQ as an important parameter in environmental comfort and sustainability.[11]

The construction characteristics of a building directly influence the IAQ.[12] Factors such as the building age, internal partitioning, location and size of the apertures and ventilation type play important roles in the concentration of indoor pollutants.[13] Furthermore, construction materials may be responsible for the emission of up to 40% of pollutants in the building, which may remain in the ambient air for a short period or linger for a longer time.[14] Additionally, human activities inside these buildings could strongly affect the final concentration of indoor pollutants. These activities include cooking, smoking, sweeping, cleaning furniture, use of cosmetics, toiletries and cleaning supplies, driving and parking vehicles and the presence of humans.[15–21]

Volatile organic compounds (VOCs) are the main pollutants emitted from building materials, coatings, decor and furniture, mainly those with plywood.[18] Other internal sources such as the use of cleaning products and personal products also emit these pollutants.[22] Among VOCs, formaldehyde is an important pollutant for IAQ due to its impact on human health, as it is carcinogen.[23] The World Health Organisation (WHO) recommends an 30-min average exposure limit of 100 $\mu g/m^3$.[24] It is known that other specific aldehydes like acrolein and acetaldehyde also cause irritation in eyes, skin and mucous membranes of the human respiratory tract. Also the acetaldehyde, for example, is classified as B2, as it is a human carcinogen of low carcinogenic hazard.[25]

Fine particles with diameters of less than 2.5 µm ($PM_{2.5}$) show high levels of toxicity and penetrate deeper in the human respiratory tract.[26] In indoor environments, the majority of fine particles originate from combustion, heating, cooking or tobacco smoke.[27] The coarse fraction, characterized by particulate material with a diameter above 2.5 µm, generally results from human presence and movement associated with a low air exchange in the environment.[28] The WHO established the average concentration limits for 24 h as 25 and 50 $\mu g/m^3$ for $PM_{2.5}$ and PM_{10}, respectively.[24] For urban areas, Abt et al.[29] have shown that for low air exchange rates, 57–80% of indoor particles from 2 to 10 µm are from indoor sources, including cooking, cleaning and movement of people and only 20–43% from outdoor sources. According to Ji and Zhao,[30] outdoor-originating particles contribute the most to indoor $PM_{2.5}$ concentration, with a contribution of 54–63% when windows are closed and over 92% when windows are open. In contrast, for Antarctic buildings indoor particle generation are more important for all size ranges, since particle concentration outdoors is very small.[5]

Building typology and human activities performed in the building are also directly related to microbial air pollutants. Other factors include the amount of available substrate, meteorological and geographical conditions.[31] Fungi are considered biomarkers of air quality for microbial air pollutants. There is no uniformity in the suggested guidelines for acceptable levels of fungi in indoor ambient air. For indoor spaces, the WHO established a recommended limit of <50 CFU/m^3 when one fungus species has been detected, $\leq$150 CFU/m^3 for mixed spores and 500 CFU/m^3 for mixed spores with *Cladosporium* being dominating species.[32,33] Cabral[34] reported that there should be a higher concentration of *Cladosporium*, a predominantly universal fungus, compared to the concentration of *Penicillium, Aspergillus* and others. Any change in the proportion of these fungi may indicate the existence of a significant number of internal fungal sources, which is a characteristic of sick buildings, that is to say if concentrations of other fungi are larger than the concentration of *Cladosporium* there may be a significant number of internal fungal sources.[35]

The objectives of this study are to (i) investigate the IAQ based on measurements obtained at the EACF by assessing three groups of contaminants: aldehydes, particulate matter and fungi; (ii) associate these contaminants with emission sources in the internal environment such as construction materials and human activities used/performed in different compartments of the EACF and (iii) list a series of recommendations on building design, materials and operation as an strategy to avoid air pollutant emissions inside the building and enhance dispersion.

Materials and methods

The Antarctic Research Station

The Brazilian Comandante Ferraz Antarctic Station (EACF) is located in Admiralty Bay on King George Island at 62°05′ S, 58°24 W. EACF is populated by approximately 65 people, who are permitted to stay in the station for periods ranging from 1 month to 1 year. The EACF was founded in 1984 with a floor area of 150 m^2 to accommodate up to 12 people. The station later underwent extensive renovation, and by 2012, its surface area was approximately 2500 m^2 (Figure 1). In some compartments with air heating systems, windows are regularly left open to renew indoor air (subject to weather conditions), since there is no mechanical ventilation system in the building.

Field experiments were conducted between 13 January and 3 February 2012 during the Antarctic summer and maximum station occupancy. The concentrations of aldehydes, particles and fungi were evaluated in indoor environments, which were occupied for longer periods of time and contained more potential sources of air pollution (Figure 2). The station is divided in two large environments consisting of conditioned and unconditioned compartments. The conditioned compartments are the station personnel living quarters, encompassing the dormitories, gym, library, living room, kitchen and bathrooms. The unconditioned compartments are the service and utilities areas, which include the station maintenance workshop, energy generation, incinerator, garage, storage and a transition

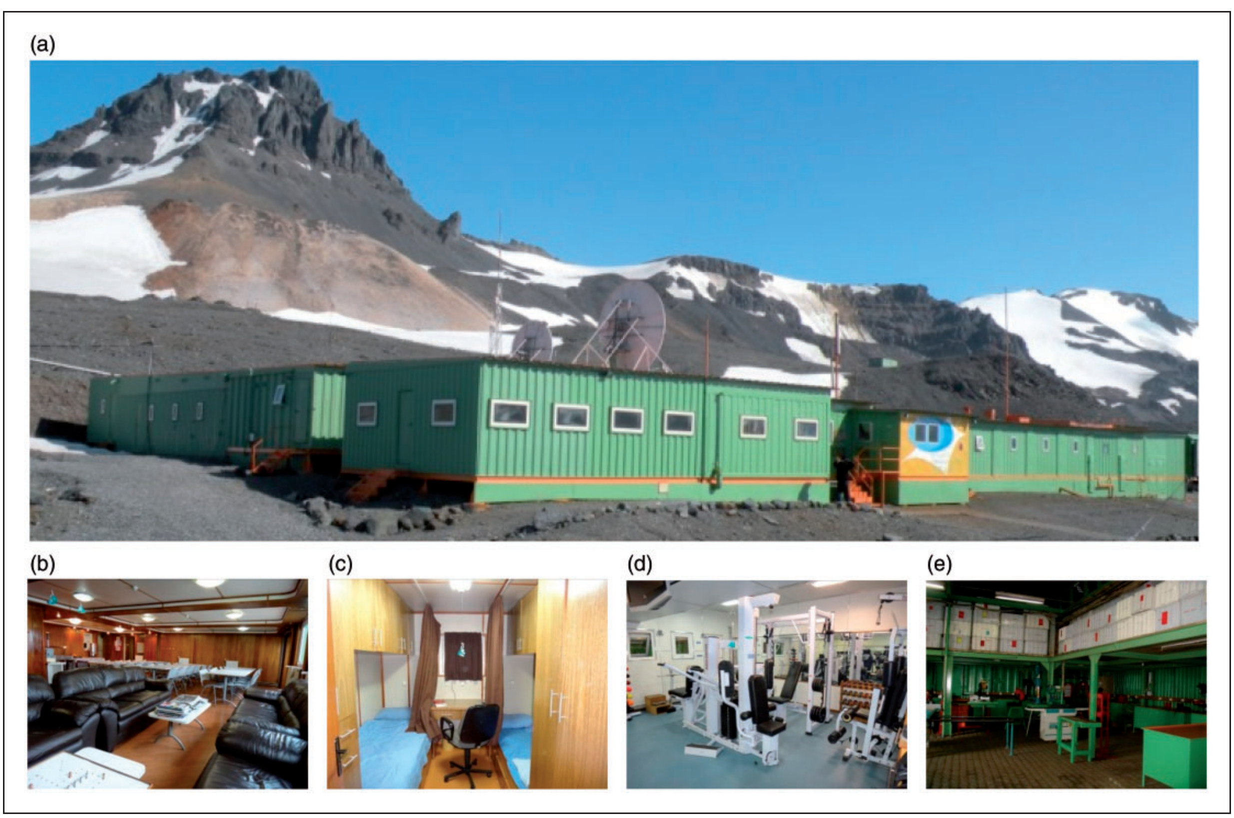

Figure 1. (a) Outdoor, (b) living room, (c) cabin 21, (d) gym and (e) workshop of EACF in February 2012.

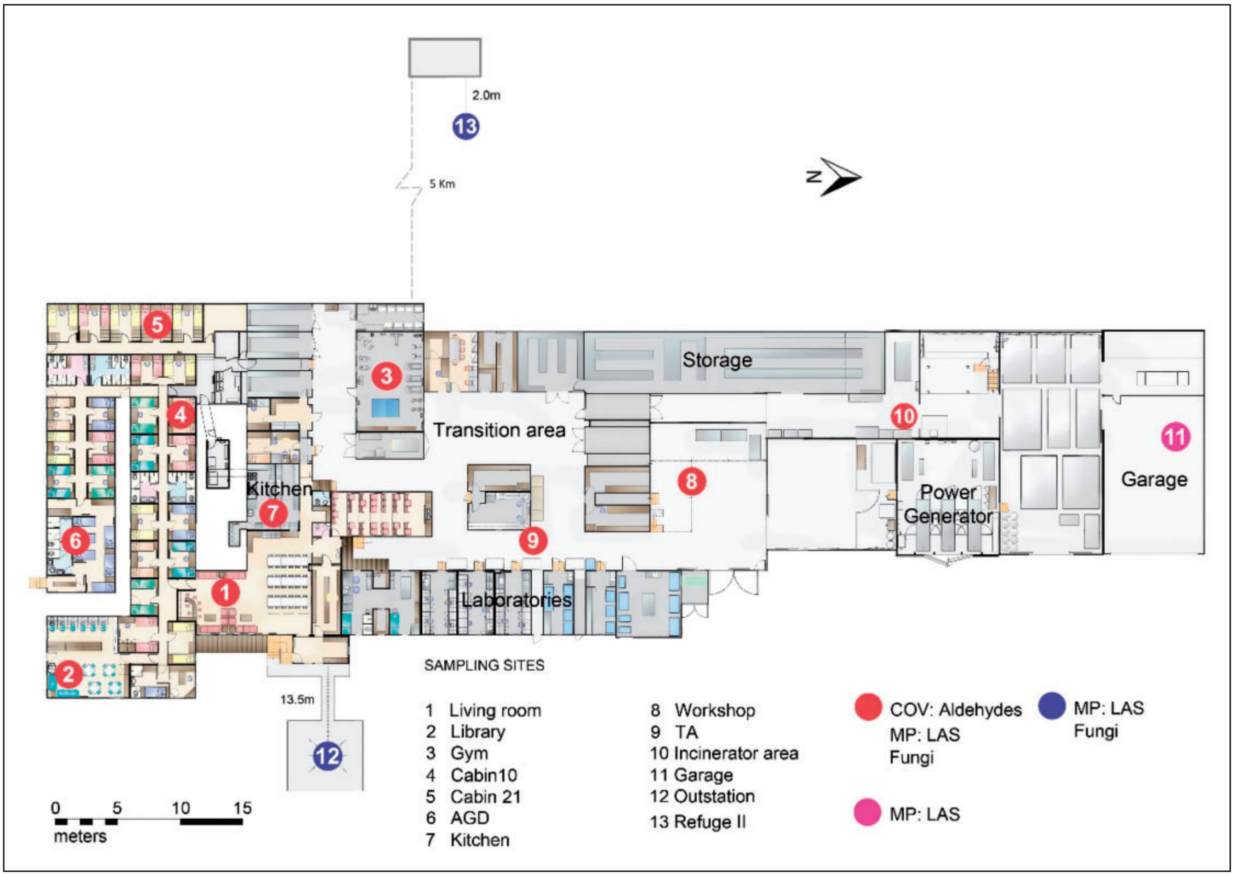

Figure 2. Schematic floor plan of the EACF indicating the sampling sites.

area (TA) between the operating sectors. While the conditioned areas have heating, the unconditioned areas have only basic protection from the outside weather (no temperature control). This arrangement is very common in Antarctic stations because the severity of the weather restricts movement between buildings, especially during winter. Thus, service areas are usually linked to living quarters and laboratories by a protected covered environment, which is called the TA.

Compartments occupied for long periods of time and contained potential sources of air pollution were selected for measurements (Figure 1). The sampling sites were grouped as follows: (i) conditioned compartments, consisting of two spaces used by all of the occupants (living room and library) and spaces for private use (Arsenal Group Dormitory – AGD, cabins 10 and 21); (ii) unconditioned compartments consisting of four service areas (workshop, incinerator area, garage and TA between the operating sectors) and (c) outdoor sites, consisting of three monitoring points known as 'outstation I' (13.5 m from the front east side of the station), 'outstation II' (6.0 m from the rear west side of the station) and 'refuge II' (5 km away from the EACF).

In addition to measurements, a field log book was made available to residents in each site to register their daily activities. Furthermore, residents completed a questionnaire based on EN ISO 16000-1/2006 for IAQ assessment.[36]

Sampling and analytical techniques

Aldehydes were sampled inside the Station using Radiello Aldehyde Samplers (Fondazione Salvatore Maugeri, Padova, Italy). These are passive samplers (cartridges) impregnated with 2,4-dinitrophenyhydrazones adsorbent in a cylindrical body. Sampling campaigns lasted seven days for all environments except the kitchen, in which sampling lasted three days. In some environments, more than one campaign was performed, totalling 16 samples and 4 controls.

After exposure, the cartridges were set in specific and identified glass tubes and stored in the refrigerator (below 4°C) in the station to be transported in the same condition to the laboratory at the Federal University of Espirito Santo in Brazil. Then, the adsorbents were put into tubes with 2 mL of acetonitrile, closed and sonicated for 30 min. The final

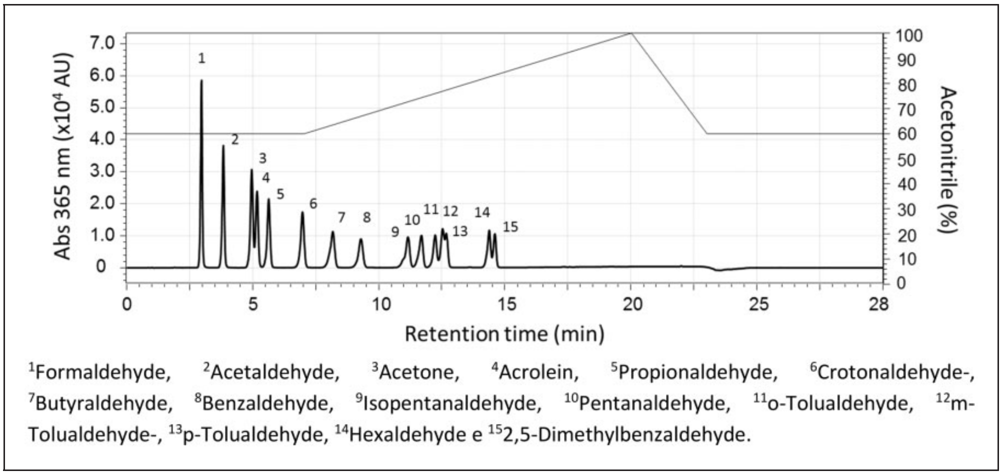

Figure 3. Chromatogram for TO11/IP-6A standard carbonyl-hydrazone at 0.1 μg/mL. [1]Formaldehyde, [2]Acetaldehyde, [3]Acetone, [4]Acrolein, [5]Propionaldehyde, [6]Crotonaldehyde-, [7]Butyraldehyde, [8]Benzaldehyde, [9]Isopentanaldehyde, [10]Pentanaldehyde, [11]o-Tolualdehyde, [12]m-Tolualdehyde-, [13]p-Tolualdehyde, [14]Hexaldehyde, [15]2,5-Dimethylbenzaldehyde.

solution of each sampler was then filtered and stored in vials, below 4°C, awaiting analysis.[37]

Sample analyses were performed using High Performance/Pressure Liquid Chromatography (Shimadzu, CBM-20A) with a UV detector operating at a wavelength of 365 nm. Qualification and quantification of the 15 aldehydes were performed by comparisons to the TO11/IP-6A standard (code 47285-U – Supelco, Bellefonte, PA, USA) including formaldehyde, acetaldehyde, acetone, acrolein, propionaldehyde, crotonaldehyde, butyraldehyde, benzaldehyde, isopentanaldehyde, pentanaldehyde, o-tolualdehyde, m-tolualdehyde-, p-tolualdehyde, hexaldehyde and 2,5-dimethylbenzaldehyde (Figure 3). Figure 4 presents some example of the chromatograms obtained for samples collected in cabin 21, AGD and Workshop.

The limits of detection and quantification were determined using standard solutions at concentrations of 0.10, 0.20, 0.30, 0.40 and 0.50 μg/mL. The instrument detection limit of all aldehydes measured was 0.07 μg/mL except for isopentanaldehyde (0.14 μg/mL) and pentanaldehyde (0.08 μg/mL). The quantification limit for aldehydes varied from 0.22 μg/mL to 0.46 μg/mL, where the lower values are for formaldehyde and butyraldehyde and the larger value for isopentanaldehyde. In this sense, the detection limit varied from 0.13 to 0.44 μg/m^3 and the quantification limit varied from 1.20 to 4.00 μg/m^3. The uptake rates of diffusive sampling of aldehydes varied from 11 mL/min for butyraldehyde to 99 mL/min for formaldehyde.[37]

Indoor and outdoor particles were analysed using an Optical Laser Aerosol Spectrometer (LAS) (Dust Monitor 1.109, Grimm Technologies, Germany) that measures 31 sizes bins ranging from 0.25 μm to >32 μm at a 1-min frequency and gives the mass and number concentration of particles distributed by diameter. The temperature, humidity and air velocity were also measured. For indoor areas, measurements were conducted for 24 h in all compartments. For outdoor areas, the monitoring period depended on weather conditions; particles were monitored at outstation I for 7 h and in Refuge II for 2 h. The measurements were not conducted simultaneously at outside and inside sampling sites.

Fungi were collected by a sampler of one stage CF-6 Andersen Impactor (Criffer, Brazil) with an air flow of 1.698 m^3/h (28.3 L/min) for approximately 5 min. To collect samples, petri dishes with Sabouraud Dextrose Agar culture with 2% of glucose, and chloramphenicol and pH 5.6 were used in this work by promoting the growth of a range of different fungal species.[38]

The quantitative results were calculated in Colony Forming Units (CFU/m^3), and the samples were identified by macro and micromorphology using an Olympus BX41 microscope. Three collections of fungi were performed on three days inside and outside the Station, resulting in 36 samples.

Results and discussion

Aldehydes

The average concentration of total aldehydes calculated based on 16 samples in the EACF was 177 ± 99.3 μg/m^3, above the concentration recorded by other studies in indoor areas located in urban regions. For instance, Orecchio et al.[39] analysed indoor aldehydes in museums, libraries, laboratories, corridors, meeting

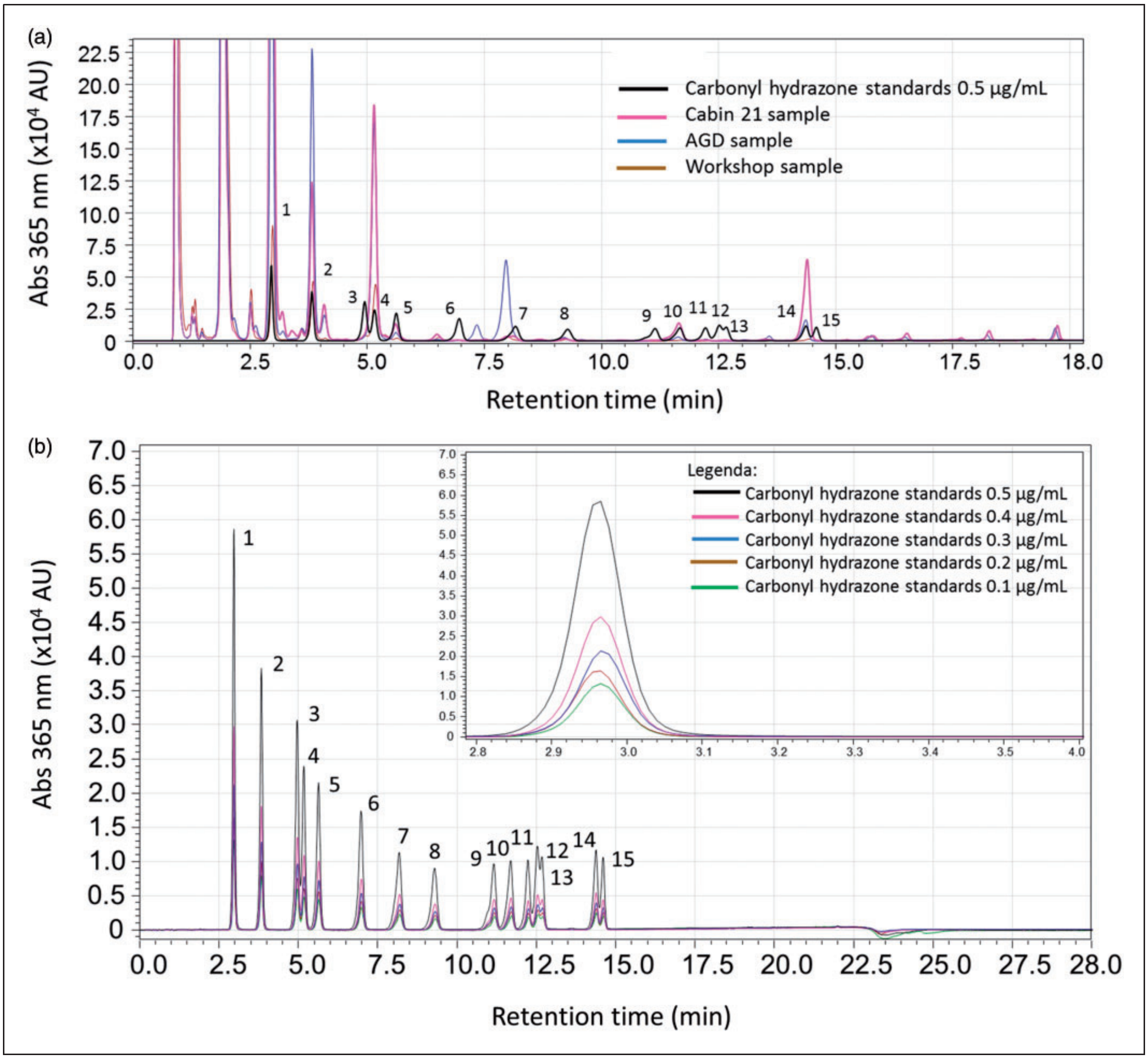

Figure 4. Chromatogram of (a) samples collected in cabin 21, AGD and Workshop and standard at 0.5 µg/mL and (b) standards at 0.1, 0.2, 0.3, 0.4 and 0.5 µg/mL, pointing out the relationship between area and concentration. The formaldehyde peak is shown in detail on the top right corner.

rooms, photocopying room, machine shop and terrace in Palermo, Italy. The authors found formaldehyde concentrations ranged from 2.6 to 85 µg/m^3 (median = 32 µg/m^3), while the sum of other aldehydes ranged from 2 to 25 µg/m^3 (median = 2.4 µg/m^3). Another study that analysed the indoor aldehyde concentrations in Chinese residences found the mean concentration of the total carbonyl compounds in summer was 222.6 µg/m^3, higher than that in winter (68.5 µg/m^3).[40]

In our study, the highest aldehyde concentration was related to acrolein, followed by acetaldehyde, formaldehyde and hexanaldehyde, which represented 24.8%, 21.0%, 18.5% and 15.4% of the total aldehydes, respectively. In general, these compounds are found in similar or higher concentration in other types of internal environments.[41,42]

Figure 5 shows that the highest 7-day-mean acrolein concentration was found in cabin 10 (68.6 µg/m^3) followed by cabin 21 (63.2 µg/m^3), library (59.4 µg/m^3) and AGD (59.0 µg/m^3). These concentrations were even higher than the 3-day average concentration in the kitchen (47.7 µg/m^3) and the 7-day average concentration in the living room (42.2 µg/m^3). The high levels of acrolein found in the Antarctica station in nearly all compartments may be explained by the constant cooking activity in the building with all doors and windows closed most of the time. In addition, the kitchen air exchange system was deficient, as the cooker hood geometry was not appropriate for the cooktop and the flow rate was not sufficient to capture all fumes emitted. Seaman et al.[43] found high acrolein concentrations in the range of 26.4 to 64.5 µg/m^3 inside a small

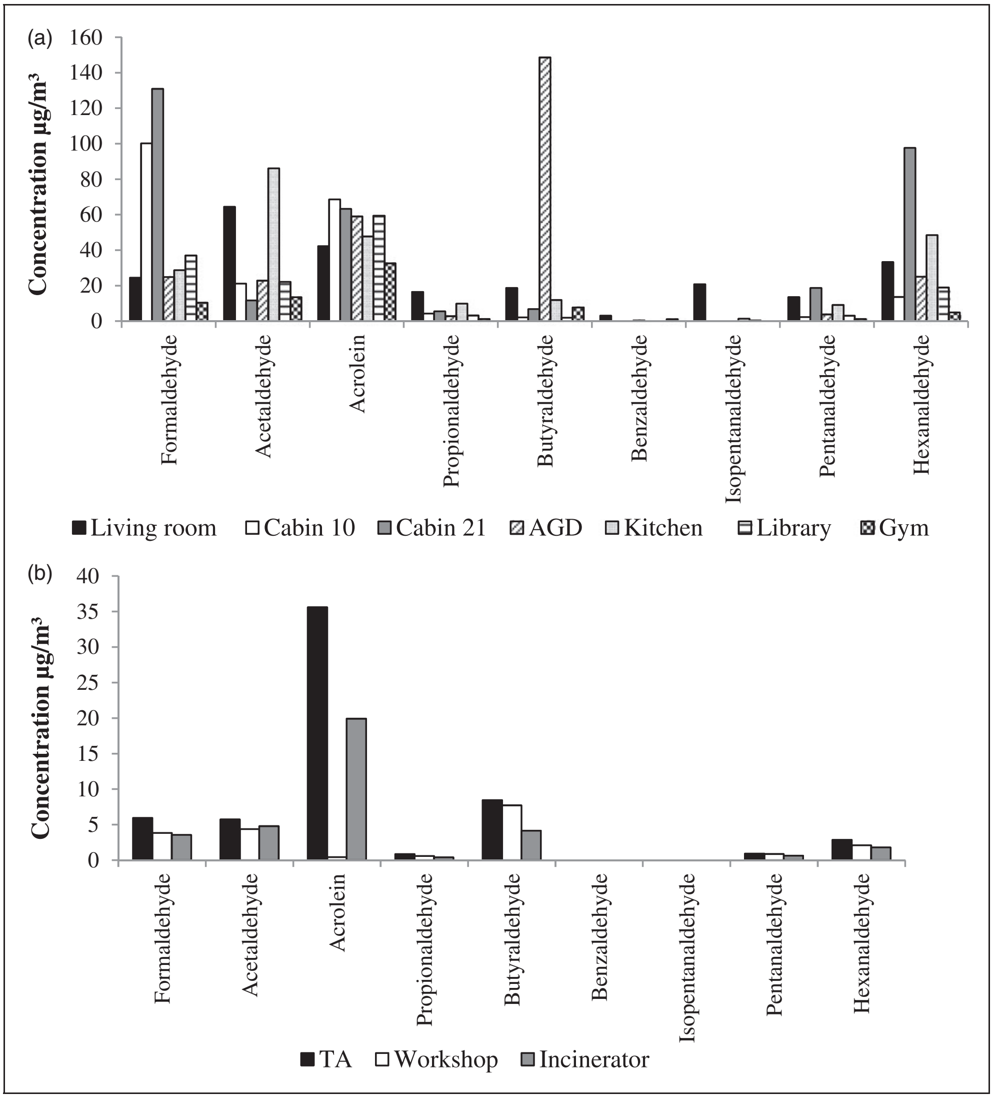

Figure 5. Mean concentrations of aldehydes found in the (a) conditioned and (b) unconditioned compartments.

one-room apartment with the door closed, during cooking using vegetable oils in the USA. According to these authors, the half-life for acrolein was 14.4 ± 2.6 h, indicating that the indoor concentration of this substance may persist for a considerable time after cooking in a poorly ventilated building.

Although the acetaldehyde 3-day average concentration in the kitchen (86.0 µg/m^3) and 7-day average concentration in the living room (64.5 µg/m^3) were above the guidelines for indoor concentrations of some countries, such as Japan (48 µg/m^3),[44] the values are comparable with values found in urban housing. For instance, Gilbert et al.[45] reported acetaldehyde concentrations in air samples taken in Canadian houses ranging from 4.4 to 79.1 µg/m^3. Park and Ikeda[46] reported concentrations in Japanese houses ranging from 25.0 to 220 µg/m^3 and Kato et al.[44] found concentrations in newly built houses in Tokyo ranging from 31.0 to 469 µg/m^3.

Antarctic stations have areas for meeting, socializing and eating for inhabitants, which are constantly cleaned because of their heavy use. In the EACF, the living room and kitchen play these roles. Therefore, they are cleaned with bleach, alcohol and other cleaning products approximately four times a day, every day, unlike other station compartments that are cleaned once a week. Domestic cleaning products are main sources of acetaldehyde and other aldehydes. Acetaldehyde can also be emitted by cooking[47] and wood products such as doors, wall linings and the wooden flooring laminate found in the living room as well as perfumes and polyester resins.[48]

Formaldehyde presented the highest 7-day average concentrations in cabins 10 and 21. Cabin 21 showed the highest concentration of formaldehyde, most likely because it was part of the recently built station wing, which was first occupied in 2012. These cabins had laminated wood floorings and industrial furniture made of plywood. Both of these materials have been identified as major indoor emission sources of formaldehyde.[14] Cabin 21 also showed the highest 7-day mean concentration of total aldehydes among all monitored sites. Plywood is commonly found in the lining and furniture in Antarctic stations as it is a good thermal protection and ease to install.

The library showed significant levels of formaldehyde and acetaldehyde. A variety of VOCs are emitted from the degradation of paper and other cellulose-based materials, including aldehydes such as formaldehyde and acetaldehyde.[49] Typical library furniture, composed of laminated tables and workstations, is a major source of formaldehyde in these spaces.[50]

The highest 7-day average concentration of hexanaldehyde was observed in cabin 21 but not cabin 10, which contained the same construction materials. According to Marchand et al.,[51] hexanaldehyde is emitted in abundance in the first two years after the installation of laminated wood lining in indoor spaces. As cabin 21 was built one year before measurements were conducted, it can be inferred that the laminated wood lining was the major source of hexanaldehyde in cabin 21.

For formaldehyde, the concentration differences found between cabins 10 and 21 were about 30%. These cabins also differ in terms of hexanaldehyde concentration. It was about five times lower in cabin 10 than it was in cabin 21. Therefore, there were significant differences between cabins 10 and 21. This is due to the fact that cabin 21 had been recently constructed (as the Station had been expanded less than a year before).

The maximum aldehyde concentration measured during the experimental campaign was found in the AGD (butyraldehyde). This environment has an attached drying room where working overalls of the construction and maintenance personnels were kept. Butyraldehyde was detected in emissions from diesel engines[52] and may therefore be emitted by working clothes kept in this attached environment.

Low concentrations of isopentanaldehyde, pentanaldehyde, propionaldehyde and benzaldehyde were found, equivalent to indoor concentrations reported by Clarisse et al.[53] The average concentrations of aldehydes were lower in unconditioned compartments than in conditioned compartments. Most likely it is because these unconditioned areas are larger spaces with frequent natural ventilation via the access door to the workshop.

Figure 6 shows the 3-day (kitchen) and 7-day average concentrations (other environments) of acrolein and formaldehyde compared to maximum limits as given by the WHO. The maximum limit of acrolein exposure recommended by the WHO for a 30-min average is 50 $\mu g/m^3$.[54] This limit was surpassed by the environments of cabin 10, cabin 21, the library, AGD and the kitchen. Similarly, the maximum formaldehyde exposure recommended by the WHO for a 30-min average[24] was exceeded by cabins 10 and 21. In this study, concentrations were averaged for three days in the kitchen and for seven days in other environments. Therefore, exceeding the WHO limit recommended for an average of 30 min of exposure to these contaminants is a matter of great worry for the health of inhabitants in an Antarctic Station.

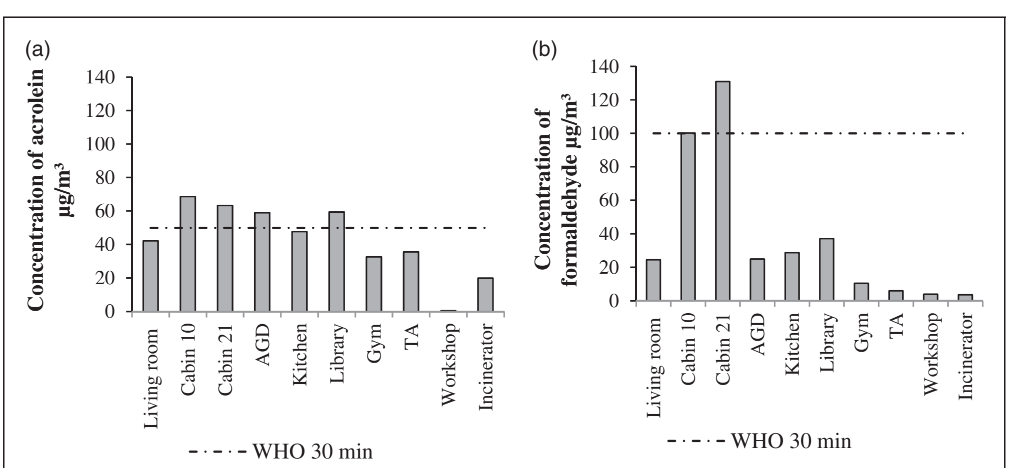

Figure 6. Three-day (kitchen) and seven-day (other environments) average concentrations of (a) acrolein and (b) formaldehyde in relation to the WHO maximum limits.

Outdoor concentrations of aldehydes were not measured in this work, since the sampling technique was not adequate for very low temperatures. Nonetheless, previous studies reported very low ambient concentrations of aldehydes in comparison to indoor measurements. Results reported by Hutterli et al.[55] indicate that formaldehyde concentration in the Antarctic atmosphere was less than 1/100 the indoor values observed in this work. Thus, it is reasonable to assume that pollutant infiltration was not very significant.

Particulate matter and environmental conditions

Table 1 shows the average number and mass concentrations of particles over 24 h as well as the environmental conditions in each monitored location. Monitoring conducted in the kitchen was not considered in the analysis because a social gathering occurred in the room and a fog machine was used on the day of the measurement, which would influence particles concentrations.

The highest 24-h-average number concentration for PM_1, $PM_{2.5}$, PM_{10} and TSP were found in conditioned compartments (199.7, 201.9, 202.3 and 202.3 particles/cm^3, respectively), followed by unconditioned compartments (185.2, 187.5, 187.9 and 187.9 particles/cm^3, respectively) and the outside (35.2, 35.6, 35.6 and 35.6 particles/cm^3, respectively). These values indicate the importance of indoor particle generation.

Highest 24-h-average mass concentrations for PM_1, $PM_{2.5}$ and PM_{10} were also recorded in conditioned compartments (12.0, 22.0 and 52.4 $\mu g/m^3$, respectively), followed by unconditioned compartments (9.7, 20.1 and 46.5 $\mu g/m^3$, respectively), except for the TSP, whose highest mean value was found in unconditioned compartments (91.5 $\mu g/m^3$) rather than the conditioned compartments (77.2 $\mu g/m^3$). These values were also lower than 24-h-average mass concentrations typically found indoors in urban areas.[56] However, PM_{10} found in the conditioned compartments exceeded the WHO limit.

Among these conditioned compartments, the gym environment showed highest 24-h-average number concentrations of $PM_{2.5}$ and PM_{10} (769.6 and 769.7 particles/cm^3, respectively) as well as highest mass concentration of $PM_{2.5}$ (44.5 $\mu g/m^3$), exceeding the WHO limit. However, the first highest 24-h mass concentration of PM_{10} was found in cabin 21 and the second highest mass concentration of PM_{10} was found the living room. The WHO limit was exceeded in both places.

During the gym monitoring period, a barbecue was made in the TA environment, which explains the large number and mass concentration of fine particles shown in this area.[57] In cabins 10 and 21, the use of personal spray products was recorded, which was more intense in cabin 21 resulting in larger average mass concentration of both coarse and fine particles in this environment.[15] In relation to the living room, a significant mass concentration of fine particles may be associated with cooking activities carried out in the integrated kitchen environment.[58]

Barbecue activity in a Brazilian station is associated with cultural practice and may not represent similar situations in stations of other nationalities. However, even if sporadically held, barbecues must be taken into consideration because this activity could significantly influence the average level of particles in the indoor air. Cooking activity and the use of personal products within the cabin environments without attached bathrooms are probably common in Antarctic stations, representing a worrisome situation for human health.

Living rooms or lounge areas are commonly used for meetings, social gatherings and meals in Antarctic stations. These areas are characterized by constant people traffic and intense use, which explains the 24-h-average concentration of coarse particles found in this environment.[59] Moreover, on the day of monitoring, the living room was influenced by cleaning activities such as sweeping the floor and cleaning the furniture, which contributed to the suspension of fine and coarse particles previously settled on the floor and furniture and causes the increase of particles number and mass concentration.[60] Similarly, activities of people and clothing movement could cause resuspend dust to be released from furniture and soil, and these could strongly influence coarse particles concentration in the AGD.

The library is located in a more private area of the station and is not as often occupied as other compartments. As a consequence, it presented the lowest 24-h-average mass concentrations of fine and coarse particles.

The highest values of 24-h-average mass concentrations for all particle sizes in the unconditioned compartments were found in the workshop, which represents the operational area for maintenance services. The workshop is located near the EACF machinery sector, which houses the power generation system that runs on diesel. This configuration, along with the movement of people and resuspension and infiltration of dust from external soil by natural ventilation through access doors could contribute to exceeding the 24-h-average WHO limit for PM_{10}.

Antarctic buildings usually have protected environments that are not necessarily conditioned, designed especially for parking vehicles and supply storage. The arrangement of these environments and loading and unloading operations could significantly influence the vehicle traffic in the station. In the EACF, the traffic

Table 1. Environmental conditions and PM concentrations inside and outside the EACF.

		Number of particles/cm^3; (st.d.)				Concentration μg/m^3; (st.d.)				Environmental conditions		
Sampling sites	Sampling time	PM_1	$PM_{2.5}$	PM_{10}	TSP	PM_1	$PM_{.2.5}$	PM_{10}	TSP	T (°C)	RH(%)	Air velocity (m/s)
Conditioned environments												
Living room	01/17/2012 Tuesday (00:00–23:59)	194.4 (306.3)	197.0 (307.2)	197.0 (307.4)	197.0 (17.7)	10.9 (17.7)	19.6 (23)	59.0 (98)	88.6 (134.5)	24.2 (1.0)	29.8 (4.2)	0.0 (0.0)
Cabin 10	01/21/2012 Saturday (16:00–15:59)	72.2 (122)	74.1 (125.4)	74.3 (125.5)	74.3 (125.5)	6.3 (10.5)	14.2 (24.8)	29.7 (38.2)	46.4 (54.0)	28.7 (0.6)	27.8 (2.0)	0.0 (0.0)
Cabin 21	01/23/2012 Monday (15:00–14:59)	108.3 (203.7)	114.4 (217.8)	115.3 (220.0)	115.4 (220.0)	10.4 (21.2)	39.3 (90.9)	109.4 (227.0)	152.0 (245.2)	24.3 (0.5)	31.4 (7.0)	0.0 (0.0)
AGD	01/24/2012 Tuesday (15:00–14:59)	21.9 (16.4)	23.0 (17.3)	23.4 (17.8)	23.4 (17.7)	1.9 (1.3)	7.7 (7.2)	47.0 (56.5)	91.9 (91.5)	26.0 (1.2)	28.2 (3.1)	0.0 (0.0)
Library	01/25/2012 Wednesday (17:00–16:59)	33.2 (57.2)	34.0 (58.2)	34.1 (58.3)	34.1 (58.3)	3.7 (7.5)	6.7 (10.1)	19.8 (32.8)	33.4 (64.0)	25.0 (1.9)	25.5 (1.5)	0.0 (0.0)
Gym	01/28/2012 Saturday (18:00–17:59)	768.0 (1540.5)	769.6 (1543.6)	769.7 (1543.7)	769.6 (1543.6)	38.8 (84.9)	44.5 (94.7)	49.3 (99.1)	51.0 (99.7)	27.1 (0.9)	19.0 (2.5)	0.0 (0.0)
Mean		199.7	201.9	202.3	202.3	12.0	22.0	52.4	77.2	25.9	26.9	0.0
Min		21.8	23.0	23.4	23.4	1.9	6.7	19.8	33.4	24.2	18.9	0.0
Max		768.0	769.6	769.7	769.6	38.8	44.5	109.4	152.0	28.7	31.4	0.0
SD		260.4	260.3	260.3	260.2	12.4	14.8	28.6	39.8	1.6	4.0	0.0
Unconditioned environments												
TA	01/29/2012 Sunday (19:00–18:59)	70.1 (45.4)	71.3 (46.0)	71.5 (46.1)	71.5 (46.1)	4.7 (5.0)	9.7 (7.6)	27.0 (18.6)	42.4 (35.0)	9.0 (1.4)	45.7 (4.0)	0.0 (0.0)
Incinerator	30/01/2012 Monday (01:00–00:59)	190.3 (220.7)	192.6 (222.4)	192.8 (222.5)	192.8 (222.5)	11.2 (13.9)	19.5 (21.1)	42.5 (49.7)	77.7 (144.3)	9.8 (1.8)	44.5 (4.9)	0.2 (0.2)
Workshop	02/02/2012 Thursday (14:00–13:59)	374.6 (594.6)	377.9 (594.9)	378.5 (595.2)	378.5 (595.2)	17.6 (26.8)	33.2 (29.8)	79.2 (89.8)	197.5 (374.2)	8.6 (0.7)	61.0 (2.7)	0.4 (0.3)

(continued)

Table 1. Continued

		Number of particles/cm^3; (st.d.)				Concentration µg/m^3; (st.d.)				Environmental conditions		
Sampling sites	Sampling time	PM_1	$PM_{2.5}$	PM_{10}	TSP	PM_1	$PM_{.2.5}$	PM_{10}	TSP	T (°C)	RH(%)	Air velocity (m/s)
Garage	02/03/2012 Friday (21:00–20:59)	105.7 (72.5)	108.3 (72.2)	108.7 (72.1)	108.7 (72.1)	5.3 (2.01)	18.0 (4.0)	37.4 (8.5)	48.5 (22.1)	7.1 (1.0)	64.0 (7.3)	0.7 (0.6)
Mean		185.2	187.5	187.9	187.9	9.7	20.1	46.5	91.5	8.6	53.8	0.3
Min		70.1	71.3	71.5	71.5	4.7	9.7	27.0	42.4	7.1	44.5	0.0
Max		374.6	377.9	378.5	378.5	17.6	33.2	79.2	197.5	9.8	64.0	0.7
SD		117.8	118.4	118.5	118.5	5.2	8.5	19.6	62.6	1.0	8.8	0.3
Outdoor areas												
Outstation	13/01/2012 Friday (11:10–17:59)	52.2 (27.9)	52.7 (28.0)	52.7 (28.0)	52.7 (28.0)	2.0 (0.8)	3.8 (2.2)	6.1 (3.1)	13.9 (10.4)	10.8 (1.9)	50.0 (6.3)	1.4 (0.3)
Refuge II	01/02/2012 Wednesday (16:10–17:29)	18.2 (0.8)	18.6 (0.9)	18.6 (0.9)	18.6 (0.9)	0.7 (0.0)	2.6 (0.2)	4.3 (0.5)	6.7 (3.0)	4.9 (0.5)	57.5 (2.57)	2.4 (0.2)
Mean		35.2	35.6	35.6	35.6	1.3	3.2	5.2	10.3	7.8	53.8	1.9
Min		18.2	18.6	18.6	18.6	0.7	2.6	4.3	6.7	4.9	50.0	1.4
Max		52.2	52.7	52.7	52.7	2.0	3.8	6.1	13.9	10.8	57.5	2.4
SD		17.0	17.0	17.0	17.0	0.6	0.6	0.9	3.6	3.0	3.7	0.5

EACF: Estação Antártica Comandante Ferraz; PM: particulate matter < 1 micron; PM2.5: particulate matter < 2.5 micron; PM 10: particulate matter < 10 micron; TSP: Total Suspended Particulate; T (°C): Temperature; RH (%): Relative Humidity; (st.d.): standard deviation.

of light vehicles in the TA and the different emission sources in the workshop environment may be responsible for the increase of fine particles concentration.

The metal containers that constitutes the EACF undergo intense corrosion[10] and require constant periodic maintenance, which could cause particles emission, especially in unheated areas where metal walls have no inner lining. These particles emissions could also affect the living room, which has a direct access door to these unheated areas.[5]

The Madrid Protocol,[61] linked to the Antarctic Treaty, provides strict regulations seeking to preserve the Antarctic environment as well as access control and transportation on the continent. In this sense, the incineration of organic waste is permitted and is commonly adopted in most of Antarctic buildings. However, even if certified equipment with appropriate filters was used, fugitive particles were reported in the EACF, causing the exceedance of the limit for $PM_{2.5}$ recommended by the WHO. High particles concentration due to waste incineration has already been verified by other studies in urban environments.[62,63]

Finally, lowest average mass concentrations were found outside for all particles sizes. Refuge II, located at 5 km away from the EACF, presented lower 10 min-average mass concentrations than at the Outstation, which is located closer to EACF buildings. This fact suggests that the presence of buildings could affect the outdoor air quality, which has already been reported in a previous study.[64] However, more data are needed to confirm this hypothesis.

The 24-h-average temperature and air velocity recorded in the conditioned and unconditioned areas were 25.9°C and 8.6°C and 0.0 and 0.3 m/s, respectively. As expected, the 24-h-average relative humidity was lower in the conditioned areas (26.9%) than in the unconditioned areas (53.8%). Outdoors, the 24-h-average temperature, relative humidity and air velocity were 10.8 and 4.9°C, 50.0 and 57.5%, 1.4 and 2.4 m/s for the outstation and Refuge II, respectively.

Fungi

The fungi samples were collected on 27 January 2012, 29 January 2012 and 1 February 2012. The average concentrations of fungi of the seven conditioned environments were 113, 106 and 28 CFU/m^3 and of the three unconditioned environments were 7, 247 and 2 CFU/m^3. These values were much lower if compared to studies of buildings in subtropical and tropical climates, but was similar to results of other studies conducted during winter season or in subarctic areas.[65,66] Figure 7 shows fungal concentrations in the internal and external sampling points compared to the limit recommended by the WHO.

The highest fungal concentration in the conditioned compartments was found on January 27 in the kitchen and exceeded the limit recommended by the WHO. Sampling in the kitchen was performed during dinner preparation, a common activity, with frequent movement of people in the environment. On 29 January, largest fungal concentrations were found in cabin 10. On this day, three people were talking in cabin 10 with the window and door closed during sample collection. Human presence and its activities are known to increase the amount of fungi in the environment.[67,68]

The fungal concentrations were higher in the conditioned areas than in unconditioned areas for all three days. This result may be associated with the presence of a greater number of people in enclosed spaces. The

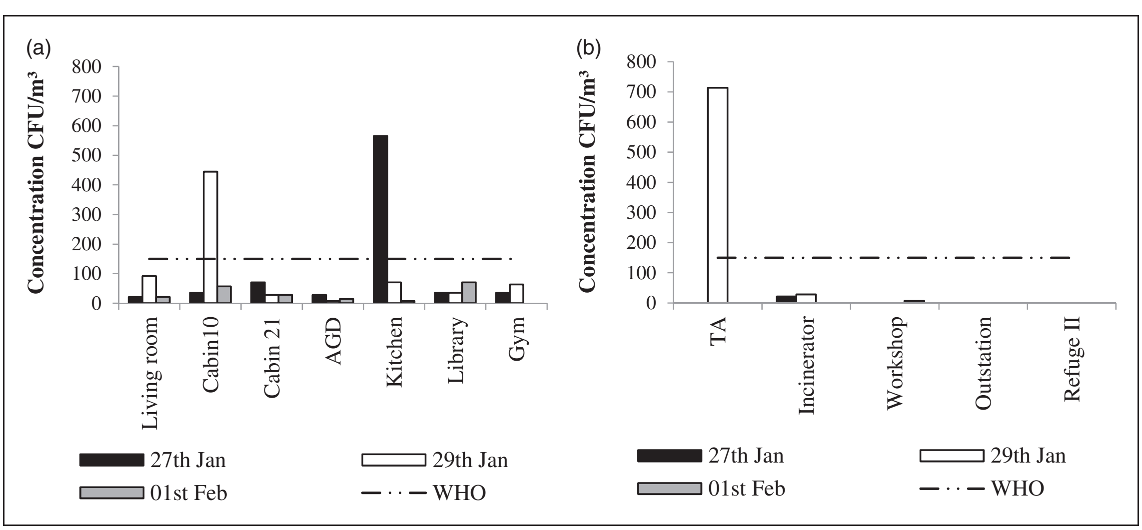

Figure 7. Concentration of fungi in (a) conditioned and (b) unconditioned compartments and outdoor areas.

unconditioned compartments have natural ventilation via access doors to the workshop to disperse contaminants.

On 29 January, fungal concentration (714 CFU/m^3) exceeded the WHO guideline[32] in the TA. This may be explained by the gathering during barbecue and the visit of a group of researchers from the Polish Henryk Arctowski Station. Thus, the high number of people within the location and the presence of organic matter certainly interfered with the result.

Zero fungi concentration was found in external locations near and far from the station, similar to results reported by Duncan et al.,[69] who monitored fungi in the indoor and outdoor air of three historic huts built on Ross Island in Antarctica. Therefore, fungi were brought to EACF by inhabitants on their clothes and utensils where they found ideal conditions for survival.[67]

A total of 29 colonies selected based on similar macroscopic aspects and microscopic analysis of the original colony for phenotypic identification of fungi.[70–72] *Aspergillus versicolor* was identified in 10 colonies, the genus *Penicillium* sp. was identified in 7 colonies, and the genus *Cladosporium* sp. was found in only one isolated colony in cabin 21 during sampling on 29 January. Among the selected colonies, 11 showed no growth on the culture media, due to the microorganisms' death. Table 2 shows number of colonies encountered and identified in each compartment.

Penicillium and *Aspergillus* are widespread fungi generally found in indoor environments,[73,74] as less than 4% of their spores are formed in the outside air, unlike the *Cladosporium* fungus.[34] Their spores are more resistant and can survive for long periods, even years, while other species may have a rapidly declining lifespan.[75] Although many *Penicillium* species are associated to particular food products,[76] some studies report that wood is highly vulnerable to attack by fungi of the genus *Penicillium*. For example, furniture and industrialized plywood products are sensitive to attack by *Penicillium* and *Aspergillus*.[68] Porous materials that allow absorption and accumulation of dust are generally excellent substrates for the growth of *Aspergillus versicolor*.[77] The species *Aspergillus versicolor* is one of the most aggressive species to health, with known allergenic and pathogenic characteristics.[78] Furthermore, both *Penicillium* and *Aspergillus* possess species that produce mycotoxins and may be responsible for some of the symptoms associated to sick building syndrome.[34]

Recommended strategies to achieve good IAQ in Antarctic buildings

The main influence on IAQ in EACF comes from building materials, human activities and air renewal systems. Indoor formaldehyde concentrations were found above the limit recommended by WHO for indoor areas. Therefore, wooden doors, wall linings and wooden flooring laminate associated with aldehydes emissions and commonly used in stations's in Antarctic may cause harm to the health of stations inhabitants. Daily activities such as cooking should also be carefully planned as high levels of acrolein were found in most compartments where air renewal was considered insufficient. Also the poor ventilation system in the kitchen might have contributed to the spread of acrolein from the kitchen to other compartments. High levels of butyraldehyde were found in AGD due to emissions from working clothes in the

Table 2. Identification of fungi sampled inside the EACF.

	27 January – Friday		29 January – Sunday		01 February – Wednesday	
Genus/species	Sites	No. of colonies	Sites	No. of colonies	Sites	No. of colonies
Penicillium sp.	Living room	2	Gym	7	Living room	2
	Cabin 21	3	TA	100	AGD	2
	AGD	4	Incinerator	1		
Aspergillus versicolor	Living room	1	Living room	13	Cabin 21	2
	Cabin 10	5	Cabin 10	63	Library	1
	Cabin 21	7	AGD	1	Workshop	1
	Library	5	Kitchen	10		
	Gym	3	Library	5		
	Incinerator	3	TA	1		
Cladosporium sp.			Cabin 21	1		

EACF: Estação Antártica Comandante Ferraz.

Table 3. Recommended strategies to achieve good IAQ in Antarctic buildings.

Stage	Recommended strategies	Goal	Pollutant of concern
Project	Compartmentalization of environments according to their function, especially physical separation between the residential, work and industrial locations.	Avoid spread of pollutants to residential areas where inhabitants spend long hours	Aldehydes, particulate matter, fungi
	Preference for the design of single and double cabins equipped with bathrooms instead of collective dormitories and shared bathrooms.	Reduce dust resuspension due to movement of people and decrease the use of personal cosmetic products inside dormitories	Aldehydes, particulate matter
	The building layout should be designed to minimize vehicle traffic inside the station.	Minimize infiltration of pollutants emitted by vehicles in residential areas	Particulate matter
	Selection of materials with low or zero emissivity, especially chlorine, bromine, VOCs and other gases proven to be harmful to human health. Preferably, specify materials that have this classification through emissions testing and certification assessment programs.	Avoid or minimize emission	Aldehydes
	Avoid or minimize coatings – floor, walls and ceiling – and furniture that have glues, adhesives or resins for fixing and can emit VOCs into the environment throughout their life	Decrease VOC concentration inside residential areas	Aldehydes
	Avoid fibrous materials or those that emit small particles harmful or not to human health such as glass wool, rock wool, asbestos and mineral fibres.	Avoid emission	Particulate matter
	Avoid oil paints and synthetic enamels as well as paints and varnishes containing metals, prioritizing the use of paints, solvents, lacquer and varnish that are water-based or ecologic and emit lower levels of pollutants into the air, especially VOCs.	Avoid emission	Aldehydes, particulate matter
	Give preference to materials with good durability and that require less maintenance and/or cleaning	Minimize emission	Aldehydes, particulate matter
	Specify materials that minimize the growth of fungi, bacteria and moisture accumulation and avoid highly porous materials such as velvet and carpets for lining and furniture upholstery.	Reduce fungi growth	Fungi
	Provide ventilation systems and efficient air exchange to meet the minimum exchange rate recommended by the ASHRAE Standard 62/2001, establishing the acceptable ventilation rate for IAQ, including a climate control system that ensures filtering and	Enhance internal air renewal	Aldehydes, particulate matter, fungi

(continued)

Table 3. Continued

Stage	Recommended strategies	Goal	Pollutant of concern
	cleaning of ambient air if necessary. Filters rating the Minimum Efficiency Reporting Value (MERV) between 9 and 16 are highly recommended. HVAC including the possibility of heat recovery for improved energy efficiency and sustainability.		
	Extractor cooker hoods with appropriate geometry or similar systems (in metal) should be installed above the cooking area.	Remove cooking pollutants	Aldehydes, particulate matter, fungi
	Adopt an air curtain system at the external openings of the service areas to avoid the entry of dust from outside.	Avoid particles infiltration from outside emissions.	Particulate matter
Construction	Consider construction as a sequence of the project, respecting the installation of certified materials with low pollutant emissions and avoiding the use of adhesives, glues and toxic sealants to minimize the accumulation of contaminants during construction.	Avoid emission that can last after construction	Aldehydes
	External sealing of the building to minimize the infiltration of air and water to the interior.	Reduce fungi growth	Fungi
Operation	Establish a periodic maintenance and regular cleaning plan for the filters and air-conditioning systems.	Avoid dust accumulation and fungi growth	Particulate matter, fungi
	Adopt clean cooking methods such as roasting and grilling instead of frying with oil.	Decrease particles and acrolein emissions	Aldehydes, particulate matter
	Adopt non-toxic cleaning supplies and those with proven low emissivity.	Reduce emission from cleaning products	Aldehydes
	Recommend that inhabitants use toiletries and cosmetics free of aerosols and recommend that use of these products be limited to places where people spend little time, such as bathrooms and changing rooms.	Reduce emission from personal cosmetic products	Aldehydes, particulate matter
	Prohibit smoking inside the building (as already stated in current regulation)	Avoid emissions	Particulate matter and aldehydes
	Minimize the use of internal combustion engines in vehicles, machinery and equipment near the station, replacing them wherever possible with cleaner technologies with renewable energy sources. If the use of diesel is necessary, use fuel with low sulphur content	Reduce emissions from vehicles and equipments	Particulate matter and aldehydes
	Establish an on-going IAQ monitoring plan	Educate the inhabitants to secure IAQ	Aldehydes, particulate matter, fungi

drying room, which indicates the need for isolation between these two areas and to other compartments.

Waste incineration, cooking, use of personal cosmetic products and light vehicles emissions contributed to the high levels of sub micrometrics particles. However, workshop areas were found to be the major source of fine and coarse particles. As pointed out by Pagel et al.,[5] incinerator loading and activities that involves dust resuspension from furniture or the ground, such as cleaning, the movement of people and physical exercise, are responsible for an increased coarse particle concentration. Although high fine particles concentration was associated with waste incineration, traffic and parking of diesel vehicles, these activities were performed away from the station, but were responsible for the emission of particles with high toxic potential such as S, Zn e *Black Carbon*.[5] The EACF was built using metallic containers covered with corrugated galvanized steel, which needs constant maintenance due to the aggressive environment in Antarctic and emits particles of Fe and Zn found inside the station.

Fungi concentration outside the station was found null; therefore, fungi must be brought to the station from outside Antarctic together with clothing, supplies and gadgets. In order to grow, the fungi require appropriate conditions inside the station. Similar to sick building in cities, the fungi *Penicillum* and *Aspergillus* were found inside EACF. This indicates the necessity of a good air renewing system, as well as the use of construction materials, furniture and decorations that are not suitable for fungi growth.

The main recommendation to lower exposure to indoor pollutants is to devise strategies for source control. However, after applying appropriate source control, ventilation is an effective method of lowering exposure. Table 3 summarizes the recommended strategies to achieve good IAQ in Antarctic buildings based on reported results. These findings and recommendations presented here were used to produce the Terms of Reference for an international competitive bidding to reconstruct the EACF areas destroyed by fire in February 2012. The IAQ parameter was included for the first time as an architectural design guideline for the Brazilian Antarctic Building.

Conclusions

The aldehydes concentrations varied among the stations' conditioned compartments. Acrolein is mainly emitted by cooking activities, but it was detected in several monitoring points inside the station, probably due to its transport and long life spam. Acetaldehyde was linked to the use of cleaning products in the kitchen and living room. The highest concentrations of formaldehyde and hexanaldehyde were found in cabin 21 due to the recently installed laminated wood lining. AGD has not been well designed as it is attached to drying room and as a result it presented the maximum butyraldehyde concentration in the Station. Among the conditioned compartments, the gym showed the highest number concentration of $PM_{2.5}$ and PM_{10} as well as the highest mass concentration of $PM_{2.5}$ due to the barbecue made in the TA. However, the highest mass concentration of PM_{10} was found in cabin 21 due to the use of personal products and the second highest mass concentration of PM_{10} was found in the living room due to cooking activities and constant people traffic. Zero fungi concentration was found in external locations, which indicates that fungi were brought to EACF by inhabitants on their clothes and utensils. The peak concentration of fungi measured in the kitchen and in TA was due to cooking activity. Average concentrations of aldehydes, PM and fungi were lower in unconditioned compartments.

Research stations in Antarctica can be compared to a small city. For proper station operation, it is necessary to include places for accommodation, preparation and consumption of food, health care and recreation, as well as specific workplaces such as administrative areas and laboratories. Large-scale buildings usually contain areas for industrial usages, such as sewage and waste treatment, water supply, power generation, material storage, workshops and others. There are specific pathways created to vehicle traffic inside the station and in its close vicinity, nonetheless, vehicle traffic is frequently not limited to these areas. There is intense traffic outside demarcated pathways inside and outside these stations.

The design of an Antarctic station must go beyond functionality and practicality and consider the effects on IAQ. Given the results obtained in this study, the recommended strategies or best practices to obtain a good air quality inside Antarctic buildings should involve three aspects (Table 3): (a) the use of materials, products and equipment with low or zero emissivity; (b) the elimination or reduction of potential sources through compartmentalization of spaces and (c) the adoption of an efficient air renewal system. These aspects are key projective strategies for designing an Antarctic station for improved IAQ.

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Authors' contribution

All authors contributed equally in the preparation of this manuscript. Érica Coelho Pagel, Neyval Costa Reis Jr., Cristina Engel de Alvarez – building materials and architectural design; Érica Coelho Pagel, Neyval Costa Reis Jr., Jane Méri Santos – measurement and analysis of particles; Sandra Paule Beghi, Paulo Wagnner Pereira Antunes, Sérvio Túlio Cassini – measurement and analysis of aldehydes; José Laerte Boechat, Marília Martins Nishikawa – measurement and analysis of fungi.

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