Summer Antarctic expeditions in seasonal stations as analogs for long-duration space exploration missions: A critical review

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Abstract

This critical review aims to compare the conditions of summer Antarctic expeditions in seasonal stations with key characteristics of long-duration space exploration missions (LDSEM). Utilizing NASA's Analog Assessment Tool and data from the COMNAP Antarctic Station Catalogue, along with scientific literature, the review identifies significant parallels for LDSEM analog research. We assess how seasonal and year-round stations differ and highlight aspects of where seasonal stations serve as a better or worse analog for LDSEM. Key findings include that while summer expeditions allow for more feasible evacuations than winter-overs, their access to medical care is more limited. Crowdedness in summer stations with shared rooms better represents LDSEM conditions than the lower density of winter-over settings. Varying daylight hours in summer stations provide a closer parallel to Mars or Moon surface missions than the continuous darkness of winter-over conditions. Additionally, constant hazards, risk management strategies, isolation, sensory deprivation, workload, leadership structures, autonomy, and communication challenges in summer stations align well with LDSEM scenarios. Conclusively, we propose a shift in perceptions, recognizing seasonal Antarctic expeditions as a valuable analog of planetary LDSEM with several advantages over traditionally accepted winter-over settings. Further comparative and longitudinal studies between seasonal and year-round Antarctic stations should be pursued to enhance LDSEM analog research and support interdisciplinary collaboration. This approach will not only advance progress in space exploration research but also improve the quality of life and safety in remote and extreme environments.

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Key words: summer polar expedition, human space research, space analogs, seasonal Antarctic station, winter-overing

Introduction

The exploration of uncharted territories has always been a driving force behind human progress, leading to groundbreaking advancements. The discovery and exploration of Antarctica were driven by motivations similar to those in contemporary space exploration - political, scientific, and economic (Basberg 2017), and yielded invaluable insights into Earth's geological processes, ecosystem dynamics, and climate patterns, among many others (McLean and Rock 2016, Tin et al. 2019). The integration of remote observation and space technology has since advanced our knowledge of ice sheets, climate models, and extreme environments, addressing global issues such as climate change and resource depletion (Detsis and Detsis 2013, Kansakar and Hossain 2016, Tassa et al. 2022). However, much of this invaluable research is conducted on-site by expeditioners (Leane and Philpott 2017), whose presence allows for the flexibility, creativity, and detailed observation that remote or robotic systems cannot fully replicate. Since the first medical and psychological studies of expeditioners in the 1950s, the Antarctic environment has been highlighted as an ideal laboratory for experimental and observational studies of human psychology and behavior (Gunderson 1973, Shurley 1973, Suedfeld and Weiss 2000). We anticipate that future manned expeditions to the Moon, Mars, and near-Earth asteroids will have similarly significant impacts on our knowledge about the laws of nature, life principles, the history of Earth and the universe, and may allow us to predict future developments (Crawford et al. 2012, Ehlmann et al. 2005).

Manned space exploration beyond Low-Earth Orbit (LEO), starting with the Artemis II mission, represents the most ambitious goal since the Apollo era. The vision promises unprecedented challenges and opportunities, primarily due to the extensive mission lengths and the effects of the space exposome (Patel et al. 2020).

Furthermore, extravehicular activities (EVAs) are expected to be even more challenging and frequent in partial gravity environments on other celestial bodies (Anderson et al. 2024). The missions will be even more complex, and crews will have to be much more autonomous (Love and Harvey 2014). However, before we venture into manned missions beyond LEO, we still need to address several challenges related to astronaut health, performance, and mission success specific to long-duration space exploration missions (LDSEM). For this purpose, the National Aeronautics and Space Administration (NASA) developed a methodology for the systematic identification and mitigation of risks to astronaut health and performance, focusing specifically on Martian missions but acknowledging the vision of other missions beyond LEO (Romero and Francisco 2020). Their methodology relies on scientific evidence from case studies to randomized controlled trials proving causation, and from laboratory studies on cells and animals through terrestrial analog and spaceflight research (Romero and Francisco 2020). Although orbital missions are considered the highest-ranking analog for LDSEM (Keeton et al. 2011), especially for physiological aspects (Romero and Francisco 2020), they have their limitations. Spaceflight research chronically suffers from low sample sizes and inconsistencies in data collection methods. Tests in orbital stations are limited by hosting, financial, and operational capacities (Cromwell et al. 2021, Suedfeld 2018), resulting in limited data on long-term confinement and minimal data on conditions with limited connection to Earth (Romero and Francisco 2020). Furthermore, research on orbital stations does not fully represent the conditions expected in LDSEM. For example, astronauts have feasible rescue options, and the number of EVAs is minimal compared to future missions (Romero and Francisco 2020). To address critical questions for mission preparation, increase sample sizes, and achieve objectives more rapidly, experts have been utilizing so-called space analog environments (Romero and Francisco 2020, Tafforin 2015).

Space analogs can be defined as "*a facility located on Earth to simulate aspects of a spacecraft/habitat or have physical similarities to the extreme extra-terrestrial environments for the purposes of benefiting human spaceflight*" (Allain et al. 2023). Analogs serve as platforms for testing protocols, methods (Foucher et al. 2021), or the psychosocial and biological effects of life in conditions simulating spaceflight in some key aspects (Crucian et al. 2014, Van Ombergen et al. 2021). These analogs come in various forms, including bedrest and dry immersion facilities, ICC environments (isolated, confined, controlled), and ICE environments (isolated, controlled, extreme), with Antarctic stations being notable examples (Cromwell et al. 2021). Despite their significant variability in characteristics like size, population, environmental conditions, living facilities, team structure, *etc*., they still share some critical variables for spaceflight analogs, such as total institutional settings, monotonous, controlled, and extreme conditions, evacuation challenges, isolation, and confinement (Suedfeld 2018).

However, it's crucial to distinguish between two contexts of space analogs. The first context replicates the environment of a crewed spacecraft and orbital stations, such as Mir, International Space Station (ISS), and future Gateway or other commercial stations. These analogs often use multi-chamber facilities with severely limited EVA capabilities. Examples include CAPSULS, ISEMSI, NEEMO, HERA, Hydronaut DeepLab, and Mars500. For this purpose, winter-over studies in Antarctic stations such as Concordia, Vostok, Amundsen-Scott South Pole Station, Dumont D'Urville, Neumayer-III, British Halley I, and McMurdo have been used as the expeditioners are exposed to extreme form of isolation from outside world, external life and resources limitations, feasibly approximating life on orbital stations in more realistic setting than controlled studies (Pagel and Choukèr 2016, Suedfeld 2018, Tafforin 2015).

In contrast, the second context simulates the housing structures and conditions of Martian and Lunar exploration missions. These are represented in analogs and analog missions like MDRS, Biosphere 2, HMP, HI-SEAS, CHAPEA, Astroland, AMADEE, CHILL ICE, and FMARS among many others (Elorzaa et al. 2020, Groemer et al. 2020, Smith et al. 2022, Suedfeld 2018, Tafforin 2015, Vyshnav and Muller 2016, Yashar et al. 2022). And especially for this context the seasonal Antarctic expeditions, while generally overlooked, offer distinctive advantages for high-fidelity simulations of planetary exploration, providing a context of "real expedition" compared to ICC settings of other space analog stations. This article aims to uncover these overlooked parallels and argue that summer Antarctic expeditions offer a significant yet underutilized analog for LDSEM research.

The paper presents a critical review of relations between summer Antarctic expeditions and key characteristics for LDSEM analog. The paper begins by introducing the characteristics, detailed in NASA's Analog Assessment Tool (Keeton et al. 2011). It will then use the key research characteristics as a benchmark for comparison with summer Antarctic expeditions based on the Antarctic Station Catalogue (Council of Managers of National Antarctic Programs, 2017[3]), or respective state-of-the-art literature. As Suedfeld (2018) points out, the intention should not be to compare them as it's mutual imitation, rather we should think about them as analogous experiences and situations sharing some similarities. His work focuses on psychosocial aspects and their comparability, highlighting the limits posed by high inter-station variability, especially between seasonal and year-round stations. We intend to address this aspect, which has not been delineated in literature before, and provide crucial points for discussion on the degree of similarities and their usefulness in these key characteristics.

Characteristics of Long-Duration Space Missions

The attempts to draw inferences from situations simulating long-duration spaceflight are reaching to mid-20th century (Gunderson 2012). Since that time, analogs have been increasingly utilized, and nowadays we have a plethora of opportunities that vary significantly in their appropriateness due to factors such as location, environmental hostility, crew size, activities, backgrounds, and communication with the outside world (Keeton et al. 2011, Pagel and Choukèr 2016). Making a priori judgments about the relative merit of analogs can misdirect attention and conclusions, necessitating the development of objective assessment methodologies.

Smith (1969; cited in Stuster 1986) was among the first to compile a list of characteristics defining a space station analog, including group size, composition, compatibility, privacy, motivation, morale, past accomplishments, group-maintenance skills, leadership, grievance handling, interpersonal hostility avoidance, interdependence, trust, confinement-endurance training, duration of confinement, perceived monotony, mission and task importance, variety and interest value of subtasks, rewards for success, cost of failure or poor performance, awareness of mission duration, time-tracking ability, acceptability of food and water, and work-rest cycles and workload. Sells (1973; cited in Stuster 1986) provided a shorter list, focusing on objectives and goals, philosophy and value systems, personal composition, organization, technology, physical environment, and temporal characteristics.

In 1986, Stuster conducted a systematic analysis of analogs for studying biological, psychological, and sociological risks associated with long-duration spaceflight, deriving characteristics for comparing and evaluating alternative analogs based on Smith's and Sells' work (Stuster 1986). These characteristics included group size, task type, perceived risk, tour duration, physical isolation, personal motivation, free time, group composition, psychological isolation, mission preparedness, habitat quality, social organization, environmental hostility, and life support quality. Experts were then invited to evaluate specific analog sites based on these characteristics, although these metrics were specifically identified for permanently occupied orbital space stations, such as the ISS. The context of orbital stations and ground exoplanetary outposts differs, requiring different considerations.

Building on Stuster's tool, NASA's Human Research Program (HRP) released the Analog Assessment Tool that systematically and objectively determines suitable platforms, shifting focus from orbital stations to exploration planetary missions with the Mars mission as a focal point. This tool augmented Stuster's work by including research characteristics along with analog characteristics, adding additional research and utility characteristics (Keeton et al. 2011). The report aims to aid Behavioral Health and Performance (BHP) research but can also serve as a standard for assessing the fidelity and suitability of other available analogs for research questions related to behavioral health risks in long-duration isolated scenarios, such as future exploration missions.

The Analog Assessment Tool (Keeton et al. 2011) includes characteristics within two main categories: research characteristics that are relevant to the biomedical, team, and sleep risks research; and utility characteristics that relate to the practical aspects of research in the facilities (Table 1). Research characteristics further fall into subcategories of (a) environmental characteristics – situational factors present in analogs that influence individual and team functioning; (b) mission characteristics – structural features of the mission that influence individual and team functioning; (c) personal aspects – non-task-related factors that influence individual functioning; (d) team/personal aspects – team-related characteristics that influence crewmember interaction. Utility characteristics are then divided into two subgroups: a) NASA-Related – factors dictated by NASA's policies and procedures that would influence data collection in analogs; and b) Analog-Related – factors dictated by analog characteristics and constraints potentially influencing data collection (Keeton et al. 2011). Our critical review targets the research characteristics.

Research Characteristics		**Utility Characteristics**
Availability of Medication/Medical Care	Sensory Deprivation	Exposure Time
Crowdedness	Workload	Mission Duration
Danger	Personal Space	Mission Timeline
External Light Conditions	Rest & Recreation Options	Similarity to Astronauts
Internal Light Conditions	Quality of Life Support Conditions	Subjects/Year
Physical Isolation	Leadership	Task Relevance
Autonomy	Team Size	Cost/Study
Communication with Outside	Team Structure	Data Collection Feasibility
Sensory Conditions	Team Interdependence	Research Process/Protocol Feasibility

Table 1. Characteristics for Long Duration Space Exploration Missions (LDSEM) with key focus on future Martian mission. Extracted from NASA's Analog Assessment Tool (Keeton et al. 2011).

Advocacy for the use of seasonal polar expeditions as LDSEM analog

In 2024, 57 countries have signed the Antarctic Treaty (Secretariat of the Antarctic Treaty, 2024[5]), and 55 utilize their right to operate a research station in Antarctica. The Council of Managers of National Antarctic Programs (COMNAP) published the Antarctic Station Catalogue (2017[3]), describing information on 76 seasonal and year-round Antarctic facilities that are operated or run under COMNAP

Member national Antarctic programs. Although the list does not provide information on all facilities in the Antarctic, it provides some indication of their operational nature and dispositions.

Environment characteristics

Physical Isolation

Definition: *"The level of isolation an individual has from others outside of their team (operationalized as the amount of time it would take to escape the environment)"*. The assumption for a Long-Duration Mission: *"High; isolated to only other crew members. Escape would be impossible, or highly improbable"* (Keeton et al. 2011).

NASA's definition of physical isolation aligns fairly with the conditions of Antarctic expeditions both in summer and winter. Undoubtedly, every outpost in Antarctica can be marked as a remote region according to the definition of remote regions being those where evacuation to definitive care can take over an hour (Backer et al. 1998, Iserson 2013, Shaw and Dallimore 2005, Wakerman 2004). Medical evacuation from Antarctica is challenging, taking multiple hours, days, or weeks, even in summer, due to weather, remoteness, and transportation limitations (Lowe and Warner 2023, Tissot et al. 2023). For instance, McMurdo Station is 3,900 km from the primary air supply port in New Zealand, with modern C-130 transport taking 6-7 hours each way. Considering additional time due to the transportation between individual Antarctic stations, weather conditions, and ultimate transportation from the airport to the medical facility, this can significantly delay and/or prolong transport times (Brown et al. 2023, Mills and Mills 2008).

Presumably, compared to the interior continent, the easiest location for access is the Antarctic Peninsula, as Suedfeld claims (2018). However, this should not imply that evacuation from the Antarctic Peninsula is easy and fast. Several reports on patient evacuation from the Antarctic Peninsula highlight serious potential complications (Carron et al. 2016, 2019; Cornelius 1991, Mills and Mills 2008). For example, according to a case report presented by Carron et al. (2019), the only way for medical evacuation from the Antarctic Peninsula by air is from the Frei Station located on King George Island, which can be complicated by winds, visibility, and freezing, making it extreme compared to more temperate climates in civilized areas. This implies that stations close to King George Island still have to transport the evacuated member to the airstrip by helicopter and/or by sea (some stations do not even have both options, see supp. Medical capacity), which is subject to the limitations of accessibility of transportation devices. In case the airstrip cannot be used, the evacuation route by sea takes at least two days to cross the rough sea of Drake Passage (Carron et al. 2016, 2019). The time estimates for evacuation from stations can be also deduced from resupply logistics, usually ranging from several hours in case of air to days and weeks in naval transportation (Hughes et al. 2011). Despite being one of the more accessible locations in Antarctica, stations near the Antarctic Peninsula still face extreme isolation challenges due to the complex and potentially delayed nature of medical evacuations, as documented in the literature (Carron et al. 2016, 2019; Cornelius 1991, Mills and Mills 2008).

Danger

Definition: *"The likeliness that an individual will get injured or hurt when carrying out daily tasks."* The assumption for a Long-Duration Mission: "*Moderate to high; daily tasks carry a moderate risk of injury; ongoing environment comprises a high degree of risk of injury and/or death."* (Keeton et al. 2011).

In the context of summer Antarctic expeditions, there are several hazards intrinsic to the environment and daily activities. Reports underscore the significant risks posed by the Antarctic environment, with hypothermia being a persistent concern (Taylor and Gormly 1997). While cold-related injuries remain relatively infrequent, injuries in general constitute a notable portion of medical care sought during expeditions (Lugg 2000, Taylor and Gormly 1997). They range from soft tissue trauma, strains, and sprains to more severe cases such as dislocations, fractures, and even fatal injuries (Taylor and Gormly 1997). Younger and more adventurous expeditioners tend to require medical treatment for traumatic injuries more frequently (Lugg 2000), suggesting potential influences of personality, experience, and boredom/monotony effects (Suedfeld and Steel 2000). Injuries are common also on cruise expeditions, with an incidence rate of 17.9 people per 1000 person-days at sea. This underscores that even during transit phases, expeditioners face risks, especially with smaller vessels navigating rough waters (Visser 2020).

Several authors provide specific descriptions of injury prevalence with orthopedic and trauma injuries being the most common, followed by internal, dental, dermatological, and other medical issues (Bhatia et al. 2013, Ikeda et al. 2019, Pattarini et al. 2016). Evacuations were necessitated during the summer for cases of atrial fibrillation and renal calculi, with two additional medical movements recorded. The number of clinic visits was relatively stable in Palmer Station (4:1 throughout the year) and in Amundsen-Scott South Pole Station (8:1 in the summer, and 10:1 in the winter). The difference between the winter and summer seasons was statistically significant only in one out of three year-round stations. This may relate to expeditioners' higher tendency to report injuries and sickness in winter than in summer season. Thus, the reports suggest that the risk of injury or medical issues during summer expeditions in year-round stations may be comparable to that during winter-over periods and remain proportional to the number of expeditioners (Pattarini et al. 2016). Overall, the danger aspect of summer Antarctic expeditions in seasonal stations may offer several valuable parallels to the LDSEM context, given the prevalence of injuries and risks associated with daily work during expeditions.

Availability of medical care

Definition: *"The extent to which medication and medical care is readily available and accessible to individuals at the analog.*" The assumption for a Long-Duration Mission: "*Limited; basic emergency equipment available and standard medications. Crew members with basic training of emergency response and basic medical procedures*" (Keeton et al. 2011).

In summer Antarctic expeditions, the availability of medical care aligns with the basic emergency and medical care expectations for LDSEM, though there may be notable differences in the level and immediacy of care. Expeditioners face numerous challenges (*see* section *Danger*) and rely on adequate health care. Similarly to astronauts, they are required to be in good health and not reliant upon medication for chronic conditions. However, the possibility of unexpected illness and accidents remains (Taylor and Gormly 1997). Medical support for extended expeditions in remote and hostile environments, such as Antarctica, falls under a specialized branch of medicine known as expedition medicine, which includes diagnosis, treatment, prevention, and optimization for teams in regions where evacuation to definitive care can take over an hour (Backer et al. 1998, Iserson 2013, Shaw and Dallimore 2005). Typically, the expeditions are staffed with medical personnel (although this may not be always the case, *see* supp. *Medical capacity)* who have extensive clinical knowledge, public health insight, cross-cultural understanding, and has to be capable of providing telemedicine, innovating practice methods, making independent decisions, and assuming increased responsibility (Iserson 2013). Planning medical care for these expeditions requires comprehensive knowledge of emergency medical procedures (Shaw and Dallimore 2005). Therefore, the reliance on basic emergency equipment and training meets the criteria for LDSEM analog.

According to the Antarctic Station Catalogue (Council of Managers of National Antarctic Programs, 2017[3]), a majority (38 out of 40) year-round stations have a medical facility offering medical care ranging from basic to advanced treatments, including surgery (*see* Supp. *Medical capacity*). However, only 23 (out of 36) seasonal stations indicated the presence of a medical facility, and only three indicated higher medical capacity than basic. Therefore, during medical emergencies, evacuation procedures to advanced medical facilities in or outside Antarctica are relied upon. As stated before in the section *Physical Isolation*, evacuations are generally more feasible in the summer than in the winter but still face significant challenges and potential delays of up to several days due to adverse weather conditions, remoteness, and limited transportation options (Lowe and Warner 2023, Tissot et al. 2023). Seasonal stations near Antarctic-based medical facilities are on the South Shetland Islands, Greenwich Island, or Adelaide Island, but distances to the nearest hospital outside Antarctica exceed 900 km (*see* details in Council of Managers of National Antarctic Programs, 2017[3]). Thus, although summer Antarctic expeditions have relatively better access to medical care compared to completely isolated space missions, they still face substantial limitations in medical facilities' disposition or evacuation logistics, making them valuable analogs for studying medical care strategies.

Crowdedness

Definition: "*Crowdedness relates to the degree of crowdedness, e.g. the ratio of habitable volume divided by the number of people who must live in it*." The assumption for a Long-Duration Mission: "*Moderate to high; anticipated that the habitat will be the size of a modest-sized RV or smaller for four to six people (consider both transit vehicle and habitat on Mars or other surface)"* (Keeton et al. 2011).

Crowdedness can be defined in two ways: as the objective density of population per habitable area and as the subjective perception of there being too many people in a given space (Hotwani and Tripathi 2017). While tolerance to crowding varies due to personality characteristics, cultural context, age, and sex, in the context of the US census, households with more than 1.0 persons per room are considered overpopulated (Lepore 2012). This standard, although not directly applicable, provides a useful benchmark for understanding crowdedness in Antarctic stations. In the context of extraterrestrial missions, the anticipated number of crew members is typically four to six, and the habitat is expected to be the size of a modest-sized RV (Keeton et al. 2011). According to specifications from Neighbor Blog (Bryden 2024), a typical modest-sized RV, such as the Class C model, measures approximately 28 feet (8.53 m) in length and 8 feet (2.44 m) in width, resulting in an interior living space of roughly 224 $feet^2$ (about 20.82 $meters^2$), leading an estimate of a 56 to 37.3 $feet^2$ (5.21 m^2 to 3.47 m^2) per person. Tafforin (2015) provided an overview of space analogs from 1991 to 2011, revealing various examples such as the Mars500 mission with a crew of six in a 550m^3 space (equivalent to 91.6 m^3/person); NDRS Desert station with a crew of up to eight in 500 m^3 (eq. to 62.5 m^3/person), NEEMO underwater with a crew up to nine in a 401 m^3 space (*e.g.*, 44.6 m^3/person), among others (Tafforin 2015). Pagel and Choukér (2016) mentioned the SFINCSS-99 study, where four individuals spent 110 and 240 days in a 200 m^3 area (50 m^3/person). Comparing these analogs to summer expeditions in seasonal Antarctic stations reveals interesting parallels and differences.

According to the Antarctic Station Catalogue (Council of Managers of National Antarctic Programs, 2017[3]), crowdedness varies depending on the specific station and its facilities (Table 2). The median area under the roof of 32 reported seasonal Antarctic stations is smaller than the smallest area of the 40 reported year-round stations and is more than six times smaller than the median area of the year-round stations. Seasonal stations typically host a median of 15.5 people, which is lower than in the winter-over context. This also relates to a higher crowdedness in seasonal stations compared to that of the winter-over context. It is important to note that the Antarctic Station Catalogue doesn't specify the total area accessible by the winter-overing crew and may include inconsistencies in the reported numbers for some stations, particularly between the counts of staff and scientists compared to the number of beds or maximum personnel capacity (*see* Supp. *Crowdedness* and Antarctic Station Catalogue (Council of Managers of National Antarctic Programs, 2017[3])). Nonetheless, these data suggest that some seasonal Antarctic stations may provide context suitable for addressing the confinement challenges of LDSEM.

Station Type	**Area (m^2)**	**Number of People**	**Crowdedness (m^2/person)**
Seasonal Stations	Median: 520.5 (Min: 32, Max: 7 500)	Median: 15.5 (Min: 6, Max: 120)	Median: 27.3 (Min: 2.7, Max: 466.7)
Year-Round Stations	Median: 3,302.5 (Min: 578, Max: 32 750)	Median: 60 (Min: 9, Max: 1 000)	Median: 51.4 (Min: 12.5, Max: 188.9)
Winter-Over Context		Median: 19 (Min: 2, Max: 153)	Median: 178 (Min: 22.9, Max: 2 000)

Table 2. Variations in area, number of people, and crowdedness for seasonal stations, year-round stations and winter-over context in year-round stations. Data are extracted from the Antarctic Station Catalogue (Council of Managers of National Antarctic Programs, 2017[3]).

External Light Conditions

Definition: *"The lighting conditions outside of the habitat".* The assumption for a Long-Duration Mission: *"Moderate; exposure to sun will likely be consistent across the time during transit and on a foreign planetary surface (e.g., Mars day is very similar to Earth's, but is 37.5 minutes longer)"* (Keeton et al. 2011).

In the context of summer Antarctic expeditions, external light conditions are a critical aspect that significantly influences the daily lives and experiences of expeditioners. Unlike the continuous darkness experienced during the winter-over period, the summer season in Antarctica brings varying degrees of exposure to natural light, depending on location (latitude, and longitude). For instance, expeditions to James Ross Island were exposed to daylight ranging from 20.75 h in January to 14.25 h in March (Ráčková et al. 2024), and in Belgrano II station ranging from nearly 24 h in November to 18.6 h in March (Tortello et al. 2023; *see* also meta-analysis by Shao et al. 2024). These conditions bear resemblance to what might be encountered during future missions to Mars or the Moon, where exposure to sunlight varies based on the location of the outpost too and may be illuminated almost constantly (Amini et al. 2022, Bussey et al. 2005, Cockell 2001, Heinicke and Foing 2021, Popel and Zelenyi 2013).

However, it's crucial to note that expeditioners in summer Antarctica may face additional challenges related to ultraviolet (UV) irradiance. Due to the depleted ozone layer, particularly noticeable during spring, there's a considerable increase in UV levels (up to 85% in December), with the Antarctic Peninsula being particularly vulnerable. This heightened UV exposure poses risks of DNA damage and oxidization, especially due to surface albedo's amplifying effect (Cordero et al. 2022). This risk is greater for unprotected body parts such as the eyes or bare skin (Bogdanov et al. 2023, Fuentes–León et al. 2020, Russell et al. 2015). Similarly, UV exposure coupled with ionizing radiation poses significant health risks for astronauts, highlighting the need for effective protective measures that can be tested for usability in the summer Antarctic context (Krittanawong et al. 2022, Nicholson et al. 2005, Pavletić et al. 2022).

Internal Light Conditions

Definition: *"The lighting conditions within the habitat.* The assumption for a Long-Duration Mission: *Anticipate full artificial light spectrum (do not consider possible lighting countermeasures)"* (Keeton et al. 2011).

Internal lighting conditions in Antarctic stations are predominantly maintained by artificial light (Paul et al. 2015, Shao et al. 2024). This reliance on indoor artificial light in Antarctica directly aligns with the conditions anticipated for LDSEM, where habitats on spacecraft or planetary surfaces will need to be equipped with full-spectrum artificial lighting.

Expedition characteristics

Autonomy

Definition: *"The level of discretion that an individual and crew/team have over their choices, actions, and support in accordance with standard operating procedures*". The assumption for a Long-Duration Mission: *"Anticipate the crew to be much more autonomous than current operations; a moderate to high degree discretion of crew members over their choices and actions to complete mission objectives"* (Keeton et al. 2011).

The definition of autonomy for future Martian or Lunar missions anticipates a significant increase in crew autonomy compared to current space operations, such as those on the ISS. Historically, space missions have relied heavily on the cooperation between space crews and Earth-based controllers, who manage complex flight systems and provide real-time support. This extensive support system has limited the autonomy of spaceflight crews to periods of communication outages or in-flight emergencies, leaving a gap in developing operational concepts for future autonomous crews. The distance-related communication delays and bandwidth limitations expected in future space missions will significantly impair the ability of the control center to provide timely monitoring and assistance. Therefore, future exploration crews will need to assume tasks and functions currently performed by flight control teams without real-time support (Love and Harvey 2014).

Summer Antarctic expeditions offer a compelling analogy for studying crew autonomy in space missions. Antarctic expeditions often operate with a high degree of autonomy, making critical decisions about logistics, safety, and scientific operations without immediate external support. The specifics of autonomy for expeditioners in Antarctica vary based on cultural, station rules, seasonal, role, and environmental aspects (Golden et al. 2018, Green 2022). Literature indicates that Antarctic expeditioners have a higher level of autonomy than astronauts on the former Mir and current ISS orbital stations (Vessey and Landon 2017). Additionally, a fulfilled need for autonomy, or the ability to control situations, is a prerequisite for good adaptation to the Antarctic environment (Palinkas 2002). Too much autonomy, in the sense of maintaining certain independence from the social group, can lead to social isolation or conflict, as is illustrated in a study by Palinkas (2002, sec. Case No. 3). In settings where civilians and military personnel coexist, civilians may feel overly controlled by rigid military rules, while military personnel may perceive civilians as lacking respect for authority and discipline, leading to tensions (Palinkas 2002).

The Antarctic Search for Meteorites (ANSMET) project exemplifies this autonomy, where the principal investigator leads the field team, prioritizes work, and ensures safety, much like the autonomous operations expected in future LDSEM. The expedition team includes experienced mountaineers who keep the participants safe from environmental hazards and monitor daily operations, similar to the roles future astronauts will need to adopt (Love and Harvey 2014). In their opinion, Antarctic expeditions are "*like space exploration missions without a control center*" (Love and Harvey 2014).

In our opinion, the seasonal summer Antarctic expeditions resemble future LDSEM in terms of the autonomy level and required decision-making, rather than solely on the absence of a control center. In scientific expeditions, expeditioners often act in connection with their research groups or centers and institutions, constituting their main contact points for operational decisions, somewhat resembling the spaceflight mission control center. However, the ability to exchange information is limited due to communication availability and time zone differences (*see* section *Communication with the Outside World)*. Colleagues aiding expeditioners are not available 24/7, resembling the autonomy required in future LDSEM where crews must perform tasks and make decisions independently. Thus, even summer expedition teams can provide valuable insights into the needs and necessary improvements for autonomous team operations in LDSEM.

Communication with the Outside World

Definition: *"The level of access to communication with the outside world"*. The assumption for a Long-Duration Mission: *"Moderate to minimal; although communication options would be available, crew members will often experience communication delays with the ground ranging from 4 to 40 minutes (for a full communication loop)"* (Keeton et al. 2011).

The concept of communication will undergo a profound transformation as we move from orbital to planetary space missions. On the ISS, crews benefit from near-constant voice communication with a responsive ground control center through multiple independent radio channels, daily email exchanges, and even private medical conferences with flight surgeons. Weekly, the mission control center sends complex procedure sets and work instructions, including diagrams, photographs, and video clips. Crews can downlink hundreds of high-resolution digital photographs daily and stream complex operations via video (Love and Harvey 2014). In stark contrast, future Mars missions will face communication delays of up to 44 minutes one-way, making real-time conversation impossible, and further significantly limiting the exchange of voice messages, video, and imagery due to bandwidth constraints. Medical conferences between surgeons and the control center will also be affected by these delays (Love and Harvey 2014).

Antarctic expeditions, especially those in remote areas, experience communication limitations akin to those anticipated in LDSEM. The cost and logistical challenges of satellite telephone and internet services result in low bandwidth and unreliable connections, exacerbated by the continent's harsh environment and poor satellite geometry (Afanasieva et al. 2017, Love and Harvey 2014). Seasonal stations in Antarctica rely heavily on satellite and very high frequency (VHF) communication, though some have access to email or even the Internet. In contrast, most year-round Antarctic stations have reliable access to email and the internet (*see* Supp. *Communication*). Expeditioners, however, often face significant delays in receiving responses to emails from their colleagues and close ones due to time zone differences and working hours. Therefore, they need to wait for the response for several hours. These constraints make Antarctic expeditions an excellent analog for studying the effects of limited communication capacities anticipated in future LDSEM on individuals' well-being as well as missions' operational aspects and telemedicine.

Sensory Conditions

Definition: *The quality of environmental conditions affecting sensory perceptions including temperature, smell, noise, etc."*. The assumption for a Long-Duration Mission: *"Moderate; anticipate some negative environmental conditions that will influence the quality of the environment including the lack of fresh air, presence of* *odious smells, as well as noise from machines and support systems, etc.“* (Keeton et al. 2011).

The definition of sensory conditions in the context of LDSEM aligns with the environmental challenges encountered during summer Antarctic expeditions, where factors like temperature, odors, and noise can significantly impact individuals' sensory perceptions. Exemplary, a case study on Chinese expeditioners revealed that although the majority (76.1%) of inhabitants found the air quality comfortable, 40.8% of inhabitants would welcome improvements in indoor environment quality (Mao et al. 2024). Studies conducted in Antarctic stations reveal various indoor air quality issues, including the presence of chemical compounds (Na, K, Cl, Fe, Zn, Se, S, *etc*.), increase in CO_2 concentration and pollutants presence (particulate matter, aldehydes, polychlorinated biphenyls, organochlorine pesticides) generated from routine activities, external sources, and microorganisms, which can affect sensory conditions and overall well-being (Anzano et al. 2022, Choi et al. 2008, Pagel et al. 2016, 2018; Rodriguez-Soria et al. 2024, Van Houdt et al. 2009). The study on airborne microbial diversity found no significant differences between summer and winter measurements within the Antarctic stations. However, notable variations were observed between measurements taken in continental and coastal regions (Pearce et al. 2010). This creates an opportunity for investigation targeting environmental contamination, protective strategies, and mitigation measures, which are relevant to the LDSEM context too (Yair et al. 2021). The potential application extends from extraterrestrial habitation systems to environmental conservation objectives outlined in the Protocol on Environmental Protection to the Antarctic Treaty (Blay 1992).

Similarly, wastewater and sewage systems (Smith and Riddle 2009, Stark et al. 2015), as well as the human body and clothes drying odors (Davis 2015) may be a source of discomfort, which also has been articulated in space analog missions (Heinicke and Arnhof 2021). Noise pollution from machinery and daily operations further contributes to discomfort in these environments, especially in areas where intellectual work, verbal communication, or sleep is expected (Davis 2015, Zaganelli and Alvarez 2012). While noise sources can differ between individual Antarctic as well as space stations and habitats, they still may offer valuable insights for understanding the impact of noise in future planetary outposts. The temperature in stations is usually regulated (Mao et al. 2024). The main difference between summer expeditions and future planetary outposts is in the possibility to open windows for fresh air circulation (Mao et al. 2024).

Sensory Deprivation

Definition: “*The extent to which the environment does not provide needed sensory stimulation in terms of visual, tactile, olfactory, auditory, and taste.”* The assumption for a Long-Duration Mission: *“Moderate to high; anticipate a lack of sensory stimulation that would arouse a visual, tactile, olfactory, auditory, and/or taste response (e.g., unlikely to have fresh food, plants, etc.)”* (Keeton et al. 2011).

The notion of sensory deprivation in summer Antarctic expeditions is multifaceted, encompassing both external and internal environmental factors. While individuals may have access to sensory stimuli from the external landscape, such as landscapes, greenery, and wildlife, the overall sensory experience is constrained by internal environmental factors, including the limited availability of fresh food (*see* section *Quality of Life Support Conditions*), the absence of internet connectivity (*see* section *Communication with Outside World*) and recreational options within stations or camps (*see* section *Rest and Recreation Options*). These limitations highlight parallels with the assumptions of moderate to high sensory deprivation in LDSEM, where individuals will lack diverse sensory inputs, but still will be exposed to the landscapes of the external world.

The prerequisites for a Moon terrestrial analog environment are aridity, low temperature, and the presence of abrasive dust (ten Kate and Preston 2015). This may be partially fulfilled in de-iced Antarctic areas. For instance, the rocky, dry desert terrain found in parts of Antarctica, including the Dry Valleys, bears resemblance to the surfaces of Mars and the Moon (Cassaro et al. 2021), offering opportunities to investigate their effects on expeditioners and test missions concepts, instruments, and data collection techniques (Foucher et al. 2021).

Workload

Definition: *"The amount of work an individual has to perform on a day-to-day base"*. The assumption for a Long-Duration Mission: *"Moderate to heavy workload, with some daily personal time. However, likely for some part of the transit, periods of low workload may be an issue"* (Keeton et al. 2011).

The concept of workload in summer Antarctic expeditions bears relevance to the demands placed on individuals as they engage in daily tasks by the station or field camps. While the workload may vary depending on factors such as station operations, research objectives, and individual responsibilities, there is typically a moderate to heavy workload involved in conducting scientific research, maintaining station operations, and addressing logistical needs. Due to the prolonged exposition to daylight, some individuals opt to work exhaustively for many hours a day (Guly 2012). This workload encompasses a range of activities, including fieldwork, data collection and analysis, equipment maintenance, and administrative tasks (Palinkas and Suedfeld 2008). However, similar to the assumptions for long-duration missions, individuals in summer Antarctic expeditions also have allocated personal time for rest, relaxation, and social interactions, albeit to varying degrees depending on station routines and operational requirements. Moreover, periods of low workload may arise during transitions between research projects or logistical phases, mirroring the anticipated fluctuations in workload during certain phases of long-duration missions (Kanas et al. 2009).

Personal aspects

Personal Space

Definition: *"The amount of personal space that an individual has to himself or herself within the habitat"*. The assumption for a Long-Duration Mission: *"Low; limited personal space anticipated due to the constraints of the vehicle and habitat size"* (Keeton et al. 2011).

Unlike winter-over crews who may enjoy the privacy of individual small rooms (Keeton et al. 2011, Stieber 2024), summer expeditions often involve sharing rooms, resulting in even less personal space (*see* also *Crowdedness* section). This situation parallels the assumption for LDSEM, where constraints on vehicle and habitat size restrict individual space.

Rest and Recreation Options

Definition: *"The extent to which rest and recreation options are available to crew members"*. The assumption for a Long-Duration Mission: *"Minimal; few options for rest and recreation are currently anticipated. Those options that will be available are likely to be a standard, constrained set of options (versus a flexible, wide-range of choices and/or different venues)"* (Keeton et al. 2011).

The concept of rest and recreation options in seasonal Antarctic expeditions aligns with the assumption for LDSEM, where minimal opportunities for leisure activities are anticipated. Seasonal expeditions in Antarctica often offer limited options for rest and recreation due to the small station size, remote location, and harsh environment. In stark contrast, year-round stations like McMurdo, Palmer, and Concordia offer a plethora of recreational options including libraries, climbing walls, sports rooms, pool rooms, sauna, gym, art shows, performances, lectures, *etc.* (Canisteo Principality News, 2023[2]; ESA 2019[4]; USAP 2023[6]). These luxuries are usually not available in all stations, especially smaller seasonal ones where expeditioners may have to rely on personal items for entertainment, akin to the conditions expected in future LDSEM. An extreme example of the reduced recreation opportunities are field camps, often conducted in summer. Summer expeditions may take advantage of outdoor excursions or leisurely walks, though these may be restricted by weather conditions or operational constraints, and group requirements may limit solo activities. This is supposedly similar to the future LDSEM, which will also employ frequent EVAs outside stations. Thus, although seasonal summer expeditioners have more feasible access to the outdoor environment for leisure time, their overall recreation options may resemble those of future LDSEM missions more closely than the well-equipped winter-over stations.

Quality of Life Support Conditions

Definition: *"The quality of options related to food, hygiene, and other aspects of daily living"*. The assumption for a Long-Duration Mission: *"Minimal; some options for food, hygiene, and other aspects of daily living"* (Keeton et al. 2011).

Similarly to the definition for LDSEM, the quality of life support in summer seasonal expeditions is minimal, particularly compared to the larger year-round stations. The majority of stations included in the Antarctic Station Catalogue, seasonal and year-round, have showers and laundry facilities (Council of Managers of National Antarctic Programs, 2017[3]). The catalog does not provide information on the frequency of food supply, however, it can be assumed that while large year-round stations may receive frequent resupply during the summer season (Hunter et al. 2003), expeditions in seasonal stations and field camps receive supply only once at the beginning of the expedition, or relies on storage goods from previous expeditions (British Antarctic Survey (BAS), 2024[1]; Taylor 2007). Hence, research in seasonal summer Antarctic expeditions can provide valuable insights into coping with limited resources and restricted options for daily living, which can inform the development of strategies to enhance the quality of life support in extreme environments, including future space missions.

Team and personal aspects

Leadership

Definition: *"The extent to which the role of the leader is clearly and strongly defined and present within a team"*. The assumption for a Long-Duration Mission: *"Assigned; anticipate the role of leader to be assigned and carry a strong role within the crew; also clear designation of chain of command"* (Keeton et al. 2011).

The definition of leadership structure in LDSEM closely aligns with the organization and dynamics observed in summer Antarctic expeditions. Here, the role of the leader is clearly defined and holds significant importance within the team, often with a designated chain of command. This parallels the hierarchical leadership structures commonly found in Antarctic expeditions, where leaders are assigned and play a crucial role in decision-making and coordination of activities. There is a wealth of literature focusing on leadership in polar regions, ranging from narrative (Burrow 2015) to quantitative research perspectives. For instance, Schmidt et al. (2005) conducted a study in collaboration with NASA, analyzing leadership aspects based on data collected from Antarctic stations, highlighting the formal leadership roles and their impact on decision-making (Schmidt et al. 2005). Burke et al. (2018) focused on leadership functions, their formality, locus, and distribution. They reported that teams may adopt informal leadership structures in addition to the assigned leader, with multiple individuals fulfilling leadership roles as needed. Alternatively, in some cases, these informal structures may replace formal leadership entirely, emphasizing the effectiveness of shared leadership in extreme environments (Vessey and Landon 2017).

However, the role of station managers cannot be overlooked, as they bear significant responsibility for the safety and emotional well-being of expeditioners, requiring them to make life-critical decisions remotely and with limited organizational support (Lovegrove 2004, Stieber 2024).

Team Interdependence

Definition: *"The extent to which the completion of assigned tasks requires collaboration among crew members"*. The assumption for a Long-Duration Mission: *"Moderate to high; anticipate that many daily tasks will require crew members to work together to successfully complete mission objectives; teams also will be able to eat together, and participate in team rest and recreation activities together"* (Keeton et al. 2011).

Indeed, teamwork is foundational to the daily operations of summer seasonal Antarctic stations. Whether it's conducting scientific research, maintaining station infrastructure, or ensuring the well-being of all team members, collaboration is essential (Schmidt et al. 2005). Scientific teams rely on cooperation for tasks as basic as sharing utensils or as complex as exchanging research data. Additionally, the communal nature of Antarctic living means that team members often participate in shared activities like meal preparation and recreation, driven by group requirements for outdoor activities (Schmidt et al. 2005). Taken together, teams in summer seasonal Antarctic stations are interdependent in daily tasks and fulfilling expedition objectives.

Team Size

Definition: *"The size of the flight crew that will be on the mission"*. The assumption for a Long-Duration Mission: *"Small; four to six crew members; likely to be mixed gender and multicultural"* (Keeton et al. 2011).

According to the Antarctic Station Catalogue (Council of Managers of National Antarctic Programs, 2017[3]), summer expeditions in seasonal stations host a median of 15.5 people (min 6, max 120), which is lower than summer expeditions in year-round stations which host a median of 60 people (min 9, max 1000), but also lower than the median of people in seasonal stations is lower than the number of people in winter-over context (19 people; min 2, max 153). Given this context, although the team size is still bigger than is expected in future LDSEM, it is potentially more aligned with then crew sizes during winter-over periods.

Team Structure

Definition: *"The extent to which a clear structure (i.e., specific roles and/or tasks to be carried out by each individual) exists within a team"*. The assumption for a Long-Duration Mission: *"Clearly assigned job roles for each crew member; strong team structure"* (Keeton et al. 2011).

The concept of team structure in summer Antarctic expeditions is characterized by clearly assigned roles and tasks for each member, reflecting the specialized and small nature of these expedition teams (Vessey and Landon 2017). This structure mirrors the organization observed in year-round Australian polar expeditions, where teams comprised scientists, tradespeople, and support personnel with designated roles and autonomous professional functions (Schmidt et al. 2005). These roles, ranging from construction to data collection, are complemented by household chores shared among team members, showcasing a balanced division of labor and responsibility (Nash 2022). Furthermore, expedition teams may include individuals with diverse backgrounds and expertise, selected based on criteria such as physical condition and personality characteristics (Nash 2022). Understanding the intricacies of team structure in summer as well as year-round Antarctic expeditions provides valuable insights for optimizing team performance and collaboration in isolated and extreme environments. Researchers focusing on team structure aspects can leverage these expeditions as a rich source of data, provided that metadata on team composition and roles are collected systematically during the research period.

Summary

Our critical review has provided some views supporting the conclusion that summer seasonal Antarctic expeditions could be considered a valuable analog for LDSEM. In some aspects, the conditions may be even more aligned with conditions of planetary exploration and inhabitation, compared to winter-over stations which are more reflective of spaceflight and orbital station context. Including studies of aspects critical for LDSEM can subsequently benefit the Antarctic stations by improving local conditions, and could be possibly applied in other harsh and remote environments and civilized contexts. Table 3 summarizes the main outputs of this critical review.

The availability of medical care in summer seasonal stations aligns with LDSEM as both are limited to basic medical care and medical support trained in expedition medicine. Some stations may require expeditioners to take emergency response training. Serious cases requiring advanced medical care rely on evacuation to facilites in other Antarctic stations, or in other continents. **Physical isolation** in both seasonal and year-round stations fulfills the definition of remote regions where evacuation to definitive care takes over an hour (Wakerman 2004). Compared to year-round stations with advanced medical facilities, seasonal stations usually rely only on basic medical care and may require transportation to other facilities in Antarctica, or outside. This places further demand on evacuation in summer, which is more feasible than in winter, but still challenging and can take multiple hours or even days due to weather, remoteness, and transportation limitations. The **danger** of summer expeditions seems to be prevalent enough to be classified as moderate (injury prevalence from 2:1 to 8:1, and medical evacuation from 0.02:1 to 0.04:1 in summer seasons (Pattarini et al. 2016), aligning with the assumption of LDSEM. The ratio of clinic visits per capita in summer expeditions is comparable to that of winter-over expeditions, demonstrating that both contexts face persistent hazards of the extreme environment, and thus serve as a suitable analog for conditions of LDSEM. The risk of injury persists even during transit phases, such as cruise transportation, highlighting the continuous nature of danger in remote and extreme environments. Specific injuries include bruises, lacerations, fractures, and dislocations, particularly among teams engaged in heavy physical work in cold and rough terrain. Orthopedic injuries are the most common, followed by internal medicinal, dental, dermatological, and other medical issues. Therefore, in the aspect of medical care availability, physical isolation, and danger, the seasonal summer stations may be treated as a suitable analog for LDSEM.

Crowdedness in future LDSM will be considerable, given that the habitat size should be comparable to a modest-sized RV for four to six people, leaving around 4 m^2 per person. Such a high degree of crowdedness is not achieved even in ICC analogs where the habitable area may range from 44.6 to 91.6 m^3/person (Tafforin 2015). The available area per person in summer seasonal stations (27.3 m^2/person) is lower than that of ICC analogs, and presumably lower than in winter-over context. Winter-over crews may enjoy the luxury of separate rooms, while seasonal summer expeditions may have to rely on shared sleep rooms, leading to lower **personal space**. Nonetheless, researchers interested in crowdedness should include metadata on station size, population, access to facility, and population dynamics to better understand crowdedness variance and its impacts. Findings from these studies could find application in the development of mitigation strategies applicable also in civilized contexts with unavoidable confinement.

The exposure to **external light** during summer Antarctic expeditions varies depending on location, with prolonged daylight hours ranging from around 14 to nearly 24 hours. Compared to traditional winter-over studies with near-constant darkness, the summer conditions are more similar to what might be experienced during future missions to Mars or the Moon, where sunlight exposure also varies based on location and may be near constant. Furthermore, summer expeditioners face increased UV levels, particularly due to the depleted ozone layer, posing risks of DNA damage and oxidization. **Internal light** is managed by artificial lighting in all stations equipped with electric infrastructure.

Antarctic expeditions operate **autonomously** and offer a compelling analogy for studying crew autonomy in space missions. The specific degree of autonomy varies based on cultural context, station rules, season, role, and environmental aspects. Literature suggests that Antarctic expeditioners generally have a higher level of autonomy than astronauts on the former Mir and current ISS orbital stations (Vessey and Landon 2017). Seasonal summer Antarctic expeditions often make critical decisions about logistics, safety, and scientific operations without immediate external support. Thus, these expeditions serve as a valuable analog for future long-duration space exploration missions (LDSEM).

Communication challenges in summer Antarctic expeditions somewhat resemble those anticipated in LDSEM, particularly regarding communication delays and limited access to real-time communication. On the ISS, crews benefit from near-constant voice communication, daily email exchanges, private medical conferences, and the ability to downlink digital photographs and stream video. However, future Mars missions will face communication delays of up to 44 minutes one-way, significantly limiting real-time communication and the exchange of voice messages, video, and imagery due to bandwidth constraints. Antarctic expeditions, particularly those in less accessible parts of the continent, face similar communication limitations due to the cost and logistical challenges of satellite services, resulting in low bandwidth and unreliable connections. Seasonal stations rely heavily on satellite phones, and very high-frequency (VHF) communication, and may lack internet access, which can isolate expeditioners further.

Comparing the **sensory conditions** of summer Antarctic expeditions with those of future long-duration space exploration reveals some parallels but one key difference. Indoor air quality is challenged by various factors, including increased CO_2 levels, microorganisms, chemical compounds, and pollutants generated from routine activities or external sources. Discomfort is also caused by odors from wastewater and sewage systems, drying clothes, inadequate personal hygiene, and noise from machinery and daily operations. However, a major difference is the ability to open windows for fresh air circulation, which may positively affect sensory conditions and overall well-being. This ability to ventilate the environment somewhat limits the direct comparability of Antarctic conditions to those expected in LDSEM missions, where such ventilation is not possible.

Summer Antarctic expeditions have access to sensory stimuli from the external landscape but may be considerably limited in the variety of **recreation options**, internet access, and food variability (**quality of life support conditions**), which distinguish them substantially from the year-round stations. There are parallels between the sensory deprivation experienced in summer Antarctic expeditions and that anticipated in LDSEM. Both scenarios involve a lack of diverse sensory stimulation, although individuals are still exposed to the landscapes of the external world. Certain areas in Antarctica with arid climates and low temperatures may share similarities with surfaces on Mars or the Moon. Both LDSEM and summer Antarctic expeditions are anticipated to have minimal opportunities for leisure activities. This limitation is due to factors such as small station or habitat size, remote location, and harsh environmental conditions. Thus, summer Antarctic expeditions in remote seasonal stations may pose a great analog for studying the effect of **sensory deprivation** expected in LDSEM.

The workload in Antarctic expeditions can vary based on factors such as station operations, research objectives, and individual responsibilities. The workload encompasses a wide range of activities, including fieldwork, data collection and analysis, equipment maintenance, and administrative tasks with a prominent workload decrease during transit phases. This diversity of tasks requires individuals to adapt to various roles and responsibilities. However, due to prolonged exposure to daylight, summer expeditioners may choose to work for an extended number of hours a day, contributing to the overall workload. Conclusively, the activities and workload in seasonal summer Antarctic expeditions are akin to the future LDSEM and may be suitable for comparison.

The **leadership, team structure,** and chain of command in summer seasonal expeditions are clearly defined and hold significant importance within the team. In some cases, a shared leadership structure is adopted depending on the context. The number of expeditioners in summer seasonal expeditions is lower than in winter-overing crews (median of 15.5 people, min 6, max 120; compared to a median of 19 people, min 2, max 153). Individuals are inherently **interdependent** in daily tasks and expedition objectives as they rely on mutual cooperation, meal preparation, and recreation. Therefore, seasonal summer Antarctic expeditions with small **team size** may thus mimic conditions of LDSEM well in aspect of leadership.

The ability to utilize seasonal summer Antarctic stations as a space analog may significantly enhance our capacities for addressing critical research gaps, mitigation strategies, and operational procedures testing. The opportunities for collaborations range from observational studies, through field tests of technology, to experiments on countermeasure effectiveness. Increased number of research opportunities will lead to bigger sample sizes, and faster resolution of the key problems, leading to more successful and safe missions. Insights can also inform the development of training programs for future astronauts and enhance the preparedness of crews for the demands of planetary exploration. Vice-versa, insights from these studies may drive technological innovations, enhanced environmental sustainability practices, and quality of medical care, improving the lives of expeditioners in seasonal stations or other remote and harsh areas.

Future research should validate our arguments through comparative studies between seasonal stations and year-round stations in both summer and winter. This will further refine our understanding of which scenarios best mimic planetary LDSEM conditions, and identify specific areas where each context provides unique insights. Polar researchers may consider implementing longitudinal monitoring of the physiological and psychological parameters of participants in seasonal expeditions to gather long-term effects potentially useful for future planetary LDSEM. Further collaboration between the space sector and Antarctic research may accelerate advancements, ensure diverse perspectives, and inspire interest in STEM fields and environmental sciences.

Characteristic	LDSEM	Summer in seasonal Antarctic station	Winter-over in year-round Antarctic station
Availability of Medical Care	Limited; basic emergency equipment and standard medications. Basic training in emergency response and medical procedures.	Some medical facilities available, but usually limited to basic care, reliance on evacuation for serious cases; better than space missions, but more limited than winter-overs. Lower availability than in other ICC analogs.	Comprehensive medical facilities available in most stations; may include basic to advanced treatments, including surgery. Lower availability than in other ICC analogs.
Crowdedness	Moderate to high; habitat size comparable to a modest-sized RV for four to six people (5.21 m^2 to 3.47 m^2 per person).	Median crowdedness of 27.3 m^2/person; varies by station size; higher crowdedness than winter-over stations. Higher crowdedness than other ICC analogs.	Median crowdedness of 178 m^2/person; generally lower crowdedness due to smaller teams and larger space allocation.
Danger	Moderate to high; daily tasks carry a moderate risk of injury; ongoing environment comprises a high degree of risk of injury and/or death.	Injury rate may range from 2 to 8 per capita. Evacuations from 0.02 to 0.04 per capita.	Injury rate may range from 4 to 10 per capita. Evacuations are rare but may happen at (0.01 per capita).
External Light Conditions	Moderate; exposure to sun will likely be consistent across the time during transit and on a foreign planetary surface (*e.g.*, Mars day is very similar to Earth's, but is 37.5 minutes longer)	Exposure to external light ranges from around 14 to nearly 24 hours, depending on time and location. Similar to what might be experienced during future missions to Mars or the Moon, where sunlight exposure also varies based on location.	Continuous darkness for extended periods, with minimal to no sunlight exposure due to the region's high latitude and the tilt of the Earth's axis. Suitable for simulating spacecrafts and stations, less for planetary LDSEM.
Internal Light Conditions	Anticipate full artificial light spectrum.	Interior of stations is illuminated by artificial light.	Interior of stations is illuminated by artificial light.
Physical Isolation	High; isolated to only other crew members. Escape would be impossible, or highly improbable.	Individuals in remote stations isolated to only other crew members. Some locations (King George Island) may encounter expeditioners from other stations; evacuation to definitive care can take multiple days to weeks depending on location and weather conditions.	Isolated only to other crew members; evacuation is extremely complicated.

Autonomy	Anticipate the crew to be much more autonomous than current operations; a moderate to high degree discretion of crew members over their choices and actions to complete mission objectives.	Expeditioners act autonomously with external support limited by communication channels availability.	Expeditioners act autonomously with external support limited by communication channels availability
Communication with Outside World	Moderate to minimal; although communication options would be available, crew members will often experience communication delays with the ground ranging from 4 to 40 minutes (for a full communication loop)	Communication options limited often only to satellite phone and VHF communication, some offer also e-mail connection. Communication delays subjected to time-zone differences and work schedules.	Communication options often involve internet connection, e-mail access, satellite phone, and VHF. Communication delays subjected to time-zone differences and work schedules.
Sensory Conditions	Moderate; anticipate some negative environmental conditions that will influence the quality of the environment including the lack of fresh air, presence of odious smells, as well as noise from machines and support systems, *etc*.	Possibility for ventilation with external air, but may lead to contamination with chemical compounds, pollutants and microorganisms. Discomfort may stem from odors, noise, and microbial characteristics.	Full confinement without external air possibility. Temperature regulated, discomfort may stem from noise, odors or microbial characteristics.
Sensory Deprivation	Moderate to high; anticipate a lack of sensory stimulation that would arouse a visual, tactile, olfactory, auditory, and/or taste response (*e.g.*, unlikely to have fresh food, plants, *etc.*)	Access to sensory stimuli from the external landscape, and limitations such as the absence of fresh food, internet connectivity, and recreational options within stations or camps contribute to sensory deprivation.	Access to plethora of recreational options and internet connectivity, but restricted sensory stimuli from the external landscape. Food options may be more variable in larger stations.
Workload	Moderate to heavy with some personal time; periods of low workload may occur during transit.	Heavy; prolonged daylight and outdoor access encourage long working hours; work driven by research and station needs.	Heavy; driven by station maintenance and research; critical due to isolation and harsh conditions.
Personal Space	Low; limited due to constraints of vehicle and habitat size.	Limited; especially in smaller or seasonal stations where people share rooms; less personal space compared to winter-over.	Generally better than summer expeditions; small private rooms often available for each team member.

Rest and Recreation Options	Minimal; few options anticipated, standard and constrained set of options.	Varies by station size; larger stations like McMurdo have extensive options, smaller stations have limited; camping very limited.	Extensive options in larger stations (gyms, saunas, theaters); necessary due to prolonged stay; more limited in smaller stations.
Quality of Life Support Conditions	Minimal; basic options for food, hygiene, and daily living.	Adequate but variable; basic provisions with some variability in food quality and variety; hygiene facilities present.	Higher quality and variety due to comprehensive facilities; important for long-term well-being in isolation.
Leadership	Assigned; strong role within the crew; clear designation of chain of command.	Formal station leaders with clear roles; shared leadership can occur; leaders have significant responsibility.	Similar to summer expeditions; leaders play crucial roles in ensuring safety and well-being in harsher conditions.
Team Interdependence	Moderate to high; many daily tasks require collaboration; shared meals and recreational activities.	High; essential for research, station maintenance, and well-being; shared meals and group activities common.	High; essential due to prolonged isolation and harsh conditions; strong emphasis on teamwork and shared responsibilities.
Team Size	Small; four to six crew members; likely to be mixed gender and multicultural.	Median of 15.5 people in seasonal stations (range: 6-120); larger in year-round stations (median: 60; range: 9-1000).	Median of 19 people (range: 2-153); smaller and more specialized teams compared to summer expeditions.
Team Structure	Clearly assigned job roles for each crew member; strong team structure with specific roles and tasks.	Formal leadership with specific roles; teams include scientists, trades people, and support personnel.	Similar to summer expeditions; additional roles and responsibilities due to longer duration and harsher conditions.

Table 3. Comparison Table: Long-Duration Space Exploration Mission (LDSEM), Summer Antarctic Expedition in Seasonal Station, and Winter-Over Antarctic Expedition in Year-Round Station. Key characteristics and their definition for LDSEM are drawn from NASA's Analog Assessment Tool (Keeton et al. 2011). Antarctic expeditions are compared based on findings from this papers' literature review.

Conclusion

In conclusion, summer seasonal Antarctic expeditions offer several significant parallels to planetary LDSEM, often superior to winter-over Antarctic expeditions, particularly in terms of medical care, crowdedness, team sizes, light exposure, sensory deprivation, and communication challenges. This finding has the potential to shift our perception of seasonal Antarctic expeditions as a valuable analog for LDSEM. By proposing the inclusion of summer Antarctic expeditions in the research toolbox for space analog missions, the paper sets a vision for their justified and effective use resulting in increased research possibilities, higher sample sizes, and faster resolution of key risks of LDSEM. Furthermore, findings from these studies can considerably improve the quality of life and safety in seasonal stations, as well as other remote areas on Earth.

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