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The role of Antarctic overwintering teams and their significance for German polar research

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Abstract. Germany has been operating permanently crewed research stations in Antarctica for more than 45 years. The opening of the Georg Forster Station (1976) and Georg von Neumayer Station (1981) initiated a period of continuous environmental monitoring that allowed both the former East Germany and West Germany to become contracting parties in, and achieve consultative status with, the framework of the Antarctic Treaty. This marked a milestone in German polar research. Continuous research at the Neumayer Station III, its two predecessors, and the now-dismantled former German Democratic Republic (GDR) Georg Forster Station is undertaken by teams of so-called "overwinterers", presently with nine members, who stay at the base for longer than an entire Antarctic winter. Their long-term stay in Antarctica is defined by isolation, separation from civilization, routine work to sustain long-term scientific observations, and unique personal experiences. This article is dedicated to them and outlines their part and role in the German Antarctic research landscape.

1 Introduction

Due to his early commitment to polar research, Georg von Neumayer (1826–1909) is considered the founding father of German Antarctic research. Late in the 19th century, von Neumayer advocated sending an expedition southward to explore the hitherto sparsely explored region around the South Pole (Christmann, 1976; Kertz, 1983). He also co-organized the first International Polar Year (1882–1883) and expeditions to Baffin Island in the Arctic and South Georgia in the South Atlantic. However, he never explored the Antarctic continent himself. In the early 20th century, Erich von Drygalski led the first German Antarctic expedition, which departed from Kiel in 1901 with the polar research ship *Gauß*. Later, in 1911, Wilhelm Filchner sailed into the Weddell Sea, seeking a navigable route to the Ross Sea (Krause, 2012). Alfred Ritscher, captaining the *Schwabenland*, led a politically and economically motivated mission in 1938/1939 on behalf of the National Socialist (Nazi) regime, aiming to secure access to whale oil and therefore bolster German economic independence. The outbreak of the Second World War, however, stopped further Antarctic expeditions worldwide (Lüdecke, 2003).

After World War II and the division of Germany into the German Democratic Republic (GDR; East Germany) and the Federal Republic of Germany (FRG; West Germany), German involvement in Antarctic discovery was put on hold for years. With both the FRG and GDR sidelined, the groundwork for establishing permanently crewed research stations in Antarctica was established during the International Geophysical Year in 1957–1958, which was absent of German involvement (Lüdecke, 2021), and the Antarctic Treaty was ratified in 1961. The 12 original signatory states (Argentina, Australia, Belgium, Chile, the French Republic, Japan, New Zealand, Norway, the former Union of South Africa, the former Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland, and the United States of America) agreed that the exploration of Antarctica should be conducted for non-military scientific purposes. Beginning again in 1975, FRG marine expeditions started to explore the Atlantic sector of the Southern Ocean, including the expeditions by the research vessels *Walther Herwig*, *Meteor*, and *Polarsirkel* in the austral summer of 1980/1981 (Hempel, 1981).

German Antarctic research entered a new era when the GDR joined the Antarctic Treaty in 1974 (Lüdecke, 2021) and established a small research base (officially named Georg Forster Station after meeting the criteria for consultative status in 1987) 2 years later at the Schirmacher Oasis (Gernandt, 1984; Paech, 1992; located close to the Russian Novolazarevskaya Station; Fig. 1a). The station's eponym, Georg Forster, had accompanied James Cook on his South Sea voyages and was the first German to set foot on Antarctic ground in South Georgia in 1775. The first GDR overwintering campaign in 1976 consisted of six men who built an independent base made of containers on solid rock, which was the first prefabricated container-only station of its kind (Gernandt and Meyer, 2021b). The Georg Forster Station continued to operate until 1993, several years after German reunification in 1990. The activities of the overwinterers at Georg Forster Station focused primarily on individual and temporary projects in ionospheric plasma and meteorological and geophysical research (including ozone measurement), as well as geodetic, geological, glaciological, and biological measurements. All of these projects are documented in the monograph of Bormann and Fritzsche (1995). Furthermore, the station played an important role in the investigation of ozone depletion in the southern polar stratosphere (Gernandt, 1987; Gernandt et al., 1989). The last overwintering at Georg Forster took place in the 1991/1992 season.

The FRG joined the Antarctic Treaty in 1979 and founded the Alfred Wegener Institute (AWI) for Polar and Marine Research in 1980. The following year, the Georg von Neumayer Station in Antarctica was completed on the Ekström Ice Shelf (Fig. 1b) and allowed the FRG to acquire consultative status. The subsurface station was housed in large tubes buried in the snow on the shelf (Fleischmann, 2005). Following an initial overwintering of non-scientific staff, the station's scientific observatories began to continuously record environmental data in March 1981 (Gernandt et al., 2007). The station was replaced in 1992 by the Neumayer II station, a second construction of large buried tubes. Neumayer II was replaced in 2009 by Neumayer III, a new aboveground station, which is still in operation today (Gernandt et al., 2007; Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, 2016; Gernandt and Meyer, 2021a; Fig. 2). The establishment of permanently crewed stations ushered in the era of German overwintering teams and their contribution to long-term scientific measurements in the fields of atmospheric chemistry, meteorology, and geophysics in Antarctica.

Today, Antarctic research in Germany is carried out by numerous research centres and universities served by two year-round observatories. In addition to the Neumayer Station III, the German Antarctic Receiving Station (GARS O'Higgins) has been operated by the German Aerospace Centre (DLR) in cooperation with the Federal Agency for Cartography and Geodesy (BKG) since 1991. GARS O'Higgins is located near the Antarctic Peninsula and is mainly used to receive Earth observation data from polar-orbiting satellites and for geodetic monitoring (Klügel et al., 2014). The station has been operated in cooperation with Chile by a year-round crew of four since 2010. In addition to these two year-round crewed research stations, German polar research is also supported by summer stations that are usually only active between November and February. These include the Dallmann Laboratory and Kohnen Station (both operated by the AWI) and the Gondwana Station (operated by the Federal Institute for Geosciences and Natural Resources, BGR). These stations are used for local measurement programmes but also serve as bases for scientific expeditions. This infrastructure is not reserved for use by operating institutes but is also utilized by researchers from numerous German and international institutes and universities. To provide financial support for universities involved in German Antarctic research, the German Research Foundation (DFG) established an extra priority programme in 2003, which is still active today.

In this article, we highlight the significance of the Antarctic overwintering teams to German polar research. In particular, we address the fields of study of the overwinterers, the environmental conditions during their wintering time, and how wintering conditions and scientific objectives have changed over time. Overwintering teams are often mentioned in the acknowledgements of the scientific studies which utilize the teams' work. Nevertheless, few papers (if any) centre the overwintering teams themselves as the subject of their study. Here, we focus on the work of the overwinterers and provide an overview of the research programmes and findings that their activities have enabled. In this re-framing, we focus primarily on the overwintering activities at the Neumayer Station(s) and, to a lesser extent, those related to the former Georg Forster Station.

2 Neumayer Station – long-term environmental observations on the Ekström Ice Shelf (East Antarctica)

Neumayer Station III is currently the permanently crewed research station of the AWI and the scientific and logistical centre for German polar research in Antarctica (Gernandt and Huch, 2009; Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, 2016). Here, long-term observations have been conducted in the fields of meteorology, atmospheric chemistry, and geophysics (König-Langlo and Loose, 2007; Weller et al., 2007; Eckstaller et al., 2007). These time series reach back through the operational periods of both predecessor stations, Georg von Neumayer and Neumayer II (Gernandt et al., 2007; Kohlberg and Janneck, 2007), and are complemented by measurements from the Georg Forster Station during the period of its operation. In addition, since 2003, the Neumayer Station (from this point, we use the term "Neumayer Station" as a collective term for all three stations on the Ekström Ice Shelf) has made a significant contribution to the monitoring component of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) for nuclear weapons control, in cooperation with the Federal Agency for Geosciences and Natural Resources (Christie and Campus, 2010; CTBT Annual Report, 2020). Over time, other long-term studies have also been carried out in fields as diverse as sea ice trends (Arndt et al., 2020), wildlife populations (e.g. Boebel et al., 2006; Zitterbart et al., 2011), medicine, and space travel analogues (e.g. Steinach et al., 2016; Stahn et al., 2019). Station operations differ substantially between the Antarctic winter season, during which only the long-term measurement programmes are maintained by the overwinterers, and the summer season, with far more personnel. During this period, the station also serves as a base for numerous Antarctic airborne and land-based logistical and scientific projects in western Dronning Maud Land during the austral summer months (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, 2016). In particular, the station's direct proximity to the grounding line of the ice shelf and the adjacent inland ice enables a broad range of field studies related to the interactions of grounded and floating ice, ocean currents, and tidal forces (e.g. Neckel et al., 2012; Eisermann et al., 2020; Smith et al., 2020; Schannwell et al., 2020).

Since 2001, AWI has also operated the Antarctic summer base, Kohnen Station, located approximately 550 km south of Neumayer Station on the Antarctic Plateau. Kohnen Station was established to drill a deep ice core in Dronning Maud Land (DML; Fig. 1a) as part of the European Project for Ice Coring in Antarctica (EPICA; Oerter et al., 2009). The ∼ 2770 m long ice core provided ice samples that were over 150 000 years old at the completion of the drilling operation in 2006 (EPICA Community Members, 2006). Since then, the station afforded further detailed analyses of the internal deformation of the borehole by the ongoing flow of the ice through which it was drilled and has been repeatedly used as a base for ground-based and airborne scientific measurement campaigns on the East Antarctic Plateau (e.g. Steinhage et al., 2013; Mieth and Jokat, 2014; Weinhart et al., 2020; Franke et al., 2021; Neckel et al., 2021).

3 Overwintering teams

The overwintering teams at the present and former Neumayer Stations and the former Georg Forster Station are a backbone of German Antarctic research. Without them, the continuity of the long-term measurements and the maintenance of the stations and their logistic capabilities would not be possible. The wintering season typically lasts 14 months, of which the crew lives in complete isolation for approximately 9 months (Fig. 3a). Over more than 4 decades, the primary tasks of scientific research have remained almost unchanged. While the duration of isolation is still determined by the overwhelmingly inhospitable conditions on the Antarctic continent, the composition of the wintering teams and the working conditions they experience during their 14-month stays have changed over time.

3.1 Crew and candidates

Members of the wintering team at Neumayer Station have several responsibilities, namely (i) to ensure long-term scientific observations, (ii) to maintain the research station technically, and (iii) to ensure the safety and well-being of the overwinterers. Nine team members collaborate toward attending to these responsibilities, including four scientists, who are responsible for the operation of the scientific observatories, three technicians attending to station maintenance, power supply, and telecommunications, one physician, and one cook. One of the candidates (usually the physician) also acts as the station leader. The station leader is the contact person and representative of the overwinterers (both officially and for media enquiries). Furthermore, the station leader is also responsible for safety both at the station and in the field and must ensure that the overwinterers can act as a team (for example, in the event of an emergency such as firefighting). Unlike the wintering crew of Neumayer Station, the crew of Georg Forster Station (usually six persons; Fig. 2a) was not completely isolated. Due to the direct proximity to the former USSR's Novolazarevskaya Station (Fig. 1a), no doctor, a reduced number of technicians, and a cook was only rarely needed at Georg Forster. Furthermore, because the science at Georg Forster station was primarily focused on individual and temporary projects and therefore not on long-term monitoring programmes (except for ozone balloon soundings), the tasks of the overwinterers (and their scientific background) regularly changed.

The essential challenge during the wintering period is to work and live in isolation as part of a non-exchangeable team. Ideally, therefore, the crew members must bring the following competencies with them: high intrinsic motivation, strong communication skills, physical, psychological and emotional resilience, stress resistance, a willingness to compromise in decision-making processes, pragmatism, emotional maturity, a good sense of humour, the willingness to be part of a team, and complete dedication to the goal of their mission. For the wintering, best leadership practices minimize hierarchies and ensure the creation of team identity and the structuring of everyday life and that regular reflection on the individual needs of team members ensures that the mental strain on all participants remains manageable (personal communication with Lukas Grolle, 2021). Nonetheless, it remains difficult to predict who will cope well in extreme environments like that of Neumayer Station.

Between 1976 and 1991, a total of 100 men overwintered at the Georg Forster Station. The station was completely deconstructed between 1992 and 1996 in accor-

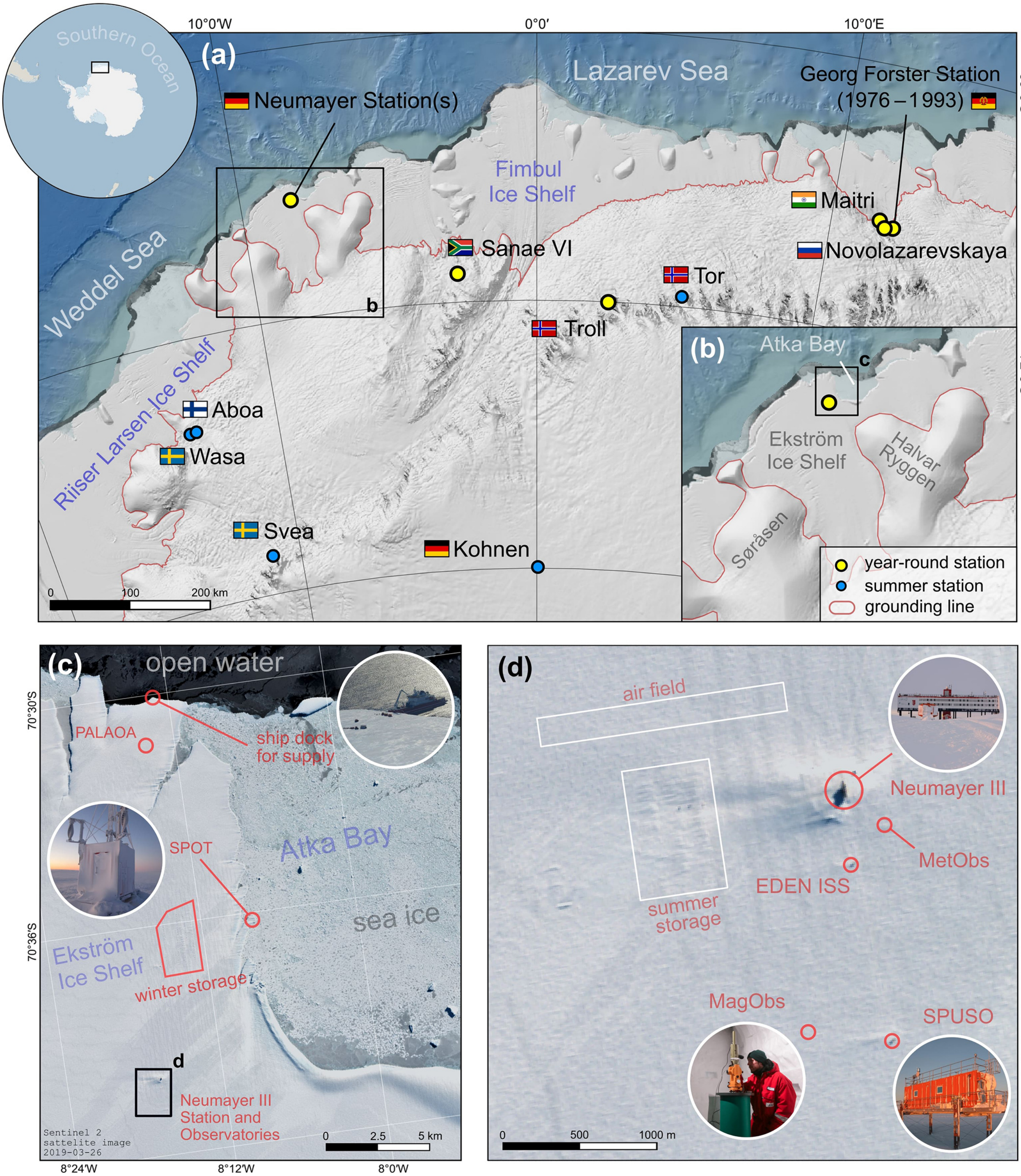

Figure 1. **(a)** Overview of research stations in western Dronning Maud Land (Antarctica). The inset **(b)** shows details of the Ekström Ice Shelf, where Neumayer Station is located. The regional setting of Atka Bay and its infrastructure, including the location of the ship dock and winter storage area is shown in panel **(c)**. Panel **(d)** shows the nearby infrastructure and the location of the long-term scientific observatories. The backgrounds in panels **(c)** and **(d)** are Sentinel-2 satellite images from March 2019. The ice surface topography and the locations of the stations in panels **(a)** and **(b)** are taken from the Quantarctica project (Matsuoka et al., 2021) and the sea floor bathymetry from Morlighem et al. (2020).

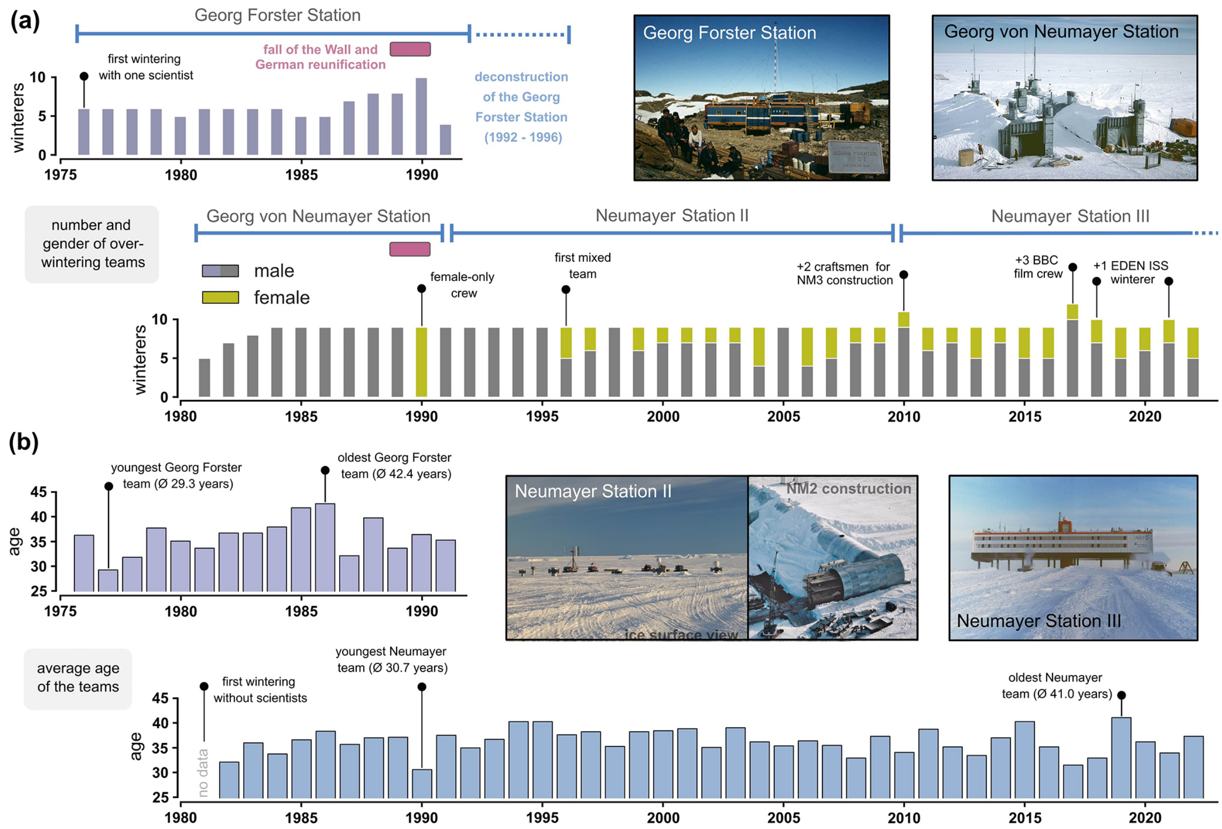

Figure 2. Development of the composition of wintering crews at the Georg Forster Station (70.77° S, 11.85° E) and Neumayer Station (for all three stations). **(a)** The number of male and female crew members for each season at the Georg Forster station (upper row) and Neumayer Station (lower row). In the same order, panel **(b)** shows the average age of the team members for both stations, respectively. Note that, for the average crew ages for Neumayer Station, only eight of nine ages were available from the seasons 1996, 1997, 2001, and 2019; for 1992, only seven of nine ages were available. Station generations are highlighted at the top of the figures in panel **(a)**. The photographs show the respective stations (partly in their construction phase) and have the following image credits: Georg Forster, Georg von Neumayer, and Neumayer Station II images by Hartwig Gernandt and the Neumayer Station III image by Steven Franke.

dance with the Protocol on Environmental Protection to the Antarctic Treaty. Since then, the site has been considered an official historic site by the Secretariat of the Antarctic Treaty in Antarctica (HSM 87; https://www.ats.aq/devph/en/apa-database/171, last access: 22 November 2022), with a plaque commemorating the former station (Fig. 2). From 1981 to 2022, the long-term scientific monitoring programmes and the continuous operation of the three Neumayer stations have been sustained by more than 370 overwinterers (Fig. 2a). However, over time, the social structure of overwintering teams at Neumayer Station has changed (Fig. 2). Mixed-gender teams were not sent until 1996. It should be emphasized that, with some exceptions, the proportion of women in crews remained (and still remains) below 50 % (Fig. 2a). The most notable exception is the all-female wintering team in 1990 (Sobiesiak and Korhammer, 1994), which was also the youngest team and also the first all-female overwintering team at any Antarctic station (Burns, 2007). The average age of the crews is between 30 and 40 years and has decreased slightly over time.

Infrastructure has also changed over time for the overwinterers. From the small containers aboveground or tubes buried in the ice which served the earlier stations (Fig. 2), Neumayer Station III has grown into a spacious and technically modern research facility. With this progress, the quality of life of the overwinterers has also changed. Nowadays, for example, a permanent internet connection enables the wintering team to remain closer to family, friends, and work colleagues than in the past. In addition, the safety and health of the overwinterers have improved significantly due to technical innovations and the introduction of telemedicine. There are also constant improvements to make wintering as environmentally friendly as possible, such as by increasing the share of alternative energy and improving waste management facilities and practices (Gernandt et al., 2007).

3.2 The wintering framework

Today, the wintering team of Neumayer Station III typically arrives in Antarctica in December and leaves again at the end of February (approximately 14 months later). Previously (at the predecessor stations), the transport of summer scientists, technicians, and wintering crew members took place mainly with icebreakers during long arrival and departure voyages, increasing the length of overwinterers' isolation well beyond their nominal 14 months on the ice. Apart from the austral summer seasons of 2020/2021 and 2021/2022, which were affected by the COVID-19 pandemic, these long journeys largely became a thing of the past because of the establishment of the DROMLAN air transport network (Dronning Maud Land Air Network) in 2002. DROMLAN operates between various hubs that enable passengers and freight to access Antarctica via South America, New Zealand, and South Africa. The common route to Neumayer Station is via Cape Town (South Africa) to one of the blue ice runways in Dronning Maud Land (e.g. Novo Airbase, located close to Novolazarevskaya Station, or the runway close to the Norwegian Troll station; Fig. 1a). For the GDR overwinterers, transport by aeroplane was possible even from 1986 with the establishment of an air traffic system to Antarctica by the Soviet Antarctic Expedition programme.

During the austral summer from November to February, the new and previous wintering teams at Neumayer Station overlap. This time is used to familiarize the arriving overwintering team members with their daily work in the station and the field, to prepare them for the coming period of isolation, and also to familiarize them with the monitoring programmes. During the Antarctic winter at Neumayer Station, the overwinterers are exposed to outdoor temperatures as low as −50 °C and wind speeds of more than 100 km h^{-1} during long-lasting snowstorms (Fig. 3b). During the months of isolation, the overwinterers must solve all emerging problems on their own. For this, not only the role of the doctor and the team leader is of central importance but also the professional competence of the technicians and the cooperation within the team. To ensure this, a 4-month training and preparation phase takes place before the journey to Antarctica. Training involves, among many other things, preparation for possible emergency and conflict scenarios, including alpine and glacial rescue methods, and extensive firefighting training that takes special account of the fact that liquid water is not available in large quantities in Antarctica. These conditions differ from the wintering conditions at the Georg Forster Station. Due to the proximity to the neighbouring Russian station, the overwinterers were less socially isolated. In addition, since individual research projects and not only long-term measurement programmes were carried out, there was no long overlapping phase in which the successors had to be trained (Hartwig Gernandt, personal communication, 2022).

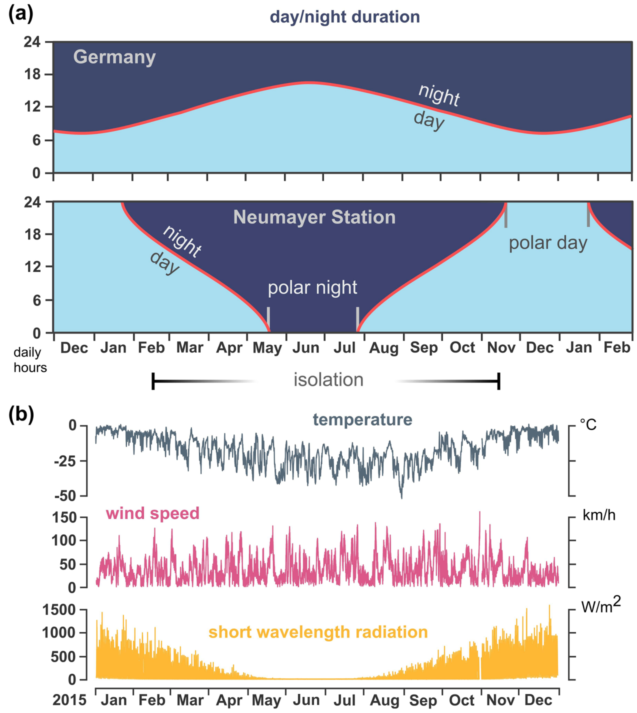

Figure 3. Panel **(a)** shows the distribution and duration of day- and nighttime hours per day (y axis) during an entire wintering cycle (∼ 14 months) in Germany (upper panel; Berlin, ∼ 52° N) and at Neumayer Station (lower panel; ∼ 70° S). Temperature, wind speed, and short-wavelength radiation are shown for the year 2015 in panel **(b)**, as recorded at the Neumayer III weather station in 1 Hz intervals and averaged to minute values.

4 Long-term observatories

The core mission and station concept of the Neumayer Station III and its predecessors has been to provide long-term scientific measurements for a better understanding of the Earth system (König-Langlo et al., 2007; Weller et al., 2007; Eckstaller et al., 2007). Since long-term measurements in Antarctica are only recorded at very few locations, they are particularly important. This section presents an overview of the long-term measurement programmes and what tasks the overwinterers have to perform to ensure the continuity of the data.

4.1 Atmospheric observations

Atmospheric conditions and essential climate variables at the Neumayer Station have been continuously measured since 1981 (König-Langlo and Loose, 2007). The meteorological data are shared with several international networks, primarily with the Global Telecommunication System (GTS) from the World Meteorological Organization (WMO) but also with the Baseline Surface Radiation Network (BSRN; Driemel et al., 2018), the Network for the Detection of Atmospheric Composition Change (NDACC), and the GCOS Reference

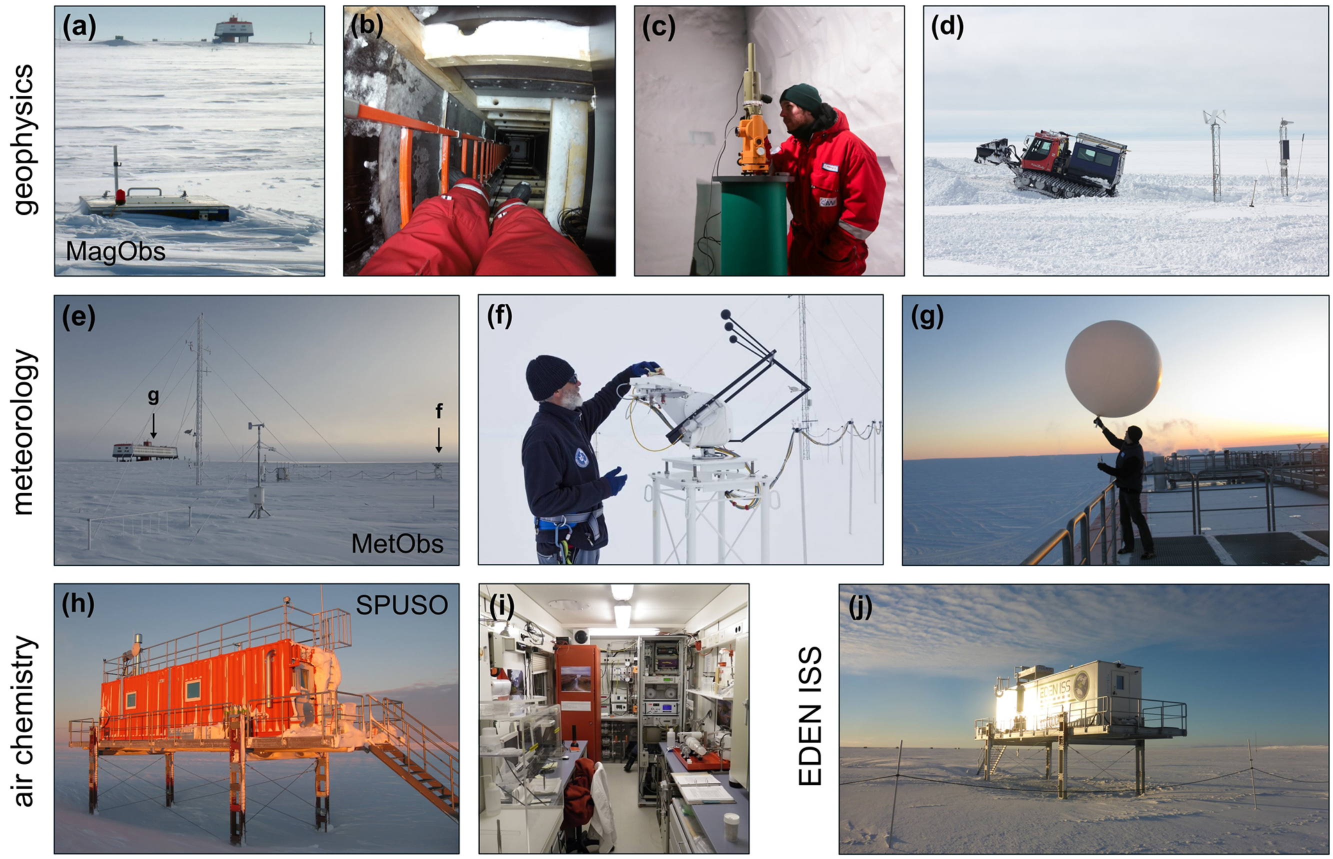

Figure 4. Photographs of the long-term observatories of Neumayer Station III and EDEN ISS (2015–2021). Panels **(a–c)** show the geophysical observatory (geomagnetics and seismology) located in the vicinity of the station, panel **(d)** shows the maintenance on a remote geophysical station (Søråsen; seismology), panels **(e–g)** show the atmospheric (meteorological) observatory network and balloon ascent, and panels **(h–i)** show the atmospheric chemistry observatory. The EDEN ISS container for plant cultivation is shown in panel **(j)**. Image credits are as follows: panels **(a–d)** by Steven Franke, panels **(e, h–j)** by Jölund Asseng, and panels **(f, g)** by Thomas Steuer.

Upper-Air Network (GRUAN). Meteorological parameters at the surface and in the upper air column are continuously recorded by an array of several measuring instruments near Neumayer Station to characterize the regional climatology (Figs. 1d and 4e–g; König-Langlo et al., 1998). Moreover, the observatory has evolved into a substantial meteorological forecast centre for the entire Dronning Maud Land region.

Strict daily routines determine the work of the overwinterers in the meteorological observatory. Visual synoptic weather observations are made outside the station for visibility, cloud cover, cloud types, and cloud heights every 3 h. This visual synoptic programme is completed every 3 h between 09:00 and 24:00 UTC. The measurements at 03:00 and 06:00 UTC are optional and complemented with automated measurements. Due to the large number of measurements taken throughout the day, it is common for the meteorologist to alternate with one of the other teammates who has to be trained in the routine work to accomplish as many measurements as possible. The synoptic measurements are used for weather forecasting worldwide, particularly for local weather monitoring and forecasting in Antarctica due to the sparse coverage of measurement stations. Physical parameters such as temperature, humidity, and wind speed/direction are automatically recorded. Furthermore, daily radiosonde ascents by balloon are performed (Fig. 4g) to record a vertical profile (up to 35 km altitude) of physical properties including temperature, relative humidity, air pressure, and wind direction and speed. Once a week, an additional ozonesonde is launched to record the vertical ozone profile throughout the troposphere and lower stratosphere (König-Langlo and Loose, 2007). Between September and December, when the ozone hole forms over Antarctica, ozone soundings are conducted up to 3 times a week to monitor this process in detail.

The discovery of the Antarctic ozone hole, and the global environmental policies it spurred, illustrates the necessity of continuous atmospheric measurements in the Antarctic (Solomon, 2019). When scientists from the British Antarctic Survey published their results on a springtime depletion of the ozone layer in the stratosphere over Antarctica in 1985 (Farman et al., 1985), which was linked to human use of chlorofluorocarbons (CFCs), this demonstrated that contemporary knowledge of the atmosphere was far from complete. Ozone measurements in the Antarctic started in the mid-1950s. After approximately 20 years of relatively constant levels, ozone in Austral spring months began to decline toward the end of the 1970s. Since then, a systematic decline in springtime ozone levels has been evident. By 1984, the thickness of the ozone layer over the Halley Research Station in Antarctica was only about two-thirds of that in previous decades (Farman et al., 1985). The wintering team from the GDR initiated the first German ozone soundings in 1985 (Gernandt, 1987; Gernandt et al., 1987), which were continued at weekly intervals (and every 3 d during Austral spring between September and November) at the Georg Forster Station until 1992 (König-Langlo and Gernandt, 2009). After that time, the ozone sounding programme was continued at Neumayer Station (König-Langlo and Gernandt, 2006) and the records of both stations together constitute a valuable scientific dataset of the vertical distribution of ozone in Antarctica (taking into account that the measurement series were obtained at two different locations; Fig. 1a). This continuous series of measurements, together with the overall measurement network in the Antarctic (in which overwinterers play a significant role), forms the basis of a detailed climatological analysis of the vertical extent and temporal variation in ozone depletion over Antarctica.

4.2 Measurement of gases and trace elements in the atmosphere

As demonstrated by the ozone layer depletion in Antarctica, the composition of gases and particles in the atmosphere responds sensitively to (human-made) environmental changes. Antarctica's air is the cleanest and least affected by human activities on Earth (Weller et al., 2007). Therefore, it can be seen as a natural baseline against which changes in the Earth system can be detected very quickly. Hence, measuring trace gases in the atmosphere, such as CO_2, methane, nitrous oxide, and various aerosols, is important from a scientific and environmental protection perspective. A better understanding of the composition of all components of the Antarctic atmosphere is also of fundamental importance for interpreting palaeoclimate based on air samples recovered from ice cores. This task requires continuous sampling and analysis of the atmosphere at many locations in Antarctica over a long period of time (Piggott et al., 1977).

The atmospheric chemistry observatory (SPUSO, short for Spurenstoff-Observatorium; Figs. 1d and 4h, i) at Neumayer Station (in operation since 1983) is a platform to conduct long-term measurements of aerosols, long-lasting and reactive trace gases such as ozone, and halogen radicals to study atmospheric processes in this region (Weller et al., 2007, 2011, 2013, 2015). In addition, samples of climate-relevant greenhouse gases such as CO_2, methane, nitrous oxide, and water vapour are collected, and their isotopic compositions are analysed (e.g. Weller et al., 2002; Levin et al., 2010). Since 1997, the observatory has been part of the Global Atmosphere Watch (GAW) network (https://community.wmo.int/activity-areas/gaw, last access: 2 January 2022). The observatory is located in a clean-air corridor about 1.5 km south of the Neumayer Station (Fig. 1d). Winds from the north are very rare, so the observatory is spared contamination by the station's emissions. The overwinterers's daily workload with respect to maintaining the observatory depends on whether something needs to be repaired, reinstalled, or restarted. The observatory is visited every day to take aerosol samples. Once or twice a month, gas samples are filled in steel cylinders and glass vessels. In addition, it is used as a base for short-term studies in which measuring instruments are operated for only one summer season or a few annual cycles. Collected samples are analysed in laboratories in the scientific home country rather than on-site. To avoid contamination of the air in the vicinity of the upper observatory, it must be visited on foot under all weather conditions. The 1.5 km route is marked with a rope in case visibility is limited during heavy snowstorms.

4.3 Geophysical observations

Because of Antarctica's inaccessibility, less is known about its geological structure, tectonic activity, and geodynamic history than in other regions on Earth. Direct studies of the subsurface are difficult because of the kilometre-thick ice cover. Therefore, much of our current knowledge is based on passive geophysical measurements, such as the recordings of earthquakes or measurements of the Earth's magnetic field, which have enabled major advances in understanding the Antarctic crust and mantle (e.g. An et al., 2015; Ritzwoller et al., 2001), and the temporal evolution of the geomagnetic core field (Bloxham et al., 2002). For a better understanding of the Antarctic continent, denser coverage with seismic and magnetic stations is needed (Pappa et al., 2019; Gaya-Piqué et al., 2006). Such data help us learn more about the geological structures beneath the ice and the long-term changes on the Earth.

Seismological observations (earthquake recordings) have been carried out continuously at and around the Ekström Ice Shelf since 1982. The permanent network consists of three sites transmitting data in real time (Eckstaller et al., 2007; Fromm et al., 2018), with (i) one on the Ekström Ice Shelf in close vicinity to Neumayer Station (integrated into the magnetic observatory, MagObs; Figs. 1d and 2a–c), (ii) a multi-instrument site on Halvfar Ryggen southeast of Neumayer Station, and (iii) a second remote site on the Søråsen ice rise southwest of the station (Fig. 1b). The entire seismological network consists of several additional long-term and mobile short-term, self-sufficient offline stations distributed throughout western Dronning Maud Land (Eckstaller et al., 2022). The seismic network is capable of detecting large earthquakes from all around the world, in addition to small regional earthquakes, and even smaller local cryogenic events – so-called “icequakes” (Eckstaller et al., 2007; Hammer et al., 2015).

The tasks of the overwinterers with respect to long-term geophysical measurements vary considerably. There is a daily routine for seismological quality assurance and earthquake detection (and other seismic registrations, such as icequakes). The entire previous day’s data are inspected, and onset readings of detected earthquakes are made. The most important aspect of this task is to provide the detected seismic phases to seismological data centres (such as the International Seismological and National Earthquake Information centres) and, if possible, to associate the arrivals with earthquakes from international catalogues. Over the years, a large database of seismological information has been built based on the phase recordings of earthquakes (and other seismic events) acquired by the overwinterers. The seismological data of Neumayer Station are available to scientists worldwide to study the solid Earth system and, in particular, to better understand the local and regional Earth structure (Müller et al., 2008; Bayer et al., 2009).

Maintenance work at the more distant seismological stations at Halvfar Ryggen and Søråsen is mainly carried out during the summer months (Fig. 4d). Due to the substantial quantity of snow that can accumulate during a single year, this can involve time-consuming and physically demanding work to reposition the stations to higher ground. If a remote station malfunctions during the winter, then temperature and weather conditions must be carefully considered before deciding whether or not a servicing traverse should be attempted to bring the station into operation again.

Furthermore, three-component and total intensity measurements of the geomagnetic field have been measured continuously at Neumayer Station since 1983. The MagObs is part of a global network designed to obtain a homogeneous time series to study the long-term variations in the core field and space weather (GFZ; German Research Centre for Geosciences, 2016). The data are streamed in real time, archived at Neumayer Station, AWI, and GFZ, and post-processed data are transferred to the INTERMAGNET network (https://intermagnet.github.io/, last access: 2 January 2022). The magnetic observatory is located 1.5 km south of Neumayer Station in a (by 2021) 18 m deep ice cave (Figs. 1d and 4a–c). Every 2–3 d, manual absolute measurements must be carried out to measure the declination and inclination of the magnetic field to calibrate the recordings and validate data quality. The MagObs, like Neumayer Station III, is located on the ice shelf (which moves and rotates over time), and there is no geographically fixed reference point in the surrounding area. To account for the effects of this, a gyro measurement must be conducted each month to determine geographic north.

4.4 Sea ice monitoring

Atka Bay regularly freezes in winter, and its proximity to Neumayer Station (Fig. 1c) makes it an ideal experimental laboratory to better understand the processes and physics associated with sea ice development and its interactions with the ocean and atmosphere. The seasonal evolution of sea ice (its formation and breakup) has been monitored since 2010 as a part of the Antarctic Fast Ice Network (AFIN) at several sampling sites across the bay. Sea ice and snow thickness and temperature, platelet ice layer thickness, and freeboard heights are the primary monitoring focus (Fig. 5a, b; Arndt et al., 2020). The analysis of a compilation of these data from 2010 to 2019, and considering individual earlier observations, shows a predominantly seasonal character and that the regrowth of the so-called fast ice (fast ice is sea ice that is “fastened” to the coastline) in Atka Bay has been constant without any significant interannual trend (Arndt et al., 2020). With the continuation of the AFIN programme at Neumayer Station, these survey results provide the baseline observations from which to determine when, and if, future changes in the atmosphere and ocean due to global warming might start to affect Atka Bay. The overwinterers are responsible for all measurements during the isolation months and most of the measurements during the summer season. Surveying all points in the bay requires nearly an entire working day, during which more than 90 km have to be travelled by Ski-Doo (a brand of snowmobile). A natural break in the measurement comes when the sea ice fragments and disperses almost entirely at the end of most summer seasons. Renewed measurements are only possible after careful assessment of the accessibility and thickness of the next season’s new sea ice in the bay, to ensure the safety of those making the measurements.

4.5 Passive wildlife monitoring

In 2006, the geoscientific and atmospheric long-term measurements were supplemented by a hydro-acoustic monitoring station, the Perennial Acoustic Observatory in the Antarctic Ocean (PALAOA; Fig. 5e). The station permits the continuous and autonomous operation of underwater sound recordings over wide frequency and dynamic ranges (Boebel et al., 2006). The hydrophones record the vocalizations of marine mammals primarily to investigate their spatiotemporal habitat patterns in the eastern Weddell Sea (e.g. Schall and van Opzeeland, 2017). For example, van Opzeeland et al. (2013) show that, in this particular region, Antarctic coastal waters are likely of greater importance to humpback whales than previously assumed. The live stream of PALAOA was shut down in 2016. Since then, sound samples recorded by the underwater observatory are stored on hard drives and retrieved once a year. In addition, wildlife observations also focus on life outside the water.

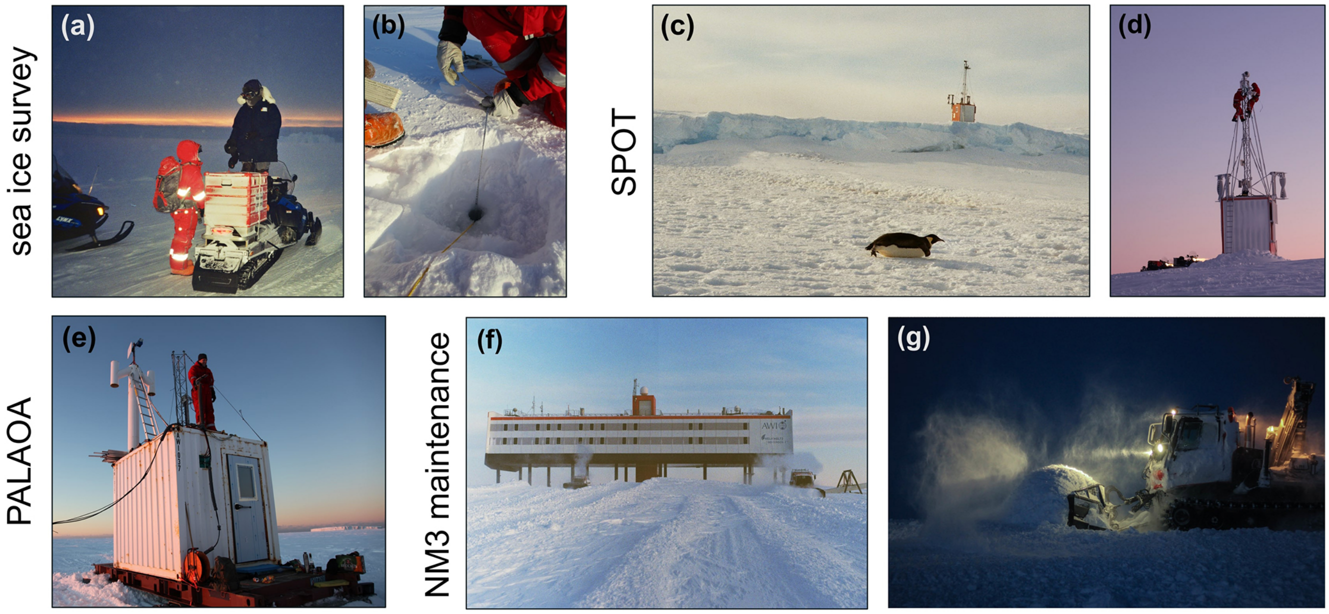

Figure 5. Panels **(a–b)** are photographs taken during the regular sea ice thickness surveys on Atka Bay. **(c–d)** The location and maintenance work on the camera system of the autonomous penguin observatory (SPOT). **(e)** The PALAOA container for passive acoustic wildlife monitoring (nowadays without live stream and no longer a large container). **(f, g)** Snowploughing with PistenBully machines (snow groomers) after a snowstorm. Image credits are as follows: panels **(a–d, f, g)** by Steven Franke and panel **(e)** by Jölund Asseng.

A remote-controlled observatory for behavioural and ecological research (SPOT – Single Penguin Observation and Tracking) was established in 2013 to monitor the emperor penguin colony in Atka Bay (Fig. 5c, d; Richter et al., 2018). The observational system is comprised of multiple overview and high-resolution cameras that continuously monitor penguin activity on sea ice (Fig. 1c). The system was used, among other things, to study biophysical phenomena, such as the huddling behaviour of penguins during the cold winter months (Zitterbart et al., 2011). Both observatories are designed to run fully autonomously with minimal maintenance throughout the year. The role of the overwintering team is to ensure that measurements restart in the event of system failures and that camera lenses are cleaned when they freeze over (Fig. 5d). In addition, the lubricating grease on the wind generators at SPOT must be refilled at regular intervals to ensure a self-sufficient energy supply. On several occasions, SPOT has needed to be moved to another location by the wintering crew as a precautionary measure because the shelf ice was threatening to break off at the previous location.

4.6 Development of plant cultivation technologies for food production in space

Between 2015 and 2021, the EDEN ISS greenhouse system (a multi-national project led by the German Aerospace Center – DLR; https://eden-iss.net/, last access: 2 January 2022) was integrated into operations at Neumayer Station. The EDEN ISS project explores the development of advanced cultivation techniques of plant-based food for use on international space stations and, in the long term, for lunar and martian habitats. The extreme remoteness and hostile environment of Neumayer Station make it a suitable space analogue and, as such, an ideal base for the project. In 2018 (DLR) and 2021 (DLR/NASA), additional overwinterers took care of the greenhouse, which was sited several hundred metres away from the station in a container. During the experimental phase in 2018 and 2019, various vegetable types with a total biomass of 646 kg were harvested (Zabel et al., 2020; Zeidler et al., 2021).

5 Maintenance, servicing, and food provisions

The technical wintering team provides the basic framework for all the station's activities (both logistical and scientific). The biggest task includes maintenance work on the station, which additional technicians ensure during the summer. During the isolation period, it is essential to secure communication and IT, in addition to power supply and heating. In particular, the reliable operation of safety technology, air conditioning, fresh water generation (via snow melting), and wastewater treatment and sanitary facilities, as well as filling of the fuel tanks, must be ensured (the fuel depot is located in the winter storage area; Fig. 1c). Preparing the runway for the arrivals and departures of polar aircraft is one of the essential tasks during the summer months (Figs. 1d and 5g). Moreover, the polar vehicles (e.g. Ski-Doo snowmobiles, PistenBully machines, and Arctic Trucks) must be maintained and repaired to ensure mobility. Snowstorms bring the special challenge of excess snow accumulation around the station, which, in the long term, must be removed to prevent the station from becoming buried (Fig. 5f, g). Another important issue is the station's food supply. For this reason, the cook must plan food for the entire season. Fresh food can be transported to the station in limited quantities only during the Antarctic summer months between November and February. Frozen food products are stored in large quantities, especially during the winter isolation period. With the start of the EDEN project, however, fresh vegetables were temporarily available even in the deepest winter.

6 Summary and outlook

Although numerous scientific studies mention the work of wintering teams in their acknowledgements, the scientific contributions of overwinterers, focusing primarily on securing long-term measurements, are often hidden in the background. Although regrettable, this oversight is not necessarily unusual, and the work of long-term monitoring teams is seldom recognized (Nisbet, 2007). In German Antarctic science, however, the scientific contribution of overwintering teams is an additional effort to that required for the maintenance of Neumayer Station as an international logistics centre for Antarctic expeditions. Generations of overwinterers have contributed continuous long-term measurements that enable research on the physics of the atmosphere and its components such as ozone, CO_2, methane, and aerosols to better understand changes and effects in the climate system (e.g. König-Langlo et al., 1998; König-Langlo and Gernandt 2006; Weller et al., 2002, 2011, 2013, 2015). Important information is also collected via geophysical measurements of the Earth's interior to better understand the geological history and structure of the Earth (e.g. Eckstaller et al., 2007; Müller et al., 2008; Bayer et al., 2009). These core scientific observatories are linked to many other scientific programmes that study, among other things, the evolution of sea ice (Arndt et al., 2020) and the behaviour of marine mammals (e.g. van Opzeeland et al., 2013; Richter et al., 2018). For all programmes, the presence and work of overwinterers is essential. Their hard work provides the foundations for present-day German research in Antarctica, and their maintenance and operation of permanently crewed research stations have substantially heightened Germany's role in long-term environmental monitoring of the Antarctic. Here, we have highlighted the essential role these teams play in Antarctic work and provided a historical overview of the work that they have helped carry out over the 60-year history of German research in the Antarctic. The physical and social challenges of the crew during Antarctic wintering expeditions formed a separate field of research with respect to human stress and adaptation in isolation. It should be emphasized that wintering nowadays has become more comfortable and safer in contrast to the German wintering pioneers of the 1970s and 1980s. Nevertheless, the motivation to promote and facilitate scientific research, and the fundamental experiences of all overwinterers, remains the same.

Data availability. The meteorological data from Neumayer Station are archived on PANGAEA (to access the individual data sets and data collections, see https://www.awi.de/en/science/long-term-observations/atmosphere/antarctic-neumayer/meteorology/datasets.html, last access: 28 November 2022). Moreover, meteorological data from Neumayer Station are archived in the various international data networks mentioned in Sect. 4.1.

Yearly air chemistry data from Neumyer Station are archived on PANGAEA under the search term "Air chemistry at Neumayer station, Antarctica, during the year [YYYY]", where [YYYY] represents the respective year. The entire collection can be accessed from https://www.pangaea.de/?q=Airchemistry+at+Neumayer+station,+Antarctica+during+the+year (last access: 22 November 2022). Moreover, the data from the air chemistry observatory is transferred to the Global Atmosphere Watch (https://www.gaw-wdca.org/, last access: 22 November 2022) and ICOS (Integrating Carbon Observation System; https://www.icos-cp.eu/, last access: 22 November 2022).

Seismological data from the Geophysical Observatory of Neumayer Station III (station codes VNA1, VNA2, and VNA3; network code AW) can be obtained from the GEOFON data centre of the German Research Centre for Geosciences (GFZ; https://geofon.gfz-potsdam.de, last access: 22 November 2022). Magnetic data from the geophysical observatory of Neumayer Station III can be obtained from the International Real-time Magnetic Observatory Network (INTERMAGNET; https://intermagnet.github.io/, last access: 22 November 2022).

Author contributions. SF wrote the paper with contributions from all co-authors. All authors of this paper have overwintered at Neumayer Station and thus represent a cross section of expertise from the different parts of the scientific operation and wintering experience. AE was a member of the first scientific wintering team in 1982 and established the geophysical observatory. To this day, he is still one of the observatory operators. TH is a field operations manager and medical coordinator for the Neumayer Station and is responsible for coordinating the annually rotating wintering teams. He overwintered in Antarctica in 2017 as a physician and station manager. JA worked as a meteorologist and station manager during the overwintering in 2011 and has since been part of the team that operates the geophysical observatory. TS and SF were part of the 2016 overwintering team and managed the operations of the Air Chemistry Observatory (TS) and the Geophysical Observatory (SF).

Competing interests. The contact author has declared that none of the authors has any competing interests.

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