Polar Research

PERSPECTIVE

The Troll Observing Network (TONe): plugging observation holes in Dronning Maud Land, Antarctica

Christina A. Pedersen,[1] Birgit Njåstad,[1] Wenche Aas,[2] Elin Darelius,[3] Sébastien Descamps,[1] Stig Flått,[1] Tore Hattermann,[1] Stephen R. Hudson,[1] Wojciech J. Miloch,[4] Simen Rykkje,[1] Johannes Schweitzer,[5] Rune Storvold[6] & Stein Tronstad[1]

[1]Norwegian Polar Institute, Tromsø, Norway; [2]NILU, Kjeller, Norway; [3]Geophysical Institute, University of Bergen, Bergen, Norway; [4]Department of Physics, University of Oslo, Oslo, Norway; [5]NORSAR, Kjeller, Norway; [6]NORCE Norwegian Research Center AS, Tromsø, Norway

Abstract

Understanding how Antarctica is changing and how these changes influence the rest of the Earth is fundamental to the future robustness of human society. Strengthening our understanding of these changes and their implications requires dedicated, sustained and coordinated observations of key Antarctic indicators. The Troll Observing Network (TONe), now under development, is Norway's contribution to the global need for sustained, coordinated, complementary and societally relevant observations from Antarctica. When fully implemented within the coming three years, TONe will be a state-of-the-art, multi-platform, multi-disciplinary observing network in data-sparse Dronning Maud Land. A critical part of the network is a data management system that will ensure broad, free access to all TONe data to the international research community.

Keywords

Research infrastructure; access to data; international collaboration; atmosphere; solid Earth; marine–cryosphere interaction

Correspondence

Christina A. Pedersen, Norwegian Polar Institute, Fram Centre, PO Box 6606 Stakkevollan, NO-9296 Tromsø, Norway. E-mail: christina.pedersen@npolar.no

Abbreviations

ACO: Atmospheric Composition Observatory (TONe)
ATCM: Antarctic Treaty Consultative Meeting
DML: Dronning Maud Land, Antarctica
FIO: Fimbulisen Ice Shelf Observatory (TONe)
IA: Infrasound Array (TONe)
ICO: Integrated Cloud Observatory (TONe)
IO: Ionosphere Observatory (TONe)
MOMO: Multidisciplinary Ocean Moored Observatory (TONe)
NPI: Norwegian Polar Institute
RPAS service: Remotely Piloted Aircraft System service (TONe)
SA: Seismic Array (TONe)
SMO: Seabird Monitoring Observatory (TONe)
TONe: Troll Observing Network
Troll RS: Troll Research Station (Norway)

Antarctica—key to global change

Human societies are currently confronted with a wide range of interconnected and interacting challenges, as highlighted *inter alia* in the latest assessment from the Intergovernmental Panel on Climate Change (Shukla et al. 2022) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Díaz et al. 2019). The consequences of the ongoing climate and environmental changes permeate numerous aspects of human existence, including food security, health risks, disrupted livelihoods and relocation needs. Understanding how the key climate and biodiversity drivers evolve, as well as implications of these changes, is crucial to enable mitigation and societal adaptation. Long-term observations enhance our understanding of the processes, provide an early warning system for potential disruptions and help the development of informed policies for societal development and environmental conservation.

Antarctica and the Southern Ocean play important roles in the ongoing change. Its physical and biological properties interlink with the rest of the Earth through atmospheric, cryospheric and oceanic connections and, as a result, impact climate, weather, ecosystems, ecosystem services, etc. well beyond the region. Chown et al. (2022) provide a summary of, and insight into, the key Antarctic global connectors. Understanding how Antarctica is changing and how these changes influence global changes is fundamental to future global societal robustness.

Citation: *Polar Research* 2024, *43*, 10370, http://dx.doi.org/10.33265/polar.v43.10370

Building and strengthening our understanding of these changes and implications require dedicated, sustained and coordinated observations of key Antarctic indicators.

Antarctica is a large continent, covering 14 million km^2, or roughly one and a half times the area of Europe, the USA or China. An extensive observation and data-gathering effort is required across the entire Antarctic continent and its surrounding ocean to better inform research and modelling; vast areas of the continent lack any form of sustained observation system. Long-term observations from the continent are limited both in space and time and are unevenly distributed, mainly taking place near the almost 80 (seasonal and permanent) research stations, of which most are located on the Antarctic Peninsula or along the Antarctic coast. The Council of Operators and Managers of Antarctic Programs provides a simplified overview of the permanent observation capabilities associated with the existing research stations in its Antarctic Station Catalogue (COMNAP 2017).

Norway has a long presence in Antarctica, with Norwegian explorers and whalers contributing substantially to 19th- and 20th-century scientific explorations of the continent and its waters. Dedicated scientific investigations have been the key activity during the last half century, and Norway aims to maintain its active role in international scientific efforts to better understand Antarctica's role in the Earth system. To support these efforts, Norway operates Troll RS in DML (20°W to 44°38′E; Fig. 1). Troll RS is one of six all-year stations in DML. While most of the other stations in DML are at or near the coast, Troll RS has a unique inland location on the slope of the Antarctic plateau. Norway is now planning to modernize Troll RS to provide a new, efficient and functional platform for researchers working at, or remotely from, the station. During this process, how to better utilize Troll RS for sustained observation efforts has been given careful consideration.

The Troll Observing Network (TONe)

TONe is the Norwegian response to the call for sustained, coordinated, complementary, geographically spread and societally relevant long-term observations from Antarctica. When fully implemented, TONe will be a state-of-the-art, multi-platform, multi-disciplinary observing network in data-sparse DML.

TONe is centred at Troll RS (Fig. 1), the location of which makes it excellent for studying processes in, and anthropogenic influences on, the Earth's atmosphere and climate (Kallenborn et al. 2013), space weather phenomena over DML and inter-hemispheric asymmetries in ionosphere response to geomagnetic activity in the polar regions (Sato et al. 2015; Alfonsi et al. 2022). The low level of background noise renders it well suited for seismic monitoring (Schweitzer et al. 2014). The nearby coast of DML is an ideal location for ocean research because of its influence on Antarctica's contribution to sea-level rise through ocean–ice-shelf interactions and the ocean system (Vernet et al. 2019), including the biological carbon pump in the Southern Ocean (Moreau et al. 2020). At nearby Svarthamaren, one of the world's largest Antarctic petrel *(Thalassoica antarctica)* colonies has been monitored for the last 35 years and will continue to yield important insights into seabird biology, the health of the marine environment and the impact of climate change on ecology (Descamps et al. 2015; Descamps et al. 2023).

The TONe infrastructure comprises eight dedicated observatories that will enhance our understanding of climate, atmospheric and oceanic processes, the dynamics of the inland ice sheets and their influence on sea level and the marine ecosystems. It also establishes an RPAS as the first of several planned shared research infrastructure services, providing a cost-efficient manner to collect a wide variety of data over a significant portion of DML with a limited environmental footprint. A critical part of the network is a well-structured data management system that will ensure broad, free access to all TONe data to the wider research community (Fig. 2; Table 1).

The observing network in detail

TONe is financed through the Research Council of Norway's Funding for Research Infrastructure of National Importance, which aims to give the Norwegian research community and business sector access to relevant, up-to-date infrastructure that facilitates high-quality research for an innovative, sustainable society.

The NPI is responsible for coordinating the establishment of the TONe infrastructure, while the University of Oslo, the University of Bergen, the climate and environmental research institute NILU, the seismology research institute NORSAR and the Norwegian Research Centre NORCE are Norwegian partners and co-owners (with the NPI) of the infrastructure and will be responsible for its future operation. The British Antarctic Survey, the University of Leeds, Washington State University and the University of Kansas Center for Research, Inc. contribute expertise in specific fields and provide in-kind instrumentation to supplement the infrastructure financed by the Research Council of Norway.

Implementing TONe will take five years, and the full infrastructure is expected to be established and ready for use from 2027.

Citation: *Polar Research* 2024, *43*, 10370, http://dx.doi.org/10.33265/polar.v43.10370

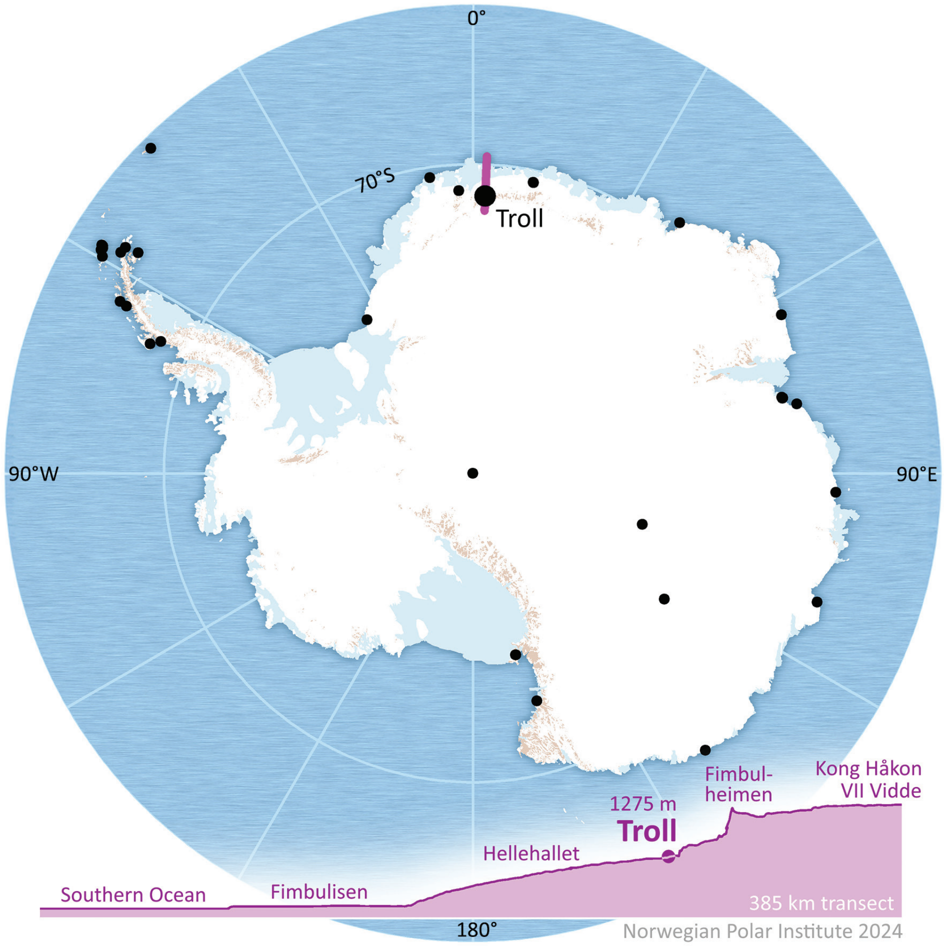

Fig. 1 Troll RS is in an exceptional place: no other permanent station is further inland in DML or elsewhere on the slope of East Antarctica. The black dots represent year-round stations. Troll RS also facilitates access to key locations in the DML region and its coast. At and around Troll RS, TONe fills the observational void in this region.

Troll RS was established in 1989 and upgraded to a year-round station in 2005. The station accommodates an overwintering team of six and up to 50 staff and scientists during the Antarctic summer. People and light cargo are transported to Troll RS by planes, which land on a blue-ice airfield 7 km from the station. Normally, there are one or two intercontinental flights per month during the summer months of November–February. Heavier cargo is transported by ship to the ice edge and thence by tracked vehicles to the station, about 200 km inland. The size of the main station building is currently about 500 m^2. There are several additional support and living buildings separated from the main building.

The Ionosphere Observatory (IO)

IO focuses on studies of the upper atmosphere, which is partially ionized (i.e., includes free electrons and ions) and which in the polar regions is directly coupled to the near-Earth space environment. This magnetosphere–ionosphere–thermosphere coupling is complex. It often results in strong flows in the upper polar atmosphere and leads to the development of instabilities and turbulence and consequently to irregularities at various scales in the ionospheric plasma density. In the polar regions, this coupling is also characterized by precipitation of energetic particles from the solar wind and magnetosphere down to the upper atmosphere. The aurora australis (Southern Lights) is a visual manifestation of these interactions. Associated space weather effects can severely impact man-made infrastructure both on Earth and in space, such as satellite-based navigation and radio communication (Bothmer & Daglis 2007). It is therefore crucial for society to understand these phenomena and to develop space weather models and forecasts. The polar ionosphere in the Southern Hemisphere is on average more

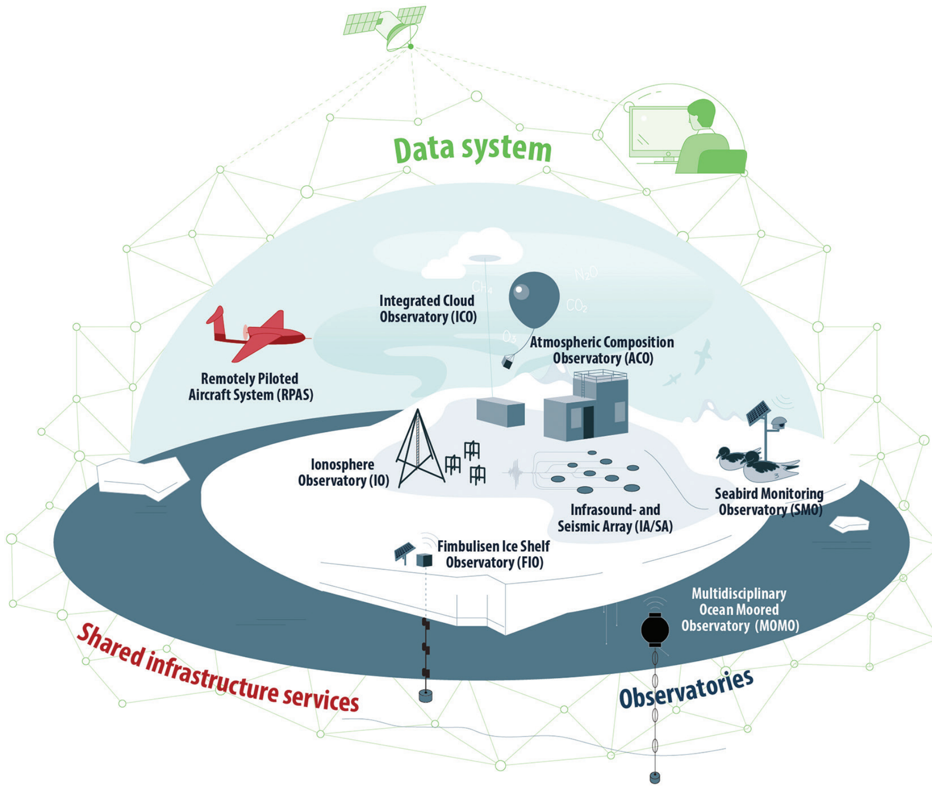

Fig. 2 TONe is a state-of-the-art, multiplatform, multidisciplinary observation network, consisting of eight distinct observatories, an RPAS service and a data management system that will provide wide and free access to the observational data.

structured and turbulent than in the north, and it is vital to understand these differences and allow for long-term monitoring (Jin et al. 2019; Tsagouri, Belehaki et al. in press). Through TONe, the ionospheric observations currently at Troll RS will be expanded by a digital ionosonde, which is an ionospheric radar capable of measuring the dynamics of ionospheric irregularities and obtaining electron density profiles in the ionosphere (Reinisch et al. 2009). Together with an all-sky-imager, which monitors auroral emissions, global navigation satellite system, global ionospheric scintillation and total electron content monitoring receivers and magnetometers will provide a complete picture of ionospheric dynamics in this part of Antarctica. The IO at Troll RS will become a key observatory and will provide long-term measurements of electron profiles and ionospheric structuring (Alfonsi et al. 2022). Combining these measurements with complementary measurements from other Antarctic stations will contribute to the development of models for the entire upper atmosphere (Tsagouri, Themens et al. in press).

SANAE-IV and Neumayer III are the closest research stations to Troll RS in DML. They are located more Equatorward from the statistical auroral oval and provide complementary measurements, such as magnetometers and global ionospheric scintillation and total electron content monitoring receivers that are used in collaborative studies (Skjæveland et al. 2021). The high-frequency SuperDARN radar at SANAE-IV points towards Troll RS, providing measurements right above the IO at Troll RS. Other stations with space weather instrumentation in DML are located on the coast: Maitri, Novolazarevskaya and Syowa. Only a handful of digisondes are deployed in other sectors of Antarctica (e.g., at Davis, Zhong Shan and Jang Bogo). In general, ionospheric instrumentation in Antarctica is sparse and is co-located with permanent research stations. International collaboration is required to understand the ionospheric dynamics over the continent (Alfonsi et al. 2022). IO at Troll RS fills the observational gap in DLM and will contribute to such collaborative initiatives.

The Atmospheric Composition Observatory (ACO)

ACO monitors atmospheric chemical composition and properties. The ACO expands NILU's current atmospheric observatory at Trollhaugen, a peak 1 km east of Troll RS, which already holds some of Antarctica's longest year-round, high-quality atmospheric series of measurements

Table 1 Overview of the TONe observatories and services, their instruments, observations, owners and responsible researchers.

Observatory or service[a]	Infrastructure owner (responsible researcher)	Instruments and observed variables
ICO	NPI (Stephen Hudson)	Year-round measurement programme; microwave radiometer, two lidar systems, cloud radar and weather balloons/radiosondes; measures cloud properties (temperature, height, thickness, density and particle size, shape and phase) and their impact on the surface energy balance.
ACO	NILU (Wenche Aas)	Three new instruments: a Piccaro cavity ring-down spectrometer measuring CO_2, CH_4 and CO; a TSI aerosol particle sizer for larger particles (0.6 – 25 µm), a Pandora remote sensing spectrometer for vertical column of trace gases (O_3, NO_2, SO_2 and formaldehyde).
IO	Univ. of Oslo (Wojciech Miloch)	Digisonde-Portable-Sounder-4D (a digital ionosonde produced by Lowell Digisonde International), including multiple antennas (transmitter and receiver). The system measures electron density profiles, turbulent structures and their movement in the ionosphere.
IA	NORSAR (Johannes Schweitzer)	An infrasound array consisting of nine sensors (co-located with the nine SA sites) measuring low-frequency sound signals from events in the atmosphere and the ice.
SA	NORSAR (Johannes Schweitzer)	A seismic array consisting of 10 sensors at nine locations will provide information on seismic activity in DML, throughout Antarctica and the whole globe. It estimates amplitude, frequency, velocity and direction of seismic signals caused by earthquakes, icequakes, explosions, etc.
FIO	NPI (Tore Hattermann)	For time series of ice-shelf mass balance and warm-water inflow, instrumentation at two locations will measure currents, temperature and salinity in the water column beneath the ice shelf, turbulence in the ice-shelf–ocean boundary layer, sound sources for future glider campaigns under the ice and melt rate.
MOMO	NPI and Univ. of Bergen (Tore Hattermann and Elin Darelius)	Instrumented ocean moorings over the continental shelf at 6°E for measuring temperature, salinity, currents, ice thickness, oxygen, carbon dioxide, chlorophyll-a, echo soundings and passive acoustics. Navigational instruments for under-ice gliders.
SMO	NPI (Sébastien Descamps)	Automated monitoring using time-lapse camera to provide information about colony size, breeding phenology and breeding success. These observations will be complemented with regional studies from RPAS.
RPAS	NORCE and NPI (Rune Storvold and Stig Flått)	Two large fixed-wing aircraft, with VHF radar system, GHz UWB radar, aerial camera, meteorological sensors and a hyperspectral imager. Encrypted communication system with high bandwidth for line-of-sight transmissions up to 200 km, in addition to satellite communication beyond this. Flight endurance of 10 hours, providing a range of 1000 to 1500 km.
DATA	NPI (Stein Tronstad)	At Troll RS, data are stored on two servers in a cluster, to ensure maximum uptime and secure storage. Via the local station network, they will communicate with the observatories to collect data. Data from observatories that are not connected to the local network will be manually transferred to the server when researchers return from the field.

[a] ICO: Integrated Cloud Observatory; ACO: Atmospheric Composition Observatory; IO: Ionosphere Observatory; IA: Infrasound Array; SA: Seismic Array; FIO: Fimbulisen Ice Shelf Observatory; MOMO: Multidisciplinary Ocean Moored Observatory; SMO: Seabird Monitoring Observatory; RPAS: Remotely Piloted Aircraft System service.

of contaminants, aerosols, trace gases and UV/ozone. The measurements started in 2007, but the observatory itself was moved to its current location in 2014. The new observations include state-of-the-art instrumentations to monitor trace gases and aerosols that are relevant for understanding the climate and the ozone hole. Through such observations, we will detect changes that may have implications for global climate and study long-range transport of air pollutants into DML. The ACO will strengthen the foundation for understanding the Antarctic atmosphere and its impact on climate, provide input to large-scale models in polar regions and contribute to global satellite validation.

Three instruments have been installed at ACO as part of TONe. (1) A Picarro cavity ring-down spectrometer gives measurements of CO_2, CH_4 and CO that are quality assured in accordance with the international standards for greenhouse monitoring developed by the Integrated Carbon Observation System and the World Data Centre for Greenhouse Gases. (2) A TSI aerosol particle sizer that measures aerosols at different size fractions expands the size distribution information available from a differential mobility particle sizer focusing on particles smaller than 0.8 mm. The measured sizes will now range from 0.01 mm to 25 mm. The measurements comply with the guidelines developed by the Aerosol, Clouds and Trace

Gases Research Infrastructure and contribute to the World Data Centre for Aerosols. (3) A Pandora instrument measures trace amounts of O_3, NO_2, SO_2 and formaldehyde in the atmospheric column using differential optical absorption spectroscopy. This instrument is part of the Pandonia Global Network, which ensures systematic processing and dissemination of data and especially targets satellite validation of atmospheric trace gases for the US and European space agencies.

The Pandora and the aerosol particle sizer instruments are the first of their kind to be installed and to measure continuously in Antarctica. While there are sites occasionally measuring the size distribution of smaller aerosols, this is, to our knowledge, the only continuous, year-round measurement of aerosol size distribution of this wide size range of particles in Antarctica. For climate gas studies, the US National Oceanic and Atmospheric Administration has been conducting continuous CO_2 measurements at the South Pole since 1975 and has a long CO_2 and CH_4 time series collected through flask sampling at Halley and Syowa stations since the 1980s. Additionally, there are sites with sporadic and more campaign-based climate gas measurements. The high-resolution Picarro instrument is to the best of our knowledge unique.

The Integrated Cloud Observatory (ICO)

ICO targets the properties and radiative effects of clouds and aerosols, which constitute two of the largest uncertainties in global climate models, especially in the polar regions. It consists of a suite of ground-based remote sensing instruments to measure macro- and microphysical properties of clouds and aerosols and increased meteorological and radiative measurements. This combination of cloud radar, depolarisation and Raman lidars and microwave radiometer, with in situ validation by radiosondes, has been deployed at several sites around the world and has provided valuable insight into clouds' effect on the surface energy budget (e.g., Bennartz et al. 2013), among other things. During 2016, the Atmospheric Radiation Measurement West Antarctic Radiation Experiment project had campaigns to carry out similar measurements at McMurdo Station and on the West Antarctic Ice Sheet, and there have been campaigns with similar instruments at Princess Elisabeth Station. The Continuous Observations of Aerosol–Cloud Interactions in Antarctica project has been carrying out ground-based remote sensing measurements of clouds at Neumayer Station in DML since 2023; these measurements have been ongoing for only a year but are meant to continue. Other than these, we are not aware of any similar measurements carried out in Antarctica. The unique location of Troll RS—between the high inland ice plateau and the coast, right on the boundary between cold and cool (around freezing point) summers—will make these measurements a valuable resource for Antarctic climate studies. The measurements will complement the observations in the ACO and allow studies of factors that influence evaporation/sublimation and surface and sub-surface melt and refreezing in areas around the station that are dominated by exposed mountain tops, blue ice and perennial snow cover. RPAS-based radiometers for net radiation and albedo measurements will improve our understanding of spatial inhomogeneities in the cloud cover and how inhomogeneous ground conditions affects representativeness of the point measurements for the wider region.

The Seismic Array (SA)

SA focuses on the dynamics of the ice and solid Earth in DML. A simple seismic station installed by NORSAR at Troll RS in 2012 has shown that the area is one of the best places to measure seismic waves in Antarctica. It is located away from the coast and is therefore less influenced by oceanic noise, and it is on solid ground, so the sensors do not move with the ice. The new seismic array will upgrade this existing station into a high-quality seismic observatory, not only compared to other stations in Antarctica but also in a global context. The array will record signals from all types of seismic events, including earthquakes, icequakes, iceberg calving, explosions and oceanic swell. The new seismic array will record not only much smaller signals than the existing single station does, but it will also measure the propagation directions and velocities of these signals (Schweitzer et al. 2012). This additional information will be essential to associate observed seismic and infrasound signals to common sources and to locate them in the dynamic cryosphere.

The new array will be the southernmost installation of its type installed on solid ground. It will comprise 10 seismic sensors located in 10 boreholes at nine array sites close to Troll RS. The boreholes will be 3–5 m deep and will be drilled in the permafrost to reduce the influence of yearly and daily temperature changes on the highly sensitive sensors. At all nine sites, very broadband instruments and at one site one additional extreme low-frequency broadband instrument will be installed. All array data will be digitized and transferred in near-real time to contribute to the Norwegian node of the European archive for seismic data. The only other seismic array in DML has been operated, since 1997, near the Neumayer Station III on the Ekström Ice Shelf. Although Neumayer Station III has a less favourable location than Troll RS, analysis of the combined data from the two arrays will greatly improve the monitoring capabilities in the western DML.

Citation: *Polar Research* 2024, *43*, 10370, http://dx.doi.org/10.33265/polar.v43.10370

The Infrasound Array (IA)

IA measures low-frequency pressure (sound) waves generated by atmospheric events, such as meteors, volcanoes, explosions and oceanic swell, as well as abrupt ice movements (icequakes). These waves can be used to analyse atmospheric dynamics and vertical coupling between different parts of the atmosphere. The propagation of infrasound waves in the atmosphere is influenced by weather conditions such as wind and temperature. This allows infrasound waves from known sources (such as storm systems, volcanoes and oceanic swell) to be used for analysing the state of the middle and high atmosphere.

Nine infrasound sensors, along with their noise reduction systems, will be installed in an array configuration. To reduce the ecological impact and the logistics requirements and to achieve the greatest possible synergy for the data analysis, the nine sensors will be co-located with the seismic array.

Four other infrasound arrays are dedicated to monitoring the international Comprehensive Test-Ban Treaty in Antarctica—all located at stations near the Antarctic coast. Only one of these four arrays is in DML; it is close to the Neumayer III Station and has been operative since 2003. Analysis of the combined infrasound data is anticipated and will help to improve the location of infrasound sources in the whole region.

The Fimbulisen Ice Shelf Observatory (FIO)

FIO will provide measurements that will help us understand the processes shaping ice sheet mass balance as well as the oceanic properties under the largest ice shelf in DML. A time series of oceanic properties beneath Fimbulisen was initially established with moorings that were deployed through hot-water-drill holes at three sites during the NPI's Fimbul field campaign in 2009/10 (Hattermann et al. 2012). Today these instruments provide the longest continuous record of ocean temperature and currents under an Antarctic ice shelf, showing that a sudden shift towards sustained warm inflow since mid-2016 was caused by large-scale changes in the Southern Ocean climate (Lauber et al. 2023). These changes had direct implications for basal melting at Fimbulisen during 2016–19 (Lindbäck et al. 2023), illustrating how remote processes impact the ice-shelf mass balance in this sector of Antarctica.

The existing instrumentation beneath Fimbulisen has surpassed its anticipated lifetime of five years, and extending these observations in time and scope is the primary objective of FIO. For that purpose, a combination of risk-minimising and cutting-edge instrumentation will be deployed under the ice shelf to carry on—at an upgraded level—the long-term monitoring of ocean properties under the northern part of Fimbulisen (which is 200 m thick) and its central part (400 m thick). Instrumentation for long-term monitoring of warm inflows beneath the ice will be complemented with detailed observations of the under-ice shelf geometry and hydrography in the ice–ocean boundary region will contribute significantly to new formulations of basal melting for global-scale climate models, ultimately reducing uncertainty in future sea level rise. FIO also includes co-located autonomous measurements of surface and basal mass balance and ice-shelf motion (snow accumulation, dynamics, tides, strain). In-situ water sampling, sediment coring and visuals through the ice-shelf borehole will provide unique insights into the past evolution of the physical environment and its connection to the marine ecosystem. Under-ice shelf sound sources for acoustic navigation (e.g., future autonomous glider campaigns) within the cavity will also—for the first time worldwide—be developed.

Although hot-water-drilling has been used to deploy oceanographic instruments beneath Antarctic ice shelves for several decades (Mac Ayeal 1984; Makinson 1994), only a few places around Antarctica have multi-year time series of ice-shelf cavity properties; continuous long-term records are extremely rare. In the 1990s, several ice-shelf cavity moorings were deployed beneath the Ronne Ice Shelf in the southern Weddell Sea (Nicholls et al. 2009), providing longer than seasonal records. One of these historical sites was re-established in 2015 (Vaňková & Nicholls 2022) and was extended with sites on the Filchner Ice Shelf (Hattermann et al. 2021), which have collected data until the present. In the early 2000s, several ice-shelf cavity moorings were operative for several years beneath the Amery Ice Shelf (Herraiz-Borreguero et al. 2013), and long-term observatories were established, in 2017, under the Ross Ice Shelf (Stevens et al. 2020).

The Multidisciplinary Ocean Moored Observatory (MOMO)

MOMO targets the physical, biogeochemical and biological properties in the Weddell Gyre inflow/Antarctic Slope Front, off the DML coast in the ocean area Kong Haakon VII Hav. Currently, there are very few observations that resolve the seasonal cycle and fluxes of near-shore biological production around the continent. MOMO will serve as a reference point at the inflow of the Weddell Gyre to increase our understanding of changes in climate dynamics and the carbon cycle in the Atlantic sector of the Southern Ocean. The combination of long-term measurements on the shelf (MOMO) and measurements underneath the ice shelf (FIO) is unique and enables studies of the relationship between the variability and trends in the current and front and the circulation and melt rate under the ice shelf. An array of three oceanographic moorings will be maintained across the continental shelf break and slope region, with instrumentation to resolve the seasonal and interannual variability of the Antarctic coastal current slope front dynamics in the 'fresh-shelf' regime (Thompson et al. 2018). Profiling current meters and conductivity–temperature–depth sensors will monitor the eastern Weddell Gyre boundary current. Densely spaced thermistors will resolve variations of the Warm Deep Water, which is transported along the shelf break as part of the large-scale circulation (Paih et al. 2020) and is the largest source of heat melting the ice shelf (Nøst et al. 2011). Biogeochemical sensors for dissolved oxygen, chlorophyll and CO_2, as well as sediment traps, will provide insights into primary productivity and carbon cycling, while passive and active acoustics link those dynamics to zooplankton and higher trophic activity. In a region with abundant deep-drafting icebergs, advanced expendable sensor technology will be employed to gain access to the surface properties that are important for physical (Zhou et al. 2014; Hattermann 2018) and biological (Kauko et al. 2020; Moreau et al. 2023) processes, but which remain largely under-sampled in the region. The work of deploying and maintaining the MOMO instruments will be coordinated with Troll RS supply cruises, which have been extended to facilitate basic oceanographic research operations. A containerized science platform has been established on the station's supply vessel to facilitate these TrollTransect cruises since 2020/21, which allow for mooring maintenance and additional hydrographic profiling and water sampling.

After pioneering efforts in the late 1960s and 1970s (Foldvik et al. 1985), moored instruments have been routinely used in ice-infested Southern Ocean waters since the 1990s. Still, most observatories south of the Polar Front and in Antarctic continental shelf regions were deployed seasonally or for just a few years. Within the past two decades, significant international efforts have been made to establish long-term observatories in the Weddell and Amundsen–Bellingshausen seas, with a primary focus on constraining the glacier–ocean interactions in these regions. With their multidisciplinary objective, MOMO's long-term time series will aid in filling critical gaps in the sparsely observed coastal environment around Antarctica. MOMO will fit into international efforts to build an Integrated East Antarctic Marine Research observatory (Gutt et al. 2022), which will allow us to understand—and project the consequences of—climate change and will support the sound management of conservation efforts in the Southern Ocean.

The Seabird Monitoring Observatory (SMO)

SMO collects data on the biology of seabird populations, with a focus on Antarctic petrels, and through this enables studies of the health of the marine environment (Piatt et al. 2007). Existing population and demographic data suggest a decline in some seabird populations in DML, suggesting that the marine environment outside DML has been rapidly changing. Continuous data collection over prolonged and regular time periods is the cornerstone of wildlife monitoring. The SMO is based on automatic monitoring in Svarthamaren and Jutulsessen, two of the largest inland seabird colonies in Antarctica. It will use automatic time-lapse cameras, combined with machine learning approaches (e.g., Hayes et al. 2021; Tuia et al. 2022) to provide information on such key parameters as population size, breeding success and timing of breeding. SMO will facilitate the expansion in time and space of existing, but limited, seabird monitoring efforts in DML. Other seabird species are similarly monitored elsewhere in Antarctica. For example, a colony of emperor penguins (*Aptenodytes forsteri*) in Atka Bay, close to the Neumayer III Station, has been monitored since 2013 by an automatic observatory based on multiple cameras (Richter et al. 2018). Several colonies of Adelie (*Pygoscelis papua*) and chinstrap (*P. antarctica*) penguins have been monitored across the Scotia Arc or on the Antarctic Peninsula via a network of time-lapse cameras (Black et al. 2018; Hinke et al. 2018). In East Antarctica, a network of 21 remotely operated time-lapse cameras has been installed in the period 2005/06–2010/11 to monitor Adelie penguin colonies along a roughly 90° longitudinal gradient (Southwell & Emmerson 2015). Combined with such seabird monitoring in other parts of the Antarctic continent, the SMO will enhance our understanding of Antarctic wildlife responses to climate change and, by extension, changes in marine ecosystems.

TONe RPAS-based services

Where the observatories provide time series from fixed locations, the RPAS service will complement and enhance them by expanding the data collection capability horizontally and vertically to cover larger parts of DML. The drone-based measurements and sensor systems will enable the collection of unique data from the atmosphere, cryosphere (e.g., precipitation distribution, glacier and ice-shelf thickness, sea-ice distribution and properties) and marine and terrestrial ecosystems (e.g., primary production at the ice edge, seabird colony distribution

Citation: *Polar Research* 2024, *43*, 10370, http://dx.doi.org/10.33265/polar.v43.10370

and sizes in the whole DML). The RPAS service will be developed, established and tested, and a pilot phase will be conducted in the Antarctic summer season of 2026/27, where a wide range of data will be collected to prove the concept of the system. The RPAS services will be made available by the end of the TONe implementation phase.

The RPAS services are designed to support the observatories that have missions requiring aerial data and to support scientists that need aerial data from the DML region. The main RPAS infrastructure will consist long-range fixed-wing drones with an endurance of about 800 km, controlled through a combination of satellite and direct radio communication. The fixed-wing drones will normally be operated out of Troll RS, but the flexible system will allow for remote field operations from field camps. The ground station will be in a mobile shelter, with a small shop allowing for deep field operations. Smaller electric multi-rotor and fixed-wing drones, with ranges up to 100 km, will be deployed as needed.

The long-range fixed-wing drone will be instrumented with one of three different instrument packages at a time. (1) The optical package will comprise a hyperspectral imager in the visual and near infrared. Planned uses are vegetation mapping, spectral albedo and ocean colour. (2) The radar systems package will combine UHF/VHF radar and a 2–8 GHz ultra-wide band radar to observe ice and ice-shelf thickness as well as surface stratigraphy, indicating annual snow accumulation and distribution. (3) The atmospheric package will be made up of broadband long- and shortwave radiometers looking both upward and downward to measure surface albedo and net radiative fluxes. This package will support modelling as well as addressing spatial inhomogeneities and the representativeness of Troll RS with regard to the DML atmosphere.

Basic aerial camera and meteorological sensors will be common to all three configurations. In addition to collecting data, the drones could also serve as data mules, using broadband radios to pick up data from remote stations.

The data management system

An essential part of the infrastructure, the data management system ensures and promotes open and unrestricted access to the data collected from the observatories and RPAS service. The data system consists of an on-site data infrastructure to ensure secure and structured management of TONe data in Antarctica, as well as permanent data storage at data centres in Norway and abroad. A planned TONe web portal will provide unified access to all TONe data.

TONe data sets will be published worldwide, making them accessible through major polar and global data portals. The open-access approach will make the data available to a much larger group of scientists (including early career researchers) and allow the wider scientific community to work on Antarctic data without having to be involved in large and costly field-based projects. The data collection capacity provided by TONe will also stimulate a wide range of new interdisciplinary studies from DML.

Conclusion

The vast and enigmatic landscapes of Antarctica hold invaluable insights into our planet's climate and environmental health. Long-term monitoring initiatives in this region are not merely academic endeavours; they are crucial for society. Despite significant advancements in sustained observations, the remoteness and harshness of Antarctica and the Southern Ocean have kept them among the least monitored regions on Earth. Gaining an in-depth understanding of how Antarctica is changing and reducing the uncertainties surrounding how these changes influence the global change requires an international effort in which nations, programmes and institutions contribute to coordinated, systematic and Earth system-based observations across Antarctica and the Southern Ocean. Through TONe, Norway aims to boost this international imperative. Initiatives such as TONe cannot be seen as isolated pursuits but rather as a part of a collective responsibility. The entire Antarctic community must champion such long-term monitoring efforts, investing in technology, international collaboration and sustained commitment in a systematic and coordinated manner. This has been clearly recognised by the Parties to the Antarctic Treaty. At the joint Committee for Environmental Protection–ATCM session on climate change implications at the 2023 ATCM in Helsinki, the Parties highlighted the needs for long-term, well-supported monitoring efforts and for integrated, coordinated approaches to scientific research on climate change.

During their deliberations, the Antarctic Treaty Parties also highlighted the importance of making all Antarctic data sets available for the international scientific community, to facilitate a better understanding of climate-change impacts and to inform decision-making. By meeting the FAIR principles—findability, accessibility, interoperability and reusability—of data sharing (Wilkinson et al. 2016), the observational data amassed through TONe will increase the benefits gained by high-cost data collection in Antarctica.

At a dedicated session during the Scientific Committee on Antarctic Research Open Science Conference in Chile, 19–23 August 2024, the Antarctic science community will explore the current state of coordinated observing efforts in Antarctica, pinpointing gaps in observation needs, investigating how closer collaboration can address the challenges and considering actionable steps to rectify shortcomings. This is an important opportunity for the community to consider how we can collectively advance our understanding of climate change, leading to more effective solutions and a sustainable future for our planet.

Disclosure statement

All authors are part of the Troll Observing Network infrastructure project.

Funding

Troll Observing Network is financed through the Research Council of Norway's Funding for Research Infrastructure of National Importance (project no. 322466).

References

Alfonsi L. Bergeot N., Cilliers P., De Franceschi G., Baddeley L., Correia E., Di Mauro D., Enell C.-F., Engebretson M., Ghoddousi-Fard R., Häggström I., Ham Y.-B., Heygster G., Jee G., Kero A., Kosch M., Kwon H.-J., Lee C., Lotz S., Macotela L., Marcucci MF., Miloch W.J., Morton Y.J., Naoi T., Negusini M., Partamies N., Petkov B.H., Pottiaux E., Prikryl P., Shreedevi P.R., Slapak R., Spogli L., Stephenson J., Triana-Gómez A.M., Troshichev O.A., Van Malderen R., Weygand J.M. & Zou S. 2022. Review of environmental monitoring by means of radio waves in the polar regions: from atmosphere to geospace. *Surveys in Geophysics 43*, 1609–1698, doi: 10.1007/s10712-022-09734-z.

Black C., Collen B., Lunn D., Filby D., Winnard S. & Hart T. 2018. Time-lapse cameras reveal latitude and season influence breeding phenology durations in penguins. *Ecology and Evolution 8,* 8286–8296, doi: 10.1002/ece3.4160.

Bennartz R., Shupe M.D., Turner D.D., Walden V.P., Steffen K., Cox C.J., Kulie M.S., Miller N.B. & Pettersen C. 2013. July 2012 Greenland melt extent enhanced by low-level liquid clouds. *Nature 496*, 83–86, doi: 10.1038/nature12002.

Bothmer V. & Daglis I.A. 2007. *Space weather—physics and effects.* New York: Springer.

Chown S.L., Leihy R.I., Naish T.R., Brooks C.M., Convey P., Henley B.J., Mackintosh A.N., Phillips L.M., Kennicutt M.C. II & Grant S.M. 2022. *Antarctic climate change and the environment: a decadal synopsis and recommendations for action*. Cambridge: Scientific Committee on Antarctic Research.

COMNAP 2017. *Antarctic station catalogue*. Christchurch: Council of Managers of National Antarctic Programs.

Descamps S., Hudson S., Sulich J., Wakefield E., Grémillet D., Carravieri A., Orskaug S. & Steen H. 2023. Extreme snowstorms lead to large-scale seabird breeding failures in Antarctica. *Current Biology 33*, R176–R177, doi: 10.1016/j.cub.2022.12.055.

Descamps S., Tarroux A., Lorentsen S.-H., Love O.P., Varpe Ø. & Yoccoz N.G. 2015. Large-scale oceanographic fluctuations drive Antarctic petrel survival and reproduction. *Ecography 39,* 496–505, doi: 10.1111/ecog.01659.

Díaz S., Settele J., E.S. Brondízio E.S., Ngo H.T., Guèze M., Agard J., Arneth A., Balvanera P., Brauman K.A., Butchart S.H.M., Chan K.M.A., Garibaldi L.A., Ichii K., Liu J., Subramanian S.M., Midgley G.F., Miloslavich P., Molnár Z., Obura D., Pfaff A., Polasky S., Purvis A., Razzaque J., Reyers B., Roy Chowdhury R., Shin Y.J., Visseren-Hamakers I.J., Willis K.J. & Zayas C.N. (eds.) 2019. *The global assessment report on biodiversity and ecosystem services. Summary for policymakers.* Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Secretariat.

Foldvik A., Gammelsrød T. & Tørresen T. 1985. Physical oceanography studies in the Weddell Sea during the Norwegian Antarctic Research Expedition 1978/79. *Polar Research 3*, 195–207, doi: 10.1111/j.1751-8369.1985.tb00507.x.

Gutt J., Arndt S., Barnes D.K.A., Bornemann H., Brey T., Eisen O., Flores H., Griffiths H., Haas C., Hain S., Hattermann T., Held C., Hoppema M., Isla E., Janout M., Le Bohec C., Link H., Mark F.C., Moreau S., Trimborn S., van Opzeeland I., Pörtner H.-O., Schaafsma F., Teschke K., Tippenhauer S., Van de Putte A., Wege M., Zitterbart D. & Piepenburg D. 2022. Reviews and syntheses: a framework to observe, understand and project ecosystem response to environmental change in the East Antarctic Southern Ocean. *Biogeosciences 19*, 5313–5342, doi: 10.5194/bg-19-5313-2022.

Hattermann T. 2018. Antarctic thermocline dynamics along a narrow shelf with easterly winds. *Journal of Physical Oceanography 48*, 2419–2443, doi: 10.1175/JPO-D-18-0064.1.

Hattermann T., Nicholls K.W., Hellmer H.H., Davis P.E.D., Janout M.A., Østerhus S., Schlosser E., Rohardt G. & Kanzow T. 2021. Observed interannual changes beneath Filchner-Ronne Ice Shelf linked to large-scale atmospheric circulation. *Nature Communications 12*, article no. 2961, doi: 10.1038/s41467-021-23131-x.

Hattermann T., Nøst O.A., Lilly J.M. & Smedsrud L.H. 2012. Two years of oceanic observations below the Fimbul Ice Shelf, Antarctica. *Geophysical Research Letters Oceans 39*, L12605, doi: 10.1029/2012GL051012.

Hayes M.C., Gray P.C., Harris G., Sedgwick W.C., Crawford V.D., Chazal N., Crofts S. & Johnston D.W. 2021. Drones and deep learning produce accurate and efficient monitoring of large-scale seabird colonies. *Ornithological Applications 123*, duab022, doi: 10.1093/ornithapp/duab022.

Herraiz-Borreguero L., Allison I., Craven M., Nicholls K.W. & Rosenberg M.A. 2013. Ice shelf/ocean interactions under the Amery Ice Shelf: seasonal variability and its effect on marine ice formation. *Journal of Geophysical Research—Oceans 118*, 7117–7131, doi: 10.1002/2013JC009158.

Hinke J.T., Barbosa A., Emmerson L.M., Hart T., Juáres M.A., Korczak-Abshire M., Milinevsky G., Santos M., Trathan P.N. & Watters G.M. 2018. Estimating nest-level phenology and reproductive success of colonial seabirds using time-lapse cameras. *Methods in Ecology and Evolution 9*, 1853–1863, doi: 10.1111/2041-210X.13015.

Jin Y., Spicher A., Xiong C., Clausen L.B.N., Kervalishvili G., Stolle C. & Miloch W.J. 2019. Ionospheric plasma irregularities characterized by the Swarm satellites: statistics at high latitudes. *Journal of Geophysical Research—Space Physics 124,* 162–1282, doi: 10.1029/2018JA026063.

Kallenborn R., Breivik K., Eckhardt S., Lunder C.R., Manø S., Schlabach M. & Stohl A. 2013. Long-term monitoring of persistent organic pollutants (POPs) at the Norwegian Troll Station in Dronning Maud Land, Antarctica. *Atmospheric Chemistry and Physics 13*, 6983–6992, doi: 10.5194/acp-13-6983-2013.

Kauko H., Rohde D., Knudsen B.R. & Sund-Olsen T. 2020. Potential of thermal energy storage for a district heating system utilizing industrial waste heat. *Energies 13*, article no. 3923, doi: 10.3390/en13153923.

Lauber J., Hattermann T., de Steur L., Darelius E., Auger M., Nøst O.A. & Moholdt G. 2023. Warming beneath an East Antarctic ice shelf due to increased subpolar westerlies and reduced sea ice. *Nature Geoscience 16*, 877–885, doi: 10.1038/s41561-023-01273-5.

Lindbäck K., Darelius E., Moholdt G., Vaňková I., Hattermann T., Lauber J. & de Steur L. 2023. Basal melting and oceanic observations beneath Fimbulisen, East Antarctica. Unreviewed preprint. *ESS Open Archive*, 27 December, doi: 10.22541/essoar.170365303.33631810/v1.

Mac Ayeal D.R. 1984. Thermohaline circulation below the Ross Ice Shelf—a consequence of tidally induced vertical mixing and basal melting. *Journal of Geophysical Research—Oceans 89,* 597–606, doi: 10.1029/JC089iC01p00597.

Makinson K. 1994. BAS hot water drilling on Ronne Ice Shelf, Antarctica. *Memoirs of National Institute of Polar Research Special Issue 49*, 192–202.

Moreau S., Boyd P.W. & Strutton P.G. 2020. Remote assessment of the fate of phytoplankton in the Southern Ocean sea-ice zone. *Nature Communication 11*, article no. 3108, doi: 10.1038/s41467-020-16931-0.

Moreau S., Hattermann T., de Steur L., Kauko H.M., Ahonen H., Ardelan M., Assmy P., Chierici M., Descamps S., Dinter T., Falkenhaug T., Fransson A., Grønningsæter E., Hallfredsson E.H., Huhn O., Lebrun A., Lowther A., Lübcker N., Monteiro P., Peeken I., Roychoudhury A., Różańska M., Ryan-Keogh T., Sanchez N., Singh A., Simonsen J.H., Steiger N., Thomalla S., van Tonder A., Wiktor J.M. & Steen H. 2023. Wind-driven upwelling of iron sustains dense blooms and food webs in the eastern Weddell Gyre. *Nature Communication 14*, article no. 1303, doi: 10.1038/s41467-023-36992-1.

Nicholls K.W., Østerhus S., Makinson K., Gammelsrød T. & Fahrbach E. 2009. Ice–ocean processes over the continental shelf of the southern Weddell Sea. Antarctica: a review. *Review of Geophysical Research 47*, RG3003, doi: 10.1029/2007RG000250.

Nøst O.A., Biuw M., Tverberg V., Lydersen C., Hattermann T., Zhou Q., Smedsrud L.H. & Kovacs K.M. 2011. Eddy overturning of the Antarctic Slope Front controls glacial melting in the eastern Weddell Sea. *Journal of Geophysical Research—Oceans 116*, C11014, doi: 10.1029/2011JC006965.

Paih N.L., Hattermann T., Boebel O., Kanzow T., Lüpkes C., Rohardt G., Strass V. & Herbette S. 2020. Coherent seasonal acceleration of the Weddell Sea boundary current system driven by upstream winds. *Journal of Geophysical Research—Oceans 125*, e2020JC016316, doi: 10.1029/2020JC016316.

Piatt J.F., Sydeman W.J. & Wiese F. 2007. Introduction: a modern role for seabirds as indicators. *Marine Ecology Progress Series 352*, 199–204, doi: 10.3354/meps07070.

Reinisch B.W., Galkin I.A., Khmyrov G.M., Kozlov A.V., Bibl K., Lisysyan I.A., Cheney G.P., Huang X., Kitrosser D.F., Paznukhov V.V., Luo Y., Jones W., Stelmash S., Hamel R. & Grochmal J. 2009. New digisonde for research and monitoring applications. *Radio Science 44*, RS0A24, doi: 10.1029/2008RS004115.

Richter S., Gerum R.C., Schneider W., Fabry B., Le Bohec C. & Zitterbart D.P. 2018. A remote-controlled observatory for behavioural and ecological research: a case study on emperor penguins. *Methods in Ecology and Evolution 9,* 1168–1178, doi: 10.1111/2041-210X.12971.

Sato N., Kadokura A., Motoba T., Hosokawa K., Björnsson G. & Saemundsson T. 2015. Interhemispheric symmetries and asymmetries of aurora from ground-based conjugate observations. In Y. Zhang & L.J. Paxton (eds.): *Auroral dynamics and space weather*. Pp. 145–161. Washington, D.C.: American Geophysical Union/Wiley.

Schweitzer J., Fyen J., Mykkeltveit S., Gibbons S.J., Pirli M., Kühn D. & Kværna T. 2012. Seismic arrays. In P. Bormann (ed.): *New manual of seismological observatory practice 2 (NMSOP-2)*. Pp. 1–80. Potsdam: German Research Centre for Geosciences.

Schweitzer J., Pirli M., Roth M. & Kværna T. 2014. Troll: a new, very broadband seismic station in Antarctica. *Seismological Research Letter 85,* 852–862, doi: 10.1785/0220130223.

Shukla P.R., Skea J., Reisinger A., Slade R., Fradera R., Pathak M., Al Khourdajie A., Belkacemi M., van Diemen R., Hasija A., Lisboa G., Luz S., Malley J., McCollum D., Some S. & Vyas P. (eds.). 2022. Summary for policymakers. In P.R. Shukla et al. (eds.): *Climate change 2022: mitigation of climate change. Contribution of Working Group III to the sixth assessment report of the Intergovernmental Panel on Climate Change.* Pp. 1–48. Cambridge: Cambridge University Press.

Skjæveland A.H., Kotova D.S. & Miloch W.J. 2021. Case studies of ionospheric plasma irregularities over Queen Maud Land, Antarctica. *Journal of Geophysical Research—Space Physics 126*, e2021JA029963, doi: 10.1029/2021JA029963.

Southwell C. & Emmerson L. 2015. Remotely-operating camera network expands Antarctic seabird observations of key breeding parameters for ecosystem monitoring and management. *Journal for Nature Conservation 23*, 1–8, doi: 10.1016/j.jnc.2014.11.002.

Stevens C., Hulbe C., Brewer M., Stewart C., Robinson N., Ohneiser C. & Jendersie S. 2020. Ocean mixing and heat transport processes observed under the Ross Ice Shelf control its basal melting. *Proceedings of the National Academy of Sciences of the United States of America 117*, 16799–16804, doi: 10.1073/pnas.1910760117.

Thompson A.F., Stewart A.L., Spence P. & Heywood K.J. 2018. The Antarctic Slope Current in a changing climate. *Reviews of Geophysics 56,* 741–770, doi: 10.1029/2018RG000624.

Tsagouri I., Belehaki A., Themens D.R., Jakowski N., Fuller-Rowell T., Hoque M.M., Nykiel G., Miloch W.J., Borries C., Morozova A., Barata T., Engelke W. & Shim J.-S. in press. Ionosphere variability I: advances in observational, monitoring and detection capabilities. *Advances in Space Research*, doi: 10.1016/j.asr.2023.07.024.

Tsagouri I., Themens D.R., Belehaki A., Shim J.-S., Hoque M.-M., Nykiel G., Borries C., Morozova A., Barata T. & Miloch W.J. in press. Ionosphere variability II: advances in theory and modeling. *Advances in Space Research*, doi: 10.1016/j.asr.2023.07.056.

Tuia D., Kellenberger B., Beery S., Costelloe B.R., Zuffi S., Risse B., Mathis A., Mathis M.W., van Langevelde F. & Burghardt T. 2022. Perspectives in machine learning for wildlife conservation. *Nature Communications 13*, article no. 792, doi: 10.1038/s41467-022-27980-y.

Vaňková I. & Nicholls K.W. 2022. Ocean variability beneath the Filchner-Ronne Ice Shelf inferred from basal melt rate time series. *Journal of Geophysical Research—Oceans 127*, e2022JC018879, doi: 10.1029/2022JC018879.

Vernet M., Geibert W., Hoppema M., Brown P.J., Haas C., Hellmer H.H., Jokat W., Jullion L., Mazloff M., Bakker D.C.E., Brearley J.A., Croot P., Hattermann T., Hauck J., Hillenbrand C.-D., Hoppe C.J.M., Huhn O., Koch B.P., Lechtenfeld O.J., Meredith M.P., Naveira Garabato A.C., Nöthig E.-M., Peeken I., Rutgers van der Loeff M.M., Schmidtko S., Schröder M., Strass V.H., Torres-Valdés S. & Verdy A. 2019. The Weddell Gyre, Southern Ocean: present knowledge and future challenges. *Reviews of Geophysics 57*, 623–708, doi: 10.1029/2018RG000604.

Wilkinson M.D., Dumontier M., Aalbersberg I.J., Appleton G., Axton M., Baak A., Blomberg N., Boiten J.W., da Silva Santos L.B., Bourne P.E., Bouwman J., Brookes A.J., Clark T., Crosas M., Dillo I., Dumon O., Edmunds S., Evelo C.T., Finkers R., Gonzalez-Beltran A., Gray A.J., Groth P., Goble C., Grethe J.S., Heringa J., 't Hoen P.A., Hooft R., Kuhn T., Kok R., Kok J., Lusher S.J., Martone M.E., Mons A., Packer A.L., Persson B., Rocca-Serra P., Roos M., van Schaik R., Sansone S.A., Schultes E., Sengstag T., Slater T., Strawn G., Swertz M.A., Thompson M., van der Lei J., van Mulligen E., Velterop J., Waagmeester A., Wittenburg P., Wolstencroft K., Zhao J. & Mons B. 2016. The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data 3,* article no. 160018, doi: 10.1038/sdata.2016.18.

Zhou Q., Hattermann T., Nøst O.A., Biuw M., Kovacs K.M. & Lydersen C. 2014. Wind-driven spreading of fresh surface water beneath ice shelves in the eastern Weddell Sea. *Journal of Geophysical Research—Oceans 119*, 3818–3833, doi: 10.1002/2013JC009556.