Advances in operational permafrost monitoring on Svalbard and in Norway

Ketil Isaksen, Julia Lutz, Atle Macdonald Sørensen, Øystein Godøy, Lara Ferrighi, Steinar Eastwood and Signe Aaboe

1 The Norwegian Meteorological Institute, PO Box 43 Blindern, Oslo 0313, Norway
2 The Norwegian Meteorological Institute, PO Box 6314 Langnes, Tromsø 9293, Norway
* Author to whom any correspondence should be addressed.

E-mail: ketili@met.no

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Abstract
The cryosphere web portal maintained by the Norwegian Meteorological Institute (MET Norway), https://cryo.met.no, provides access to the latest operational data and the current state of sea ice, snow, and permafrost in Norway, the Arctic, and the Antarctic. We present the latest addition to this portal: the operational permafrost monitoring at MET Norway and methods for visualising real-time permafrost temperature data. The latest permafrost temperatures are compared to the climatology generated from the station’s data record, including median, confidence intervals, extremes, and trends. There are additional operational weather stations with extended measurement programs at these locations. The collocated monitoring offers daily updated data for studying and monitoring the current state, trends, and the effects of, e.g. extreme climate events on permafrost temperatures. Ground temperature rates obtained from the long-term records in the warmer permafrost found in Norway are typically 0.1 °C–0.2 °C per decade. In contrast, in the colder permafrost of the High Arctic on Svalbard, a warming of up to 0.7 °C per decade is apparent. The operational monitoring provides information faster than ever before, potentially assisting in the early detection of, e.g. record high active layer thickness and pronounced permafrost temperature increases. It may also become an important cornerstone of early warning systems for natural hazards associated with permafrost warming and degradation. Currently, data are submitted manually to the international Global Terrestrial Network for Permafrost and are scheduled for integration with World Meteorological Organisation (WMO) operational services through the WMO Global Cryosphere Watch.

1. Introduction
In contrast to sea ice and snow cover, permafrost is not visible at the ground surface. Measuring ground temperatures in boreholes is the best way of monitoring long-term changes in permafrost. The most direct and comparable indicators of changes are the thermal state of permafrost (permafrost temperature) and active layer thickness (ALT) [1]. According to the Global Climate Observing System, these two variables belong to the essential climate variables [2]. These are variables that play an important role in determining the climate of the Earth and that guide the observation community in enabling evidence-based climate monitoring, science, and services [3]. Permafrost soils and deposits are the Earth’s largest terrestrial carbon sink as they retain 1070–1360 billion metric tons (PgC) of frozen and thawing carbon, of which 300–400 PgC are in the first upper metre, and the rest at deeper levels [4]. Thawing permafrost threatens to mobilise these stores and release them into the atmosphere as carbon dioxide or methane, converting the Arctic from a carbon sink to a carbon source [5]. Measurements show that permafrost is warming at a global scale [6, 7] and is affected by degradation with vast and potentially rapid impacts, influencing both natural [8–11] and human [12, 13] systems. The latest CMIP6 models project a global decrease...
in annual mean frozen permafrost volume of around 10%–40% per 1 °C of global surface air temperature change [14].

Systematic long-term monitoring of permafrost in northern Europe essentially began under the European Union-funded Permafrost and Climate in Europe (PACE) project [15] with the installation of ground temperature measurements in deep boreholes at Janssonhaugen on Svalbard in 1998 and Juuvasshøe in southern Norway in 1999 [16, 17]. These sites were among the first reference stations for permafrost monitoring in Europe [15] and provided the first opportunity for temporal trends to be analysed, adding a critical new dimension to current knowledge of permafrost conditions in northern Europe [18, 19].

Since 2000, more than 35 additional instrumented boreholes have been established in Norway and on Svalbard. For instance, a shallow borehole monitoring network was established at Snoheim-Hjerkinn (Dovrefjell) in southern Norway in 2001 [20]. In the same area, twelve additional shallow boreholes were drilled at different elevations along a continentality gradient in August 2008 [21]. During the International Polar Year (2007–2009), monitoring networks were built up in northern Norway, as well as on Svalbard [22]. In recent years (2019–2021), new permafrost boreholes have been established at remote locations on Svalbard as part of the Svalbard Integrated Arctic Earth Observing System (SIOS, https://sios-svalbard.org/) and Climate-ecological Observatory for Arctic Tundra (COAT, www.coat.no/en/) projects [23]. There are also established operational weather stations with extended measurement programmes at the same locations. This collocated monitoring provides daily updated data for investigating and monitoring the current state, trends, and impacts of e.g. extreme climate events on ground temperatures in the permafrost.

Currently, extensive monitoring activities are undertaken with the general aim of documenting the distribution, state, and changes of permafrost on a long-term basis [6, 7]. These variables are monitored globally through several national and international programmes. However, most of the data retrieval is performed manually on-site about once a year. Due to the slowness with which databases are updated or made available, the most recent data can easily be two years old or older. Consequently, the availability of real-time permafrost data is currently very limited. This is a significant bottleneck for the continuous monitoring and assessment of the cryosphere undertaken in e.g. the Global Cryosphere Watch (GCW) under the World Meteorological Organisation (WMO). Our contribution enables a significant improvement for modellers and researchers to access, analyse and evaluate the latest permafrost data. Such data will also be essential in the design of effective early warning systems related to permafrost degradation and for assessing risks from natural hazards and infrastructure damage due to warming and thawing permafrost.

The cryosphere web portal, https://cryo.met.no, provides information on the current state of the sea ice, snow on land, and permafrost in Norway, the Arctic, and the Antarctic monitored by the Norwegian Meteorological Institute (MET Norway). The latest operational data and products are visualised in daily updated graphics, with instructions on where to access the observed data. This thematic web portal was created in 2019 to gather and better visualise the work and observations of MET Norway around frozen spheres. Easy public access to nearly real-time observations of the cryosphere is essential for bringing focus and understanding to a rapidly changing climate. The work behind the different products and data benefits from several contribution sources, both internal activities at MET Norway and large European programmes, e.g. the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facility (OSI SAF), European Space Agency (ESA) Climate Change Initiative, Copernicus services, and large Norwegian projects like SIOS and COAT. This article focuses on the operational permafrost monitoring at MET Norway and the available permafrost products on https://cryo.met.no/en/permafrost. The different permafrost products are not only available for the first Norwegian reference permafrost stations, Janssonhaugen and Juuvasshøe, but also for six other sites in Norway and on Svalbard.

2. Methods

Note that more detailed information on the boreholes, the measurement instruments and methods, and the data processing is available in the appendix.

2.1. Available permafrost stations

MET Norway operates an extensive operational meteorological observation network that covers the mainland of Norway and the Svalbard archipelago. The strategy for permafrost monitoring sites has been to establish full-scale weather stations at the same location to better utilise the operational value chain that MET Norway has built up over many years. The co-location increases the usefulness of the permafrost data for e.g. permafrost researchers and model developers, but also other user groups who use the most recent data, by connecting it directly to an official national weather station where fast and easy access to data is provided. Overall, eight sites transmit ground temperature data in real-time for operational permafrost monitoring (see map in figure 1 and table 1).
2.2. Permafrost temperature sampling and measurement system
For all stations, data are registered automatically by a programmed Cambell data logger. The loggers are connected to the digital temperature sensor strings directly or, for the analogue temperature sensor strings, via a multiplexer (Janssonhaugen and Juvvasshoe). The data are transferred every 6 h via the GSM mobile network or Iridium satellite communication and allow remote access for programme...
Table 1. List of permafrost stations available on https://cryo.met.no/ per July 2022.

| National station ID | Station name         | Region   | Start year | Altitude | Maximal measurement depth |
|---------------------|----------------------|----------|------------|----------|---------------------------|
| 9380                | Snoeheim             | Norway   | 2001       | 1475 m.a.s.l. | 8.5 m                    |
| 15270               | Juvvasshoe            | Norway   | 1999       | 1894 m.a.s.l. | 100 m                    |
| 97710               | Iskoras               | Norway   | 2008       | 591 m.a.s.l.  | 52.5 m                   |
| 99875               | Janssonhaugen        | Svalbard | 1998       | 275 m.a.s.l.  | 100 m                    |
| 99882               | Nedre Sassendalen     | Svalbard | 2021       | 13 m.a.s.l.   | 30 m                     |
| 99884               | Klauva                | Svalbard | 2021       | 480 m.a.s.l.  | 30 m                     |
| 99895               | Kvadehukken           | Svalbard | 2021       | 5 m.a.s.l.    | 30 m                     |
| 99927               | Verlegenhuken         | Svalbard | 2019       | 8 m.a.s.l.    | 30 m                     |

Updates. Except for Iskoras, where 220 V is available, power is supplied by solar panels connected to batteries.

The temporal measurement interval of the thermistors is every 6 h. The exception is Snoeheim, where hourly resolution is used to better capture latent heat effects and potential non-conductive heat transfer processes associated with groundwater due to permafrost degradation and the formation of taliks (see [24]). Ground temperatures below 5 m in the main borehole at Janssonhaugen and Juvvasshoe are measured once every 24 h. To capture the high temperature variability near the ground surface, an hourly resolution is used for the undisturbed natural ground surface temperature near the boreholes. For this, distributed miniature temperature data loggers (e.g. [25, 26]) and fixed sensors at 0.05 m or 0.1 m are used to avoid atmospheric disturbances and direct solar radiation (see [24]). The fixed sensors are connected to the weather station to allow for assessing the thermal effects of the protection lid at the boreholes and capture local surface variability in nearly real-time. For more details about borehole instrumentation and the measurement system, see [16, 22].

2.3. Operational data transfer and data control system
Permafrost data from MET Norway’s stations are sent to a common reception system which consists of several scripts that convert the data before it is ingested into an internal quality control system. In addition to MET’s standard setup for submitting data as described above, MET Norway’s reception system is capable of interfacing a multitude of file formats and transport protocols, allowing information from externally owned and operated stations with equipment that does not adhere to MET Norway specifications to be submitted. In this way, all data is harmonised and streamlined for downstream value chains. Currently, a new quality control system is being developed at MET Norway, where the permafrost data will undergo several automated and manual quality control routines. The real-time observations will then be checked continuously and flagged for suspicious or incorrect values, and missing observations will be reported to immediately discover the need for station service.

All data are stored in MET’s Observation Data Archive (ODA). ODA is a distributed database that is accessible through the Frost Application Programmers Interface (API) (https://frost.met.no/) which provides free access to MET Norway’s archive of historical weather and climate data and includes the quality-controlled measurements of soil temperature presented here. Other information, like metadata about weather stations, is also available through Frost API.

2.4. Products visualising real-time permafrost temperature data
At the moment https://cryo.met.no/ features eight operational products that visualise the real-time permafrost data. However, the portal is under constant evolution and additional products may be added in the future. Not all products are visualised for every station as a certain data amount is crucial for some products. This will also change as more and more data will become available in the years to come. The current products show the following parameters:

- annual time series of near-surface ground temperature at 0.05 or 0.2 m depth;
- annual time series of temperature at the top of the permafrost;
- annual time series of the depth of the 0 °C isotherm;
- annual maximum depth of the 0 °C isotherm (active layer thickness, ALT);
- latest daily ground temperature profile down to 30 m;
- mean annual ground temperature profiles for all depths available;
- daily ground temperature time series of selected depths (Snoeheim: 0.2, 2, 4.5, and 8.5 m; other stations: 0.2, 1.6, 5, and 10 m) for the whole time period available;
- long-term changes in permafrost thermal state at 10 m and 20 m (Snoeheim: 4.5 and 8.5 m).

The products are produced daily and take into account the data up to the day before.
Janssonhaugen station, data is transferred in chunks rather than continuously throughout the day, causing products to be delayed by up to 14 days. However, the plan is to switch to a continuous data stream in the future. The portal always shows the latest available data. As a result, interruptions in the data stream can be detected quickly.

To compare the observations of the actual year or the actual day to previous observations, the past observations are shown where they are available. For newer stations with less than 6 years of data, we display each year separately. For time series longer than five years we compute the absolute minimum and maximum, the median, the interquartile range, and the range between the 10th and the 90th percentile of the past years. Thus, it is possible to quickly contextualise the actual data visually. A considerable challenge was to standardise the procedure for the different stations as several stations do not have uninterrupted data, cover different time periods and the stations have to be treated differently due to permafrost in different depths.

2.5. Operational production

The visualisation of permafrost data is done through R scripts that fetch data via Frost API and generate figures. This value chain is part of the operational production system at MET Norway and runs on a local high-performance computing system that is duplicated across two separate data rooms for redundancy. The website exposing the above-described products is implemented using Drupal\(^1\), an open-source Content Management System (CMS) solution which is flexible, well supported, and maintained by a large community. This solution allows extending the basic functionality of the CMS through a rich list of modules that can be installed or developed locally to expose new services or ad-hoc functionalities. The website can expose dynamically updated products by fetching the latest created images from a local volume that is synchronised with the production chain. The figures are generated in .PNG format with good resolution suitable for direct use in e.g. presentations and in other web portals and are available in both English and Norwegian. Moreover, the permafrost stations are geo-located on an interactive map using Leaflet\(^4\).

3. Results

Here, we present all currently available visualisation products for all available real-time stations run by MET Norway. We chose several different time periods to illustrate the long-term response of permafrost to climate change, the ongoing degradation of permafrost at two of the stations (Iskoras and Snøheim), and the influence of extreme warm spells on ground temperatures.

3.1. Long-term trends in Svalbard and Norway

Since 1998, the monitoring of permafrost thermal state provides clear evidence of warming permafrost on Svalbard and in Norway. The Janssonhaugen station on Svalbard has the longest complete time series of all the MET Norway permafrost stations. This allows for studying long-term trends in permafrost temperatures and changes in the permafrost thermal state. Figure 2 shows four different products that depict long-term temperature changes in various depths at Janssonhaugen. They all indicate considerable warming of the permafrost at this location. The warming is especially evident for the temperatures in 10 and 20 m depth where the temperature trend amounts to 0.9 °C/decade and 0.7 °C/decade, respectively. At 20 m, seasonal variations become negligible (corresponds to the Depth of Zero Annual Amplitude, DZAA), making the temperature at this depth a suitable indicator of long-term change in permafrost thermal state [7], often used in international assessment reports (e.g. [27, 28]). The trend in the time series at the near-surface depths is less obvious since the annual fluctuations are much stronger. However, from the mean annual ground temperature profiles in figure 2, it is evident that the near-surface permafrost temperature trends are high as well. Significant warming is now detectable down to 100 m depth over the last 25 years.

Further, there is a clear trend in the maximum annual depth of the 0 °C isotherm. Whereas this depth was below 1.75 m at the beginning of the time series, the values are closer to 2 m in recent years.

For the three other permafrost stations with long-term records in mainland Norway, permafrost temperatures have increased as well. At Juvvasshoe, permafrost temperatures at 10 and 20 m increased at a rate of 0.2 °C per decade (figure A1). At Snoheim (figure A1), temperatures at 4.5 and 8.5 m increased at a rate of 0.3 °C per decade, while at Iskoras (figure 3(d)), temperatures at 10 m and 20 m increased at a rate of 0.5 °C and 0.1 °C per decade, respectively.

3.2. Monitoring permafrost degradation in Norway

The Iskoras station in northern Norway and the Snoheim station in southern Norway are located in discontinuous permafrost areas where the permafrost is currently thawing. Figure 3 presents four different products that illustrate the degradation of permafrost. At Snoheim, the ground temperature at the permafrost surface at 8.5 m is very close to 0 °C already and it has increased in recent years. The mean annual ground temperature profiles for Snoheim show a similar pattern as for Janssonhaugen, although there are only eight years of data available.
The first signs of permafrost degradation and opening up of talik/water systems could be seen after the extremely warm autumn in 2006 at the nearby permafrost monitoring sites on Snøheim–Hjerkinn (Dovrefjell) by [29].

For Iskoras, the thawing is most apparent when looking at the maximum depth of the 0 °C isotherm. The maximum depth increased from around 17 m to around 22 m. Lastly, the ground temperatures in 10 and 20 m depth have increased at Iskoras. Latent heat exchanges dominate the annual temperature amplitude at 10 m depth at the beginning of the series on Iskoras. The rapid ground temperature response after permafrost degradation and increase in temperature amplitude is due to the thawing of ground ice, leading to a drier near-surface layer and thus to changes in near-surface heat exchange (see [29]). The temperature trend at 10 m is 0.5 °C/decade which is three times the warming rate observed at Juvvasshøe and one of the highest among the stations in this article.

3.3. Extreme warm spells in southern Norway 2005 and 2006

Figure 4 shows the ground temperature time series at 0.2 and 2.5 m at Juvvasshøe in southern Norway for the years 2005 and 2006. Both years feature several months with ground temperatures that are above the average or even above the former maximum. This applies to January, February, July, October, November, and December in 2005 and to January, February, November, and December in 2006. Especially during the late summer and autumn of 2006, an exceptional long-lasting warm spell affected parts of Europe, including southern Norway [30, 31] and produced record-high near-surface permafrost temperatures on Juvvasshøe and a long-lasting freeze back of the active layer. The unusual warm spell led to an extreme melting of nearby high mountain ice patches [32]. The melting revealed several archaeological artefacts such as a 3400-year-old shoe [33, 34], and had ecological implications, such as an outbreak of fatal zoonotic disease (Pasteurellosis) on a musk ox population in the region, causing the death of a large proportion of the animals [35].
Figure 3. Thawing permafrost at Snøheim (top) and Iskoras (bottom): ground temperature at the permafrost surface at 8.5 m depth (a); mean annual ground temperature profiles and mean depth of DZAA (b); maximum annual depth of the 0 °C isotherm and the corresponding day (c) and long-term changes in permafrost thermal state at 10 m and 20 m depth (d). Time series for 2022 includes data until 14 August 2022.

Figure 4. Time series of ground temperature for Juvvasshøe for the years 2005 (a), (c) and 2006 (b), (d): temperature at the top of the permafrost at 2.5 m depth (top) and near-surface ground temperature measured at 0.2 m depth (bottom). The years 2005 and 2006 are shown in blue whereas past minimum, maximum, median, and confidence intervals are shown in grey.
The extreme thaw depth and long-lasting freeze back were accompanied by abnormally high rainfall amounts, resulting in several landslides and debris flows in the nearby town of Longyearbyen and its surroundings [36]. Suddenly, homes that were previously safe were evacuated, familiar hiking terrain became dangerous and roads that had been used in previous years were closed until the unstable slopes above were frozen.

3.5. Extreme near-surface permafrost warming on Svalbard in 2006

The ground temperature profiles at Janssonhaugen (Svalbard) for the end of January and April 2006 are shown in figure 6. The near-surface layers of the permafrost (down to 5–10 m) feature very high temperatures that are significantly higher than the maximum of the previous years. The near-surface ground temperatures amount to \(-7^\circ C\) in January and \(-3^\circ C\) in April. At these days and this depth, median temperatures are typically \(6^\circ C\) lower.

These extreme ground temperatures, coupled with high near-surface temperatures in summer 2006 (not shown), affected the thaw depth of the active layer. The start of thawing was the earliest on record until then, and the maximum ALT increased by 11% compared to the mean of the preceding years [37]. In [37], they also conclude that the most striking months on Svalbard in 2006 were January and April when mean air temperatures were 12.6 °C and 12.2 °C respectively above the average of 1961–1990. April 2006 was warmer than any previously recorded May, and January 2006 was warmer than any previously recorded April. The anomaly coincided with open water in most of the fjords through the whole winter and unusually early snowmelt released extreme meltwater discharges in the valleys.

3.6. New stations with short series

Figure 7 shows some products for the newest four stations in the MET Norway network. All four stations are spread across Svalbard and have one to three years of ground temperature time series. Despite the short observations, we were able to detect a quite unusual warm spell in March 2022. The time series of near-surface temperatures at Kvadehuken and Nedre Sassandraen feature a significant temperature increase in mid-March. Meanwhile, the daily temperature profiles at Klauva and Verlegenhuken show very high temperatures close to the surface. At this time of year, a profile with decreasing temperatures towards the
surface is common. This can be seen in the previous years at Verlegenhuken, where temperatures were as low as $-24 ^\circ C$ in 2020. In 2022, the temperatures were considerably higher than $-10 ^\circ C$.

### 4. Discussion

Significant warming and marked permafrost degradation has been observed at all operational measuring stations in Norway and Svalbard that are presented here and where permafrost temperatures have been measured over many years. This is in line with the most contemporary global assessments of permafrost temperatures \[6, 7\]. However, there is considerable regional variability in the magnitude of this warming, mainly related to differences in the proximity of permafrost temperatures to 0 $^\circ C$ \[7\] and differences in climate setting. The greatest changes are observed at permafrost stations on Svalbard, which are located in a region that currently warms up until seven times faster than the global average \[38\].

Approaches to long-term permafrost documentation have always been and will continue to be, susceptible to adaptations based on new findings and experiences \[39\]. Operational permafrost monitoring necessitates effective strategies along with standards for processing, quality control, archiving, and reporting across national and international networks, as well as the definition of essential observation parameters \[39\].

Currently, data and metadata are reported to the international Global Terrestrial Network for Permafrost manually. Work is in progress to develop operational permafrost data services through the GCW. GCW data management is being integrated with the WMO Information System, which currently uses the WMO Global Telecommunication System (GTS) for real-time data exchange, but is in the process of transitioning to the WMO Information System (WIS 2.0) real-time data exchange, which will replace existing GTS functionality with Message Queue Telemetry Transport \[40\]. In essence, this implies that real-time data exchange is based on a publication/subscription approach where interested data consumers are subscribing to updates of a dataset. WMO GCW performs and publishes assessments on the state of the cryosphere and works actively to improve data availability in support of this service.

An ongoing effort by the GCW, in the context of the framework of the WMO, is to establish and publish best practices on instruments and methods for observations of permafrost and seasonally frozen ground to define reference methods for the configuration and ongoing operation of stations for in situ observations in the high mountains and polar regions. Experiences from our new operational

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**Figure 7.** Warm spell in near-surface ground temperature on Svalbard on 16 March 2022. Ground temperature for Kvadehuken at 0.05 m depth (a), ground temperature for Nedre Sassendalen at 0.05 m depth (b), ground temperature profile for Klauva (c) and Verlegenhuken (d). The year 2022 is shown in blue, while past years (if available) are shown in grey.
permafrost monitoring may be beneficial to this guide as they address gaps in the existing permafrost monitoring systems and define methods for improving the availability and visibility of real-time and updated permafrost temperatures. Furthermore, it addresses challenges at remote locations, where energy production and consumption, communication, and survivability are critical efforts to sustain monitoring between human visits.

In mainland Norway and on Svalbard, we see great advantages with permafrost stations co-located with both existing and new official weather monitoring stations. They have become part of the national meteorological infrastructure which ensures long-lasting stable operations and maintenance. In the process, the standard observation programme at the official weather stations that are co-located with permafrost stations has been extended with observations of soil moisture, snow depth, snow temperature, and surface irradiance components. This ensures consistency and close cooperation between the major national and international initiatives, a minimisation of the environmental footprint of installations, and the investments in new stations provide real new value beyond what already exists. The permafrost data becomes more readily available and better connected to the climate-, snow- and permafrost modelling communities, and the remote sensing community e.g. used for calibration and validation of data and products.

5. Conclusions

The operational permafrost monitoring on https://cryo.met.no/ provides a unique opportunity to follow the ground temperature data at eight locations in southern and northern Norway and on Svalbard, yielding information faster than ever before. The data is visualised and compared with previous years through eight different products but not all products are available for every station yet. The products are chosen such that the most important ground levels and permafrost characteristics are covered.

The daily update of the products enables early detection of, e.g. record-high active layer thickness, pronounced permafrost temperature increases, and other extreme conditions in the permafrost. It already provides clear evidence of warming permafrost throughout Norway and Svalbard, with warming rates of up to 0.7 °C per decade at the depth of zero annual amplitude (DZAA). It also provides close monitoring of the thawing and ultimately disappearance of permafrost at two of the stations. Additionally, the visualisation of the data makes it possible to discover inconsistencies and failures in the measurements.

Our goal for the future is to add other permafrost sites, including stations from external station owners, as well as other products to the portal to make it useful for permafrost assessments.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: frost.met.no.

Acknowledgments

The sites are run in cooperation with the University of Oslo, the University Centre in Svalbard, the Norwegian Polar Institute, and the Norwegian University of Science and Technology. Four of the sites, at remote locations on Svalbard (Verlegenhuken, Kvaldehukken, Nedre Sassendalen, and Klauva), were recently established as part of the Svalbard Integrated Arctic Earth Observing System - Infrastructure development of the Norwegian node (SIOS InfraNOR, https://sios-svalbard.org/), Research Council of Norway project number 269927) and Climate-ecological Observatory for Arctic Tundra (COAT, www.coat.no/en/) projects. Part of the work related to the development of new permafrost products was supported by the Arctic Monitoring and Assessment Programme (AMAP).

Appendix

Available permafrost stations (additional information)

All eight boreholes were drilled using rotary percussion drilling (down-the-hole hammer drilling) with borehole diameters of 56–110 mm. Cuttings were flushed up and out above the ground surface by the excess air of the hammer, allowing for the collection of bulk and bag samples [41, 42]. Borehole depths vary from 9 m (Snøheim) to 129 m (Juvvasshøe), and all are cased with watertight polyethylene tubes sealed at the base to protect the boreholes from being blocked by loose debris, stones and ice. The casing also protects the sensors against moisture, at the same time allowing for easy access to the instruments due to maintenance and periodic recalibration. Besides, the boreholes remain accessible for the addition of other instruments in the future. The influence of air convection within the boreholes is considered negligible (see [24]). The borehole casing, sensors and data logging equipment were assembled according to guidelines provided by the PACE project to standardise procedures and ensure comparability between sites [15]. This also ensured reliability and serviceability.
Permafrost temperature sampling and measurement system (additional information)

At the two first established drill sites, Janssonhaugen and Juvvasshoe, a 15–20 m deep control borehole was drilled between 5 and 20 m away from the main borehole [16]. These shallow boreholes were installed to detect the thermal influence of the protection structure located at the top of the main boreholes and to ensure a good resolution and quality control (e.g. to control the long-term stability of the thermistors) of the annual ground thermal variations.

For Janssonhaugen and Juvvasshoe, the borehole temperatures are measured with analogue thermistor strings with negative-temperature-coefficient thermistors (Yellow Spring Instruments YSI 44006). The absolute accuracy is estimated as $\pm0.05 \, ^\circ{C}$ and the relative accuracy as $\pm0.02 \, ^\circ{C}$ [43]. For the remaining boreholes, the ground temperature is measured with digital temperature strings (beadedstream, USA) with absolute accuracy of $\pm0.1 \, ^\circ{C}$ and a sensor resolution of $\pm0.063 \, ^\circ{C}$.

The depths of thermistors at Juvvasshoe and Janssonhaugen follow the general instructions for the PACE boreholes [15]; the levels are 0.2, 0.4, 0.8, 1.2, 1.6, 2.0, 2.5, 3.0, 5.0, 7.0, 9.0, 10.0, 13.0, 15.0, 20.0, 25.0, 30.0 and 10 m spacing to 80.0 m, and then denser again to 100.0 m. For the remaining boreholes, additional depths were measured using 0.5 m spacing between 2.0 and 6.0 m depth and 1 m spacing between 6.0 and 11.0 m. This ensures better resolution of the $0 \, ^\circ{C}$ isotherm depth within the active layer and better capture of sites experiencing degrading permafrost.

Operational data transfer and data control system (additional information)

A disadvantage of the Frost output is that the file format is not conforming to the four foundational guiding principles—Findability, Accessibility, Interoperability, and Reusability (FAIR, [44]) at the discovery and use levels. Fortunately, ODA is using standard names from the Climate and Forecast (CF) Convention\(^\text{5}\) to identify the variables. Utilising this and the Frost API, data are extracted into CF-NetCDF format using the discrete sampling geometry of the CF conventions. These files are in the process of being made discoverable through the data portals of SIOS and GCW. Using CF-NetCDF also allows automatic visualisation of the data when served through the Open-source Project for a Network Data Access Protocol (OPeNDAP). In both SIOS and GCW, the datasets described here are the first currently known permafrost datasets to be available in nearly real-time. The extraction of data into CF-NetCDF is currently being operationalised.

In addition to being available in the web portals of SIOS and GCW, the datasets will also be made discoverable through standard machine-actionable discovery metadata interfaces like OAI-PMH and OGC CSW, serving GCMD DIF and ISO19115. The latter complies with the Infrastructure for spatial information in Europe (INSPIRE) and WMO requirements.

\(^{5}\) \url{https://cfconventions.org}.\
Results (additional information)

Long-term trends in Norway (additional information)

![Graph showing long-term trends in ground temperature at Juvaasøye and Snøheim](image)

Figure A1. Long-term trends of ground temperature at Juvaasøye (a) and Snøheim (b) for the monitoring period 1999–2022 and 2001–2022, respectively. For (a) long-term changes in permafrost thermal state at 10 and 20 m depth are shown while at (b) 4 and 8.5 m are presented. Time series for 2022 include data until 14 August 2022.

ORCID iDs

Ketil Isaksen [https://orcid.org/0000-0003-2356-5330](https://orcid.org/0000-0003-2356-5330)
Julia Lutz [https://orcid.org/0000-0002-7960-7619](https://orcid.org/0000-0002-7960-7619)
Øystein Godøy [https://orcid.org/0000-0001-6410-3488](https://orcid.org/0000-0001-6410-3488)
Lara Ferrighi [https://orcid.org/0000-0001-5221-8787](https://orcid.org/0000-0001-5221-8787)
Steinar Eastwood [https://orcid.org/0000-0002-8878-0521](https://orcid.org/0000-0002-8878-0521)
Signe Aaboe [https://orcid.org/0000-0002-5618-4537](https://orcid.org/0000-0002-5618-4537)

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