Permafrost best practices: la nuova guida WMO/GIMO #8 sulle misure per il permafrost

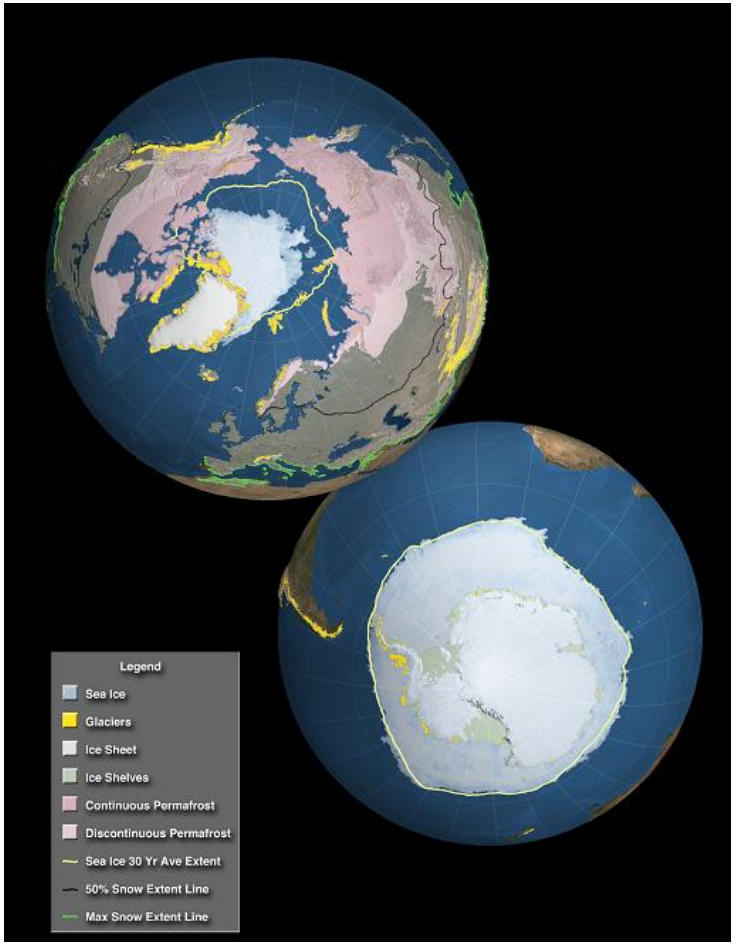
Graziano Coppa

CCT TG Air member
GRUAN WG member
GCW permafrost BP member

THE CRYOSPHERE

Part of Earth where water is in solid form

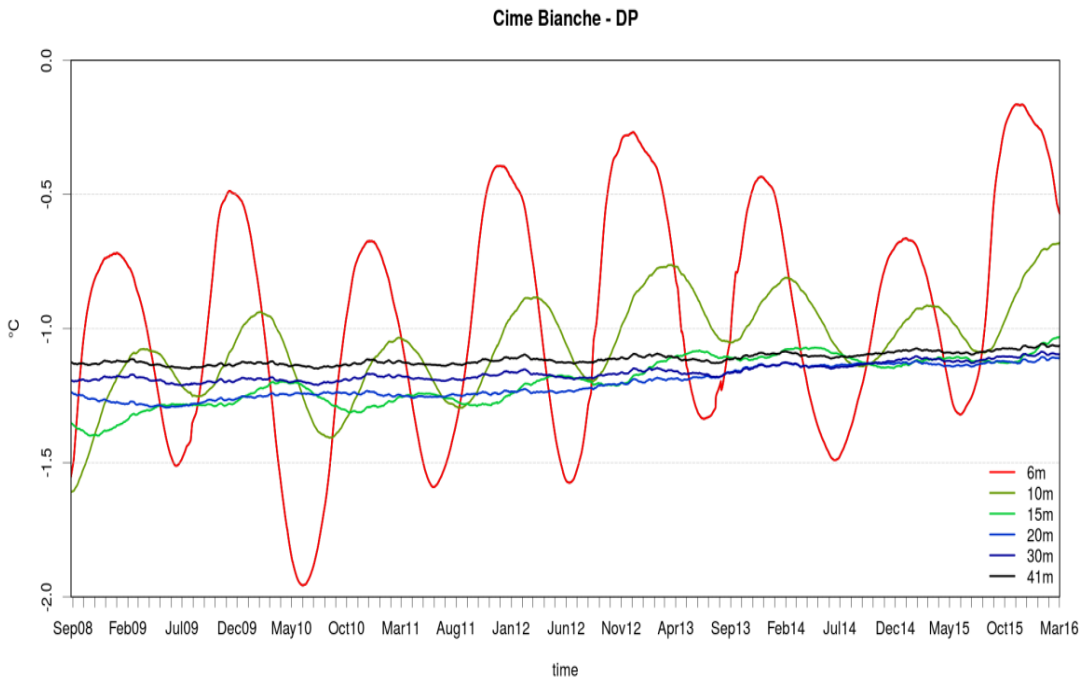
It plays a significant role in the Earth's climate.
It has global linkages and feedbacks generated through its influence on surface **energy and moisture fluxes, clouds, precipitation, hydrology.**
Snow and ice reflect a very high percentage of the radiation received from the sun, helping to **regulate the planet's temperature**. In addition, the spatial distribution of snow and ice is associated with longitudinal temperature differences, which drive **winds** and **ocean currents**.



TEMPERATURE IS A KEY QUANTITY IN DETECTING STATUS AND TRENDS IN THE CRYOSPHERE

Accurate Measurements

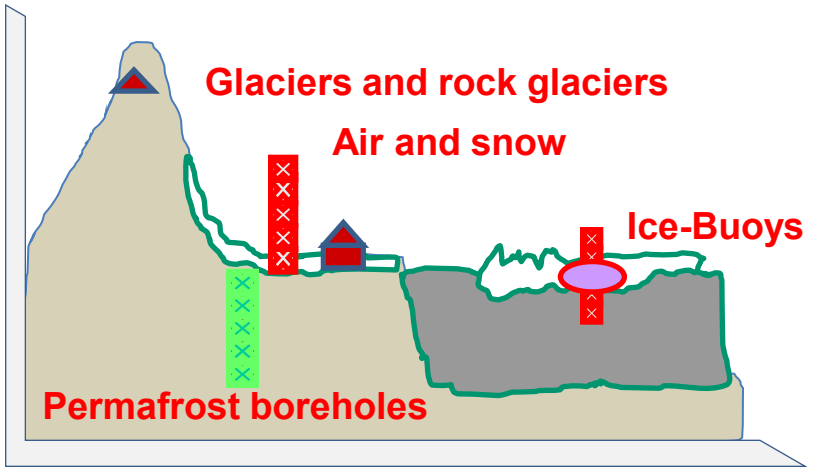
Are needed to assess and reduce time necessary to capture trends



TEMPERATURE IS A KEY QUANTITY IN DETECTING STATUS AND TRENDS IN THE CRYOSPHERE

Traceability is required
to reach full comparability

- Comparability on climate-change scales
- Comparability to fundamental physical models
- Comparability across generations
- Comparability across borders & organizations
- Comparability across metodologies



PERMAFROST IS A KEY COMPONENT OF THE

Perm… …the
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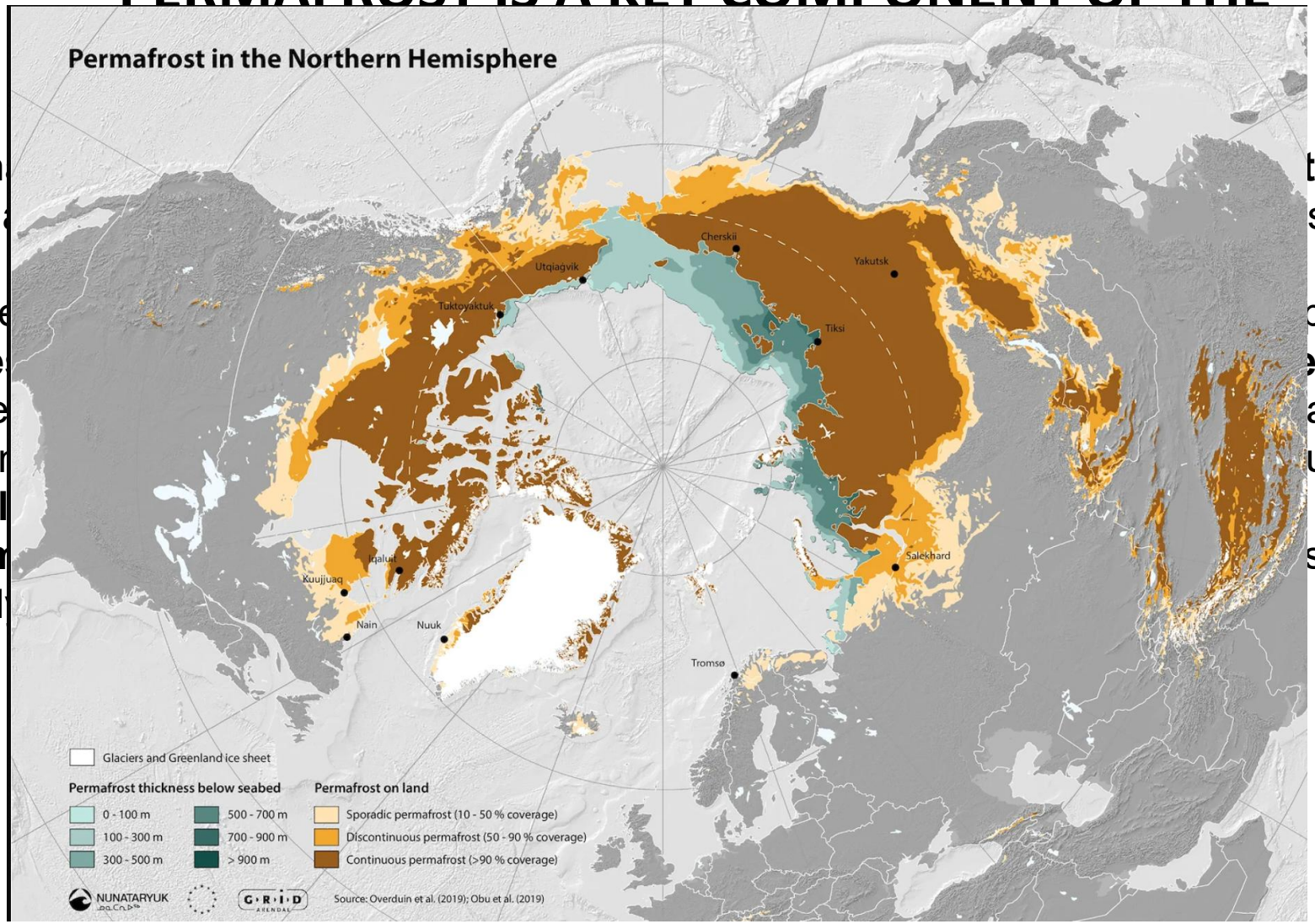
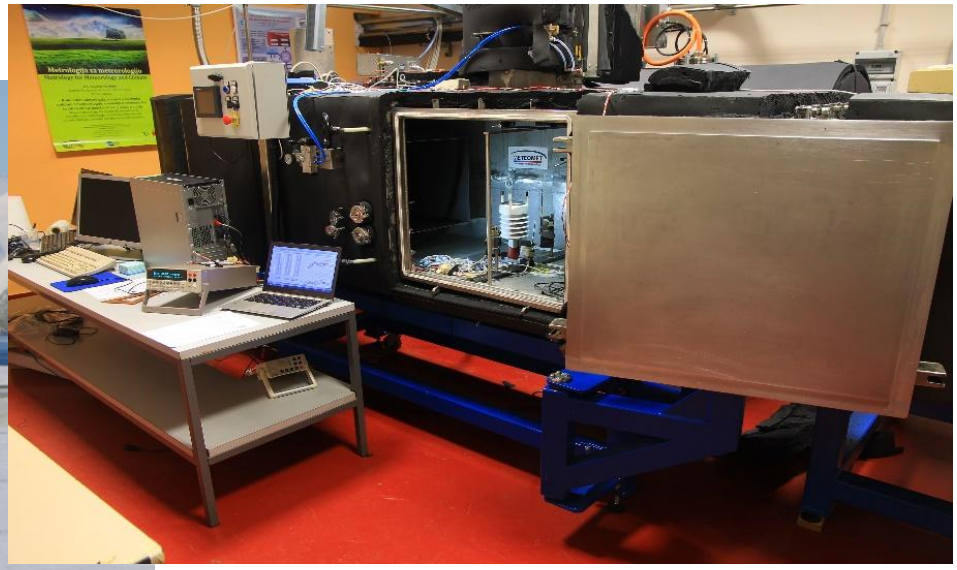


INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA


ISTITUTO NAZIONALE DI RICERCA METROLOGICA



Permafrost

July 2017, August 2018, August 2020
A metrology lab at 3000 m

METEOMET
Metrology for Meteorology

Merlone et al., *Tra* ... *mafrost temperature sens* ... 31(4), DOI:10.1002/ppp.

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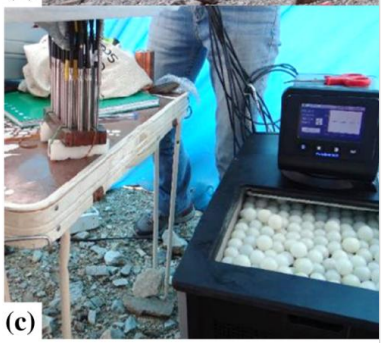

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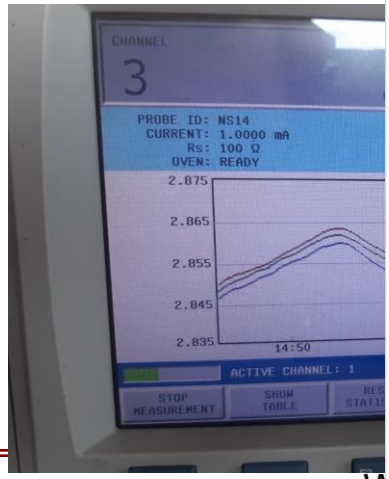

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RESEARCH ARTICLE

WILEY

Transportable system for on-site calibration of permafrost temperature sensors

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EURAMET, Grant/Award Number: EMRP - ENV58 Meteomet project

Abstract

Evaluating the degradation of permafrost is a major challenge in understanding global warming and its impact on the cryosphere. The Global Cryosphere Watch is promoting actions towards data quality and traceability, to achieve comparability of observations from different permafrost stations. In response to this, a transportable system for on-site calibrations of permafrost temperature sensors was studied, developed and tested in the field, within the project MeteoMet. The system, here described, allows users to establish metrological traceability to permafrost temperature profiles, by performing the calibration on-site, even in remote or high-elevation areas, in realistic conditions. A field campaign at 3,000 m elevation to test the system's performance and practical use is also reported. Overall calibration uncertainty in the field accounted for <0.05 °C, with contribution from reference sensors within 2 mK over the whole range; besides reducing uncertainties in each measuring point of a chain, the procedure also allows users to establish comparability among all the sensors within 0.03 °C. The self-heating effect of each sensor was also evaluated as 0.007 °C, and was thus considered a negligible component. The evolution of permafrost thawing can be more robustly evaluated, through documented data traceability together with improved comparability in space and time.

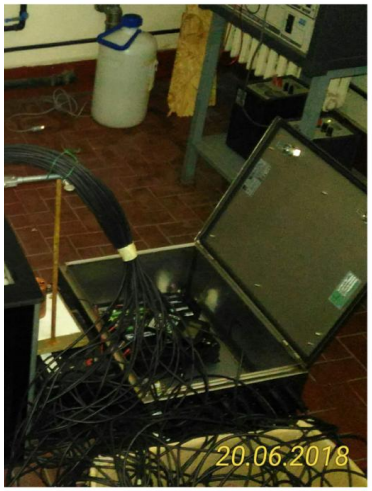
KEYWORDS

calibration uncertainty, cryosphere, environmental metrology, permafrost monitoring, sensor calibration, transportable system

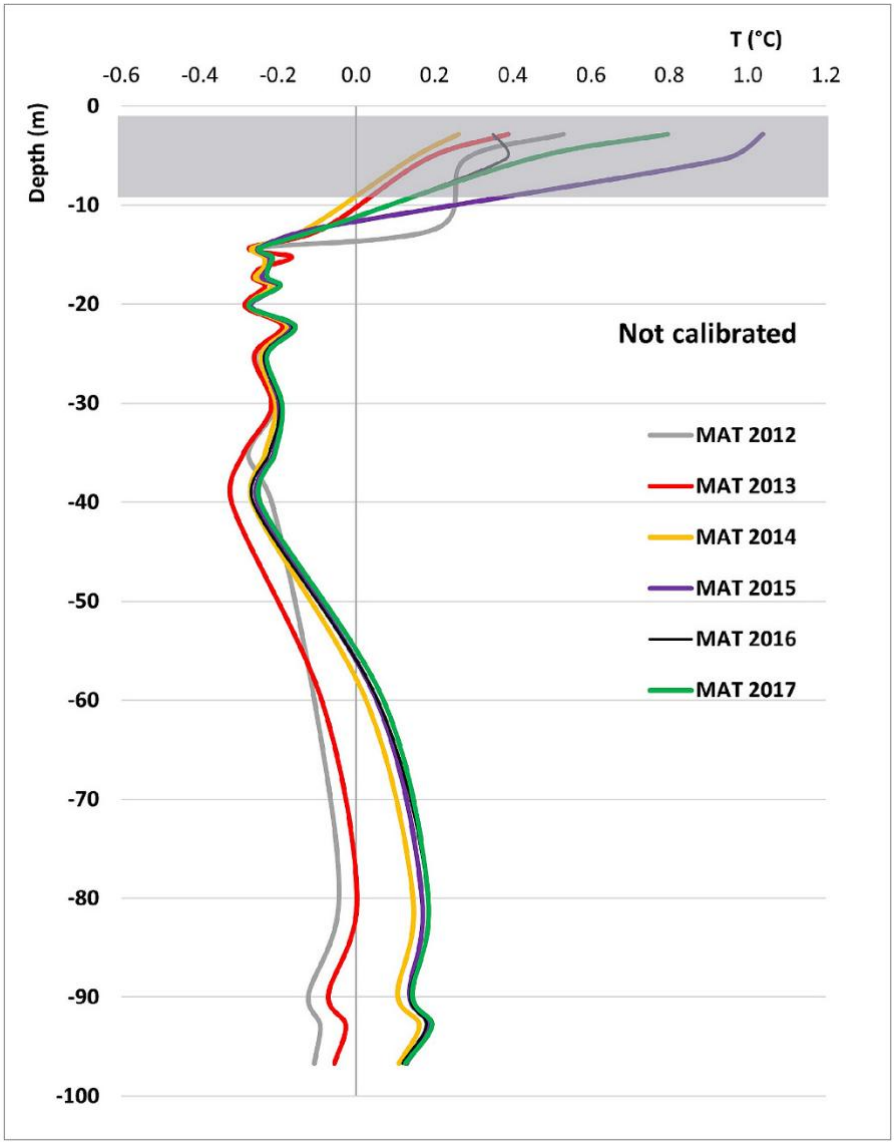
1 | INTRODUCTION

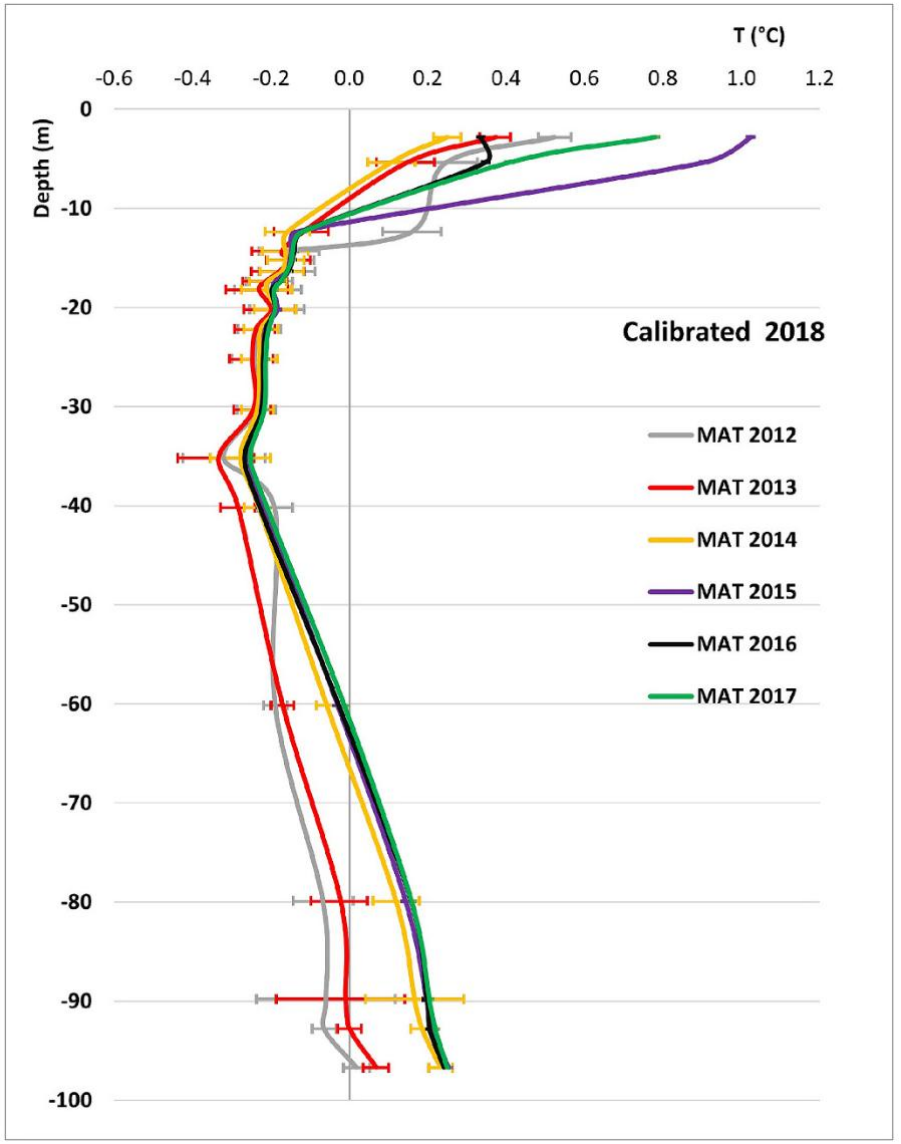
Permafrost is a key component of the cryosphere, the portions of Earth's surface where water is in solid form. It influences energy exchanges, hydrological processes and water availability, natural hazards, carbon dioxide and methane emissions, and global climate.[1] Permafrost is largely controlled by ground surface temperature and near-surface ground properties.[2] Where permafrost is present, the layer of ground that thaws seasonally, in which surface temperature rises above 0 °C, and refreezes during the cold season is known as the "active layer."[3] The position of the lower boundary surface of permafrost, known as the "permafrost base," is determined by the geothermal heat flux, subsurface properties, and the long-term surface temperature.[4] Understanding and evaluating the degradation of permafrost is seen as a major challenge in the current discussion on climate trend,[5] as both an effect and a cause of global warming.[6–8]

The World Meteorological Organization (WMO) program, through the Global Cryosphere Watch (GCW), which supports all key cryospheric *in situ* and remote sensing observations, has clearly expressed interest in implementing a metrological approach for cryosphere observations. Best practices are also requested to be included as a chapter in the new WMO no. 8 "Guide to Instruments and Methods of Observations."[9]



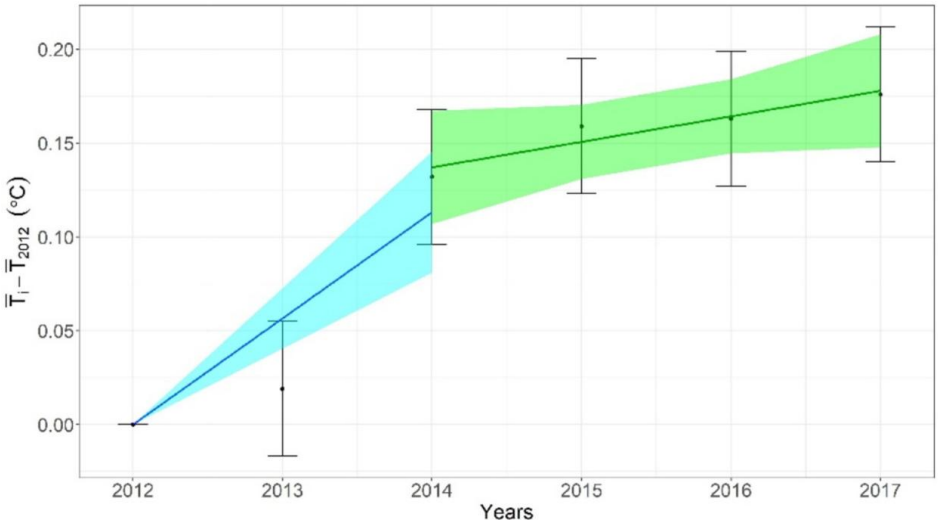
Coppa et al., *Metrological approach for permafrost temperature measurements*, Cold Reg. Sci. Technol., 2025, 229, 104364, DOI: 10.1016/j.coldregions.2024.104364





Coppa et al., *Metrological approach for permafrost temperature measurements*, Cold Reg. Sci. Technol., 2025, 229, 104364, DOI: 10.1016/j.coldregions.2024.104364

Temperature increase with respect to the 2012 value recorded by the sensor at 60 m.



Cold Regions Science and Technology 229 (2025) 104364

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Metrological approach for permafrost temperature measurements

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ARTICLE INFO

Keywords:
Permafrost monitoring
Metrology
Sensor calibration
Reference site
Calibration uncertainty

ABSTRACT

Permafrost degradation is a growing direct impact of climate change. Detecting permafrost shrinkage, in terms of extension, depth reduction and active layer shift is fundamental to capture the magnitude of trends and address actions and warnings. Temperature profiles in permafrost allow direct understanding of the status of the frozen ground layer and its evolution in time. The Sommeiller Pass permafrost monitoring station, at about 3000 m of elevation, is the key site of the regional network installed in 2009 during the European Project "PermaNET" in the Piedmont Alps (NW Italy). The station consists of three vertical boreholes with different characteristics, equipped with a total of 36 thermistors distributed in three different chains. The collected raw data shows a degradation of the permafrost base at approximately 60 m of depth since 2014, corresponding to about 0.03 °C/yr. In order to verify and better quantify this potential degradation, three *on-site* sensor calibration campaigns were carried out to understand the reliability of these measurements. By repeating calibrations in different years, two key results have been achieved: the profiles have been corrected for errors and the re-calibration allowed to distinguish the effective change of permafrost temperatures during the years, from possible drifts of the sensors, which can be of the same order of magnitude of the investigated thermal change. The warming of permafrost base at a depth of ~ 60 m has been confirmed, with a rate of $(4.2 \pm 0.5) \cdot 10^{-2}$ °C/yr. This paper reports the implementation and installation of the on-site metrology laboratory, the dedicated calibration procedure adopted, the calibration results and the resulting adjusted data, profiles and their evolution with time. It is intended as a further contribution to the ongoing studies and definition of best practices, to improve data traceability and comparability, as prescribed by the World Meteorological Organization Global Cryosphere Watch programme.

1. Introduction

Together with sea ice, snow and glaciers, permafrost is a key component of the cryosphere through its influence on energy exchanges, hydrological processes, natural hazards, carbon dioxide and methane emission and the global climate system (Riseborough et al., 2008). The thawing of permafrost leading to the destabilization of rocks and mountain slopes is an increasing hazard in alpine environments (Gruber et al., 2004; Gruber and Haeberli, 2007; Krautblatter et al., 2013). Moreover, its degradation is seen as a major challenge in the current discussion of global warming (Stocker et al., 2013), due to the possible effects on climate (Colombo et al., 2019; Harden et al., 2012; Schuur et al., 2015) also through release of trapped gases in high latitude areas. Actually, as a consequence of global warming trends, ground temperature near the depth of Zero Annual Amplitude (ZAA) increased globally by 0.29 ± 0.12 °C during the decade between 2007 and 2016 (Biskaborn et al., 2019), while the active layer is known to be progressively deepening in various parts of the cryosphere (Desyatkin et al., 2021; Li et al., 2022; Xu and Wu, 2021).

European Alps permafrost studies are a rather recent field: the first map of the permafrost distribution in the Alps was published by Boeckli et al. (2012), but generic studies on single permafrost sites are only marginally older (Haeberli, 1992), and usually hint at the poor knowledge of their state and evolution especially compared to glaciers (Haeberli and Beniston, 1998). Notable exceptions are localized in the Swiss Alps, where permafrost has been monitored since at least the 1970s (Gartner-Roer et al., 2022) or, sporadically, even before (see Haeberli et al., 2011 for a review).

Correspondingly, knowledge on permafrost in the Italian Western Alps was rather poor up until the first years of the 21st century and

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Available online 10 November 2024

What specifically is GCW doing?

GCW is fulfilling its objectives through a number of specific activities. Many build on existing information, observations, and programs. All are done in consultation with the community of cryospheric scientists and organizations. GCW is

- developing a network of surface observations called "CryoNet", which builds on existing networks;
- developing measurement guidelines and best practices;
- refining observational requirements for the WMO Rolling Review of Requirements;
- contributing to WMO's space-based capabilities database (with the Polar Space Task Group);
- engaging in, and supporting, intercomparison of products, particularly satellite products;
- formulating a set of best practices for product intercomparisons;
- creating detailed inventories of satellite products to succinctly describe their maturity and applicability;
- assessing snow cover products through the GCW Snow Watch project;
- creating unique products, e.g., the SWE Tracker, in collaboration with partners;
- engaging in historical data rescue (e.g., snow depth);
- building a cryosphere glossary;
- developing international training and outreach materials;
- providing up-to-date information on the state of the cryosphere through the GCW website;
- providing access to data through a robust catalogue, or portal, which is interoperable with other data centers;
- co-sponsoring workshops.

The observing component of GCW is a component of the WMO Integrated Global Observing System (WIGOS). Through WIGOS and the WMO Information System (WIS), GCW will provide a fundamental contribution to the Global Earth Observation System of Systems (GEOSS). GCW will organize analyses and assessments of the cryosphere to support science, decision-making, environmental policy and services through, inter alia, its foundational support to the Global Framework for Climate Services (GFCS).

A GCW overview is available in a video sideshow (7.5 min). More information on GCW background and structure is given in the Global Cryosphere Watch Implementation Plan.

WORLD METEOROLOGICAL ORGANIZATION
Weather · Climate · Water

Global Cryosphere Watch

Home | About | News | Cryosphere Now | Surface | Satellites | Activities | Reference | Data Portal | Outreach

CryoNet, the Core Component of the GCW Surface Network

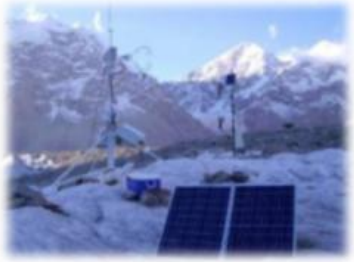
The GCW surface observation network is comprised of a core component, called **CryoNet**, and contributing stations that are not part of CryoNet. The GCW network builds on existing cryosphere observing programmes and promotes the addition of standardized cryospheric observations to existing facilities in order to create more robust environmental observatories.

Contributing stations are those that provide useful measurements of the cryosphere, but whose data records may be shorter or with large gaps, do not completely follow CryoNet measurement practices, or in some other way do not provide the quality and consistency of data required of CryoNet stations. These stations may be in remote, hard to access regions where cryospheric observations are scarce or in regions where they complement other cryospheric measurements. Additional information is available on the individual pages under the Surface menu above or in the box on the right.

See Also

- Station Types
- Requirements
- Application Process
- Recommended Variables
- Data Protocol
- Network List & Map
- Questionnaire/Application
- Measurement Methods





Why be a part of CryoNet? GCW will drive performance and provide motivation for high quality observations. Being a CryoNet site means being part of an international, operational, global observing system and thus providing observations of known quality for research and knowledge beyond a site's local region. Being part of a global network brings not only better visibility but also a recognition of the importance of the observations made at your site. This in turn can bring better support, either funding or logistical support. GCW promotes the exchange of knowledge and data, so CryoNet sites may see broader use of their data and products.

Problem with website?
Contact us

Connect with us:

Seleziona lingua

This website is operated on behalf of WMO by SSEC. It is not an official WMO website.

SSEC

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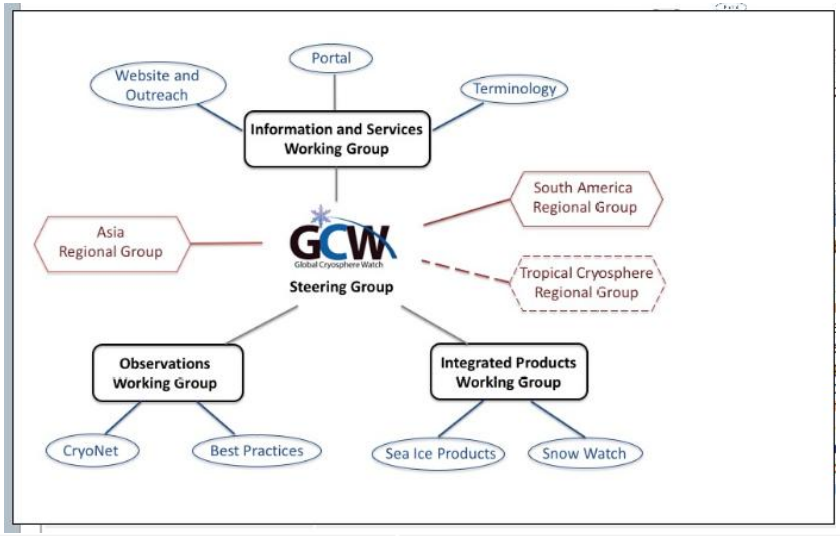
WORLD METEOROLOGICAL ORGANIZATION
Weather • Climate • Water

Global Cryosphere Watch

2019 creation of the Permafrost best practice group

Andrea Merlone	INRiM (IT)	co-chair
Anna Irrgang	AWI (DE)	co chair
Rodica Nitu	WMO-GCW	secretariat
Jeanette Noetzli	SLF (CH)	
Philippe Schoeneich	Univ.Grenoble (FR)	
Ketil Isaksen	Meteo Norway (NO)	
Charles Fierz	SLF (CH)	
Graziano Coppa	INRiM (IT)	
Alexey Portnov	University of Texas (US)	

Develop recommended practices for permafrost observations, as well as uncertainty evaluations associated with present, operational stations, for inclusion in the WMO guide No. 8.



World Meteorological Organization

Global Cryosphere Watch

Observations WG	The Observations Working Group addresses capabilities and needs for surface-based and satellite observations. It is responsible for the establishment and coordination of operations of the GCW surface-based observational network, including the core network called CryoNet. The group develops a network strategy and procedures for becoming part of the GCW network, evaluates proposed sites, and determines data availability. It develops relevant material to be included in the WMO Technical Regulations and in the WIGOS Manual. To establish CryoNet, it defined the types of sites on land or sea, operating a sustained, standardized programme for observing and monitoring as many cryospheric components and variables as possible. This Group is compiling best practices, guidelines, and standards, facilitates instrument intercomparisons, and promotes interaction and collaboration between the scientific and operational communities. It is conducting an inventory of measurement methods and infrastructure at sites that measure components of the cryosphere. The Observations Working Group assesses user needs, periodically reviews and updates observing system requirements and capabilities, and contributes to the WMO Rolling Review of Requirements database.

Decisions 2021

1. The group agreed to adapt an altered **structure** of the CIMO guide (Commission for Instruments and Methods of Observation) and start with capturing different existing definitions of the variables and collect common methods.
   The agreed points that should be addressed in the BP include the following:
   1. Variable
   2. Measurand
   3. Method(s)
   4. Instruments
   5. Configuration
   6. “strategy of measurements” (recommended by Phillippe)
   7. Recommendations
   8. Frequency and strategy of measurement
   9. Data logging and interpolation of individual measurements (e.g. derive profile)
   10. Sources of errors
   11. Consistency of time series
   12. Outstanding items which require further consideration
   13. Coordination with other programs (e.g. Implementation Plan for GTN-P, GCOS, etc.)

Notes from GCW Permafrost best practice group
(meets every month)

Actions:

- Finalize definition and terminology
- Define target (required) uncertainties
- Establish comparability among methods (temperature vs. mechanical)
- Assess comparability of historical and modern methodologies
- Establish traceability (also through field calibration)
- Prepare best practices
- Include recommendations in WMO Guide No. 8

ECV Products and Requirements for Permafrost

*These products and requirements reflect the Implementation Plan 2016 (**GCOS-200**). GCOS is reviewing and will update the requirements until 2022. More information on: **gcos.wmo.int**.*

PRODUCT	DEFINITION	FREQUENCY	RESOLUTION	REQUIRED MEASUREMENT UNCERTAINTY	STABILITY	STANDARDS/ REFERENCES
Thermal State of Permafrost	Ground temperatures measured at specified depths along profiles	Daily to weekly	Sufficient sites to characterise each bio-climate zone	0.1K		
Active Layer Thickness	Thickness of seasonally thawed ground measured in (cm)	Daily to weekly	Sufficient sites to characterise each bio-climate zone	2cm		

Permafrost temperature

3rd variable: rock glacier velocity

General definition

Definition of permafrost: Subsurface materials that remain continuously at or below 0 °C throughout at least two consecutive years.

Definition of active layer: The surface layer of the ground that is subject to annual thawing and freezing in areas underlain by permafrost.

Local definition

Phase transition temperature ≠ 0 °C

Factors influencing the melting temperature of permafrost

- Salt (relevant in coastal permafrost)
- Clay
- Chemical composition
- Debries dimensions
- Pressure
- Air

General definition

Definition of permafrost: Subsurface materials that remain continuously at or below 0 °C throughout at least two consecutive years.

Definition of active layer: The surface layer of the ground that is subject to annual thawing and freezing in areas underlain by permafrost.

Local definition

Permafrost and active layer are decoupled. Can there be permafrost without active layers and vice-versa?

What's the purpose of studying permafrost when active layers is where the fun is?

Permafrost w/o active layer (w/o water and/or ice) is still part of the cryosphere?

A discussion evolved around the need to change the current **definitions of permafrost and the active layer**, since the mineralization of the soil and fluids within may cause a freeze point depression to temperatures well below 0°C.

a. the group agreed that this is a topic for IPA and the BP group should stay pragmatic in using the current definitions.
b. The majority agreed that the definition differences may be identified, but not resolved in the BP, and retain the focus on common measurement practices;

In response to the to-be-solved issue on “frost vs. temperature” in definition of **active layer thickness measurements** a proposal was to adopt the term **“cryotic”** to solve the discrepancies in definitions (replacing freezing-thawing & 0°C temperature).

Not adopted (to my current knowledge).

NOTE Incomplete definition of the measurand can give rise to a component of uncertainty sufficiently large that it must be included in the evaluation of the uncertainty of the measurement result.

(see e.g. D.1.1, D.3.4, and D.6.2 of the GUM).

D.1.1 The first step in making a measurement is to specify the measurand — the quantity to be measured; the measurand cannot be specified by a value but only by a description of a quantity. However, in principle, a measurand cannot be *completely* described without an infinite amount of information. Thus, to the extent that it leaves room for interpretation, incomplete definition of the measurand introduces into the uncertainty of the result of a measurement a component of uncertainty that may or may not be significant relative to the accuracy required of the measurement.

CHAPTER 4. MEASUREMENT OF PERMAFROST

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4.1 **GENERAL**

4.1.1 **Introduction**

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

WMO-No. 8

- Measurement of snow
- Measurement of glaciers
- Measurement of permafrost

- Permafrost temperature
- Active layer thickness
- Rock glacier velocity

Definition of permafrost

Permafrost is defined as ground material which remains **at or below 0 °C** for at least **two consecutive years**

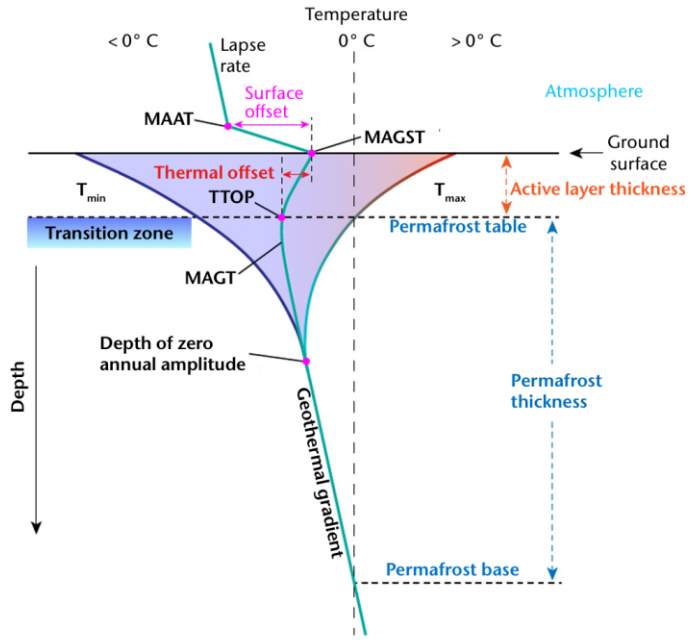

Figure 4.1. Schematic diagram of the equilibrium thermal regime of the ground and near-surface atmosphere in permafrost terrain. The mean annual ground temperature (MAGT) declines toward the temperature at the top of the permafrost (TTOP). The temperature envelope (shaded) between the ground surface and the depth of zero annual amplitude (DZAA) indicates the range of ground temperatures between the minimum (T_{min}) and maximum (T_{max}) during a year. MAAT – mean annual air temperature; MAGST – mean annual ground surface temperature.

Definition of **active layer thickness**

The term “**active layer thickness**” (ALT) in permafrost-affected regions refers to the **thickness of the thawed layer** (measured relative to the ground surface) that is reached **at the end of the warm season**. The term “thawed” can indicate either melting of ice or warming above 0 °C.

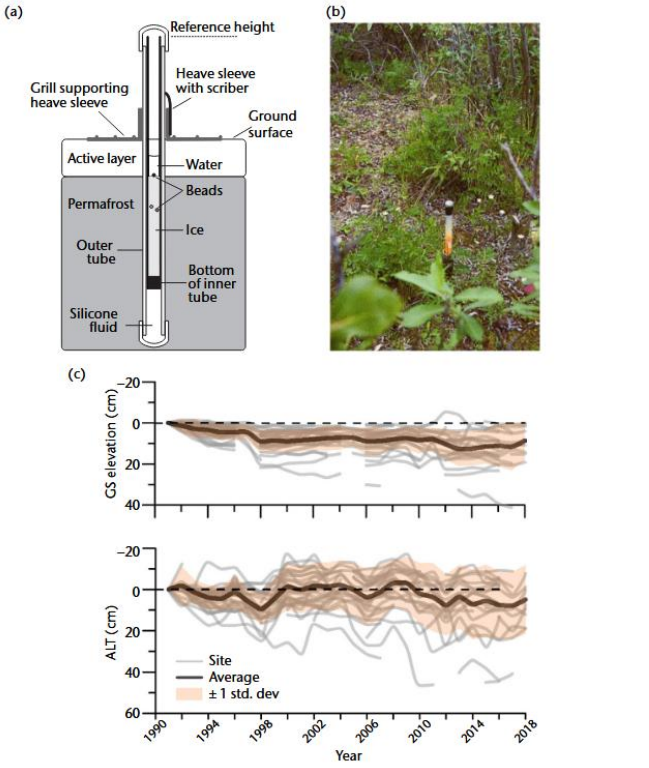

Figure 4.8. (a) Schematic diagram of the typical frost/thaw tube used to measure the active layer thickness (ALT) and ground surface (GS) elevation (after Mackay, 1973). (b) Frost/thaw tube installed at the Reindeer Depot (C07) Circumpolar Active Layer Monitoring (CALM) site in the Northwest Territories, Canada. (c) A long-term ground surface elevation and ALT record from 28 frost/thaw tube sites in north-west Canada. The values are plotted relative to the first year’s value in the record for each site (after O’Neill et al., 2023).

Source: Reproduced with permission from Natural Resources Canada

Definition of rock glacier velocity

Rock glaciers are defined as debris landforms generated by the former or current creep of permafrost, detectable in the landscape with the following morphologies: steep front and lateral margins, and optionally, ridge-and-furrow surface topography (RGIK, 2023a).
Rock glacier velocity (RGV) is defined as a time series of annualized surface velocity values expressed in m/a and measured/computed on a rock glacier unit or a part of it.

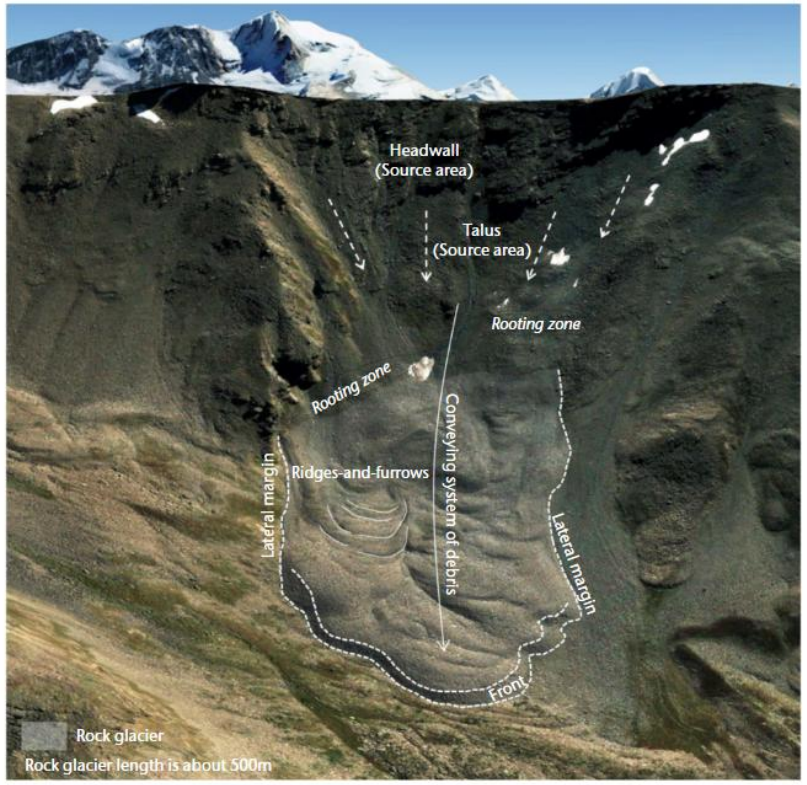

Figure 4.2. Rock glacier in the Vallone di Sort (Italy) identified in the landscape by a front (discernable talus delineating the terminal part of the moving area perpendicular to the main flow direction), lateral margins in continuity of the front and localized ridge-and-furrow surface topography.

Source: Background imagery: Google Earth. Adapted from RGIK (2023a).

4.2.3.5 **Uncertainty and sources of error**

[…]It is desired that the **measurement uncertainty of the entire measurement system remain at ±0.1 °C or less** according to the GTN-P measurement guidelines (Streletskiy et al., 2022). **Breakthrough uncertainty is reached at ≤0.05 °C**. **The ideal measurement uncertainty is ≤0.02 °C** (see, for example, the GCOS ECV requirements (GCOS-245)), since the system uncertainty should be lower than the measured changes.
[…]Depending on sensor type**, the largest contributors to uncertainty are typically potential drift, hysteresis** (ability to measure the same temperature starting from lower or higher temperature environments) **and sensitivity** (see 4.2.3.3). In addition, measurements can be influenced by the **configuration of the measurement system, which includes, for example, long cables and multiplexers**. The **environment** in which the sensors work can often be the largest source of uncertainty in measurements. Several associated quantities of influence can affect both the measurand and, more importantly, the sensors themselves. A further contributor to the measurement uncertainty in a permafrost setting, particularly for a shallow borehole, is **the degree of thermal contact between the sensor and soil**: when a permafrost sensor chain is put inside a borehole in direct contact with the air inside the hole but not the soil around it, the largest uncertainties arise given the low thermal conductivity of air itself and associated convective phenomena.
[…]Little is known about the effect of water infiltration and refreezing in the borehole on temperature measurements. Also, water may enter the borehole due to problems with the seal between casing sections (for example, deterioration of the cement or improper application of cement).

4.2.3.6 **Calibration**

Traceability, that is, the "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty" (BIPM, 2012), **is crucial to achieving comparable measurement results at different sites, with different systems, and at different times.**
Sensor calibration may not be possible in all regions or settings or for all types of equipment. […]
Sensors should be provided with a calibration certificate from an accredited laboratory. **For long-term monitoring, the sensor drift of the temperature probe** – for example, for NTC thermistors – **can lie in the range of the permafrost temperature trend to be captured. To ensure accurate measurements, instrument calibration is essential**. Calibration is a documented comparison of the measurement system to be tested against a traceable reference standard. Calibration is typically performed in a laboratory prior to permanent field installation. **Calibration of the sensors should be performed using the same instrument setup** (that is, temperature sensor chain, logging device, cables, etc.) as is used at the measurement site. **In the laboratory, sensors should be calibrated in a shaved ice bath or snow–water bath checked with an accurate reference thermometer** (Wise, 1988). If the ice bath is prepared properly and regularly stirred, it will be at 0 °C with an accuracy of at least 0.005 K. Also, a double bath (that is, a bath in a bath) is sometimes used for better insulation against the outside temperatures. **Further calibration at other temperatures can also be performed using a liquid calibration bath and reference thermometer (Merlone et al., 2020).**
Temperature calibration should involve at least three setpoints around 0 °C, to be able to interpolate (usually by means of a simple square polynomial) the behaviour of the devices under test. To do this, an alcohol bath is required in which three temperatures can be set. The temperature range of the calibration should be larger than the actual temperature range experienced by the sensors during normal operation, because extrapolation introduces larger uncertainties than interpolation**.**
To achieve and maintain the prescribed system uncertainty, sensor recalibration should be performed every 5–10 years of station operation to identify sensor drift or after changes in the measurement setup. **At reference sites or when low uncertainties are required (for example, 0.01 °C), recalibration should be performed every 2–5 years**, to correct for potential drift of sensors and systems. Ideally, sensor chains should be removed from the borehole for recalibration in the laboratory. However, the remoteness of some boreholes does not allow for that. In such cases, calibration should be performed in the field. If a second access tube is installed in the borehole, it can provide an opportunity to check the plausibility of the data registered by the long-term sensors. **One way to calibrate the sensors is to insert a high-precision, calibrated PT1000 (**a PRTD with a nominal resistance of 1 000 ohms at 0 °C) **next to the long-term sensor.** It is important to note that several hours of equilibration might be needed before the measurement can be performed. **There are systems, such as those described in Merlone et al. (2020), that can be brought to the measurement site and used for calibrating permafrost temperature sensors without the need for a complete disassembly of the system**.

Thanks