A new WMO Guide for the measurement of cryospheric variables

Craig D. Smith[1], Thorsteinn Thorsteinsson[2], Petra Heil[3], Charles Fierz[4], Rodica Nitu[5], Samuel Buisan[6], Christoph Marty[4], Anna Haberkorn[4]

[1] corresponding author, Environment and Climate Change Canada, Saskatoon, Canada, craig.smith2@canada.ca
[2] Icelandic Met Office, Reykjavik, Iceland
[3] Australian Antarctic Division, Hobart, Australia
[4] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[5] WMO Global Cryosphere Watch, Geneva, Switzerland
[6] AEMET, Zaragoza, Spain

Abstract: The Global Cryosphere Watch (GCW) is being developed by the WMO as a mechanism for providing dependable data, information, and analysis on the past, current, and future state of the cryosphere. To achieve its goals, GCW promotes consistent and sustainable measurements, of demonstrated quality, of all cryospheric components such as solid precipitation, snow, glaciers and ice caps, ice sheets, ice shelves, icebergs, sea ice, lake and river ice, and permafrost and seasonally frozen ground. As part of the GCW Observations Working Group, a Best Practices team was tasked with compiling an authoritative guide on measurement best practices for cryospheric variables for use at the GCW CryoNet stations as well as broader applications involving cryospheric observations. Recognizing the complexity and diversity of this task, the first priority has been given to the development of best practices for snow, sea ice, and glaciers. The intent of the guide proposed by GCW is to fill a void where current measurement guidelines are incomplete or fragmented and to compile and update existing measurement procedures to reflect current technologies and associated recommendations. For example, results from the recently completed WMO Solid Precipitation Inter-Comparison Experiment (SPICE) are incorporated to add recommendations on the automated measurement of snow on the ground. The Guide for the Measurement of Cryospheric Variables will include specific chapters for each component of the cryosphere and a general chapter reflecting broader aspects of cryosphere observations. These will be published in conjunction with the Guide to Meteorological Instruments and Methods of Observation, WMO-No. 8, as it evolves to broaden its scope to include the full spectrum of observations within the context of the Integrated Global Observing System. This will ensure that the information will be widely accessible and used by the community. This presentation will provide an introduction to the new Guide for the Measurement of Cryospheric Variables and most recent developments.

1. Introduction

The Global Cryosphere Watch (GCW) is a World Meteorological Organization (WMO) cross-cutting initiative that will serve as a mechanism for supporting cryospheric observations by providing "authoritative, clear, and usable data, information, and analyses on the past, current, and future state of the cryosphere" (https://globalcryospherewatch.org/), where the cryosphere is the collective components of the earth's ecosystem that contain frozen water for at least part of the year. Currently, there are 163 CryoNet or contributing stations in the GCW Surface Observing Network (https://globalcryospherewatch.org/cryonet/sites.php) committed to providing high quality observations of cryospheric components such as snow, glaciers and ice caps, ice sheets, ice shelves, icebergs, sea ice, lake and river ice, permafrost, and seasonally frozen ground.

To facilitate high quality measurements in the observing network, the GCW Observations Working Group and the GCW Best Practices team was tasked with providing an authoritative guide for the measurement of cryospheric variables. In line with the GCW commitment to bridge scientific and operational communities and the aspirations of the WMO to have one authoritative best practices guide for cryospheric observations, the GCW best practices guide will converge with the WMO Guide to Meteorological Instruments and Methods of Observations (WMO-No. 8) and become a stand-alone volume of this guide entitled "Measurement of Cryospheric Variables".

2. History and motivation

Using snow measurements as an example, there are currently several published documents that are used as guidance for measurement best practices. For most meteorological variables, the WMO Guide to Meteorological Instruments and Methods of Observations is generally the most accepted and often used guide. The current 2014 edition (with updates in 2017) includes mention of snow and snowfall (Part I, Chapter 6, Measurement of precipitation) but largely in the context of measuring precipitation as a meteorological variable. The Guide to Meteorological Instruments and Methods of Observations references the WMO Commission for Hydrological Practices Guide, Volume 1 (WMO No. 168) as the authoritative guide for measuring snowfall and snow cover (Chapter 3, Precipitation Measurement). This guide, in turn, references the Guide to Meteorological Instruments and Methods of Observations.

Besides the two WMO guides, the International Association of Cryospheric Sciences (IACS) published The International Classification for Seasonal Snow on the Ground (ICSSG) in 2009 (Fierz et al., 2009). The ICSSG is often cited as a resource for definitions of snow variables and methodologies but was only partly a functional guide for best practices. Of course, there are also a multitude of book compilations (such as the Handbook of Snow; Gray and Male, 1981) and published articles (e.g. Measurement of the physical properties of the snowpack; Kinar and Pomeroy, 2015) on the subject of measuring snow.

Given the variety of guidelines for measuring snow, the circular referencing in current WMO documents, and the need for continuous updates and improvements, the GCW decided that it was necessary to explore the compilation of a new best practices guide for the measurement of snow. Further to this, results from the WMO Solid Precipitation Inter-Comparison Experiment (presented at TECO 2016 in Madrid; Nitu et al., 2016) include updated lessons learned and improved methodology for the automated measurement of solid precipitation, both as snowfall and snow on the ground, contributing content for an updated authoritative document for snow.

Along with snow, a functional best practices document is required for other cryospheric variables such as for glacier and sea ice measurements. Glaciers, ice caps and ice sheets form an important part of the cryosphere, covering 10% of Earth´s land surface. The first worldwide inventory of glaciers was created during the International Hydrological Decade in 1965-1974 and the Global Terrestrial Network for Glaciers (GTN-G) currently oversees the management and upgrading of glacier inventories as part of a global observation strategy under the auspices of the UN. GCW has formed partnerships with existing glacier inventories and data centers and earlier guides on measurement practices published by these bodies have been used as reference material in the preparation of a GCW Guide to Best Practices in measurements on glaciers. In 1991, the Norwegian Water Resources and Energy Directorate and Environment Canada published a manual for field and office work on Glacier Mass Balance Measurements, which is still a widely cited reference (Østrem and Brugman, 1991). In 2003, a manual for mass balance measurements on mountain glaciers (Kaser et al., 2003) was issued by the International Commission for Snow and Ice and the International Association for Cryospheric Sciences published a Glossary of Glacier Mass Balance in 2011 (Cogley et al., 2011) . The methods and terminology described in the above mentioned reports are still widely used, but the GCW Guide being developed will also reflect recent developments in measurement techniques, including airborne and spaceborne observing platforms.

Sea ice is another crucial component of the cryosphere, interacting intensely with the underlying ocean and the atmosphere above. It extends over about 10% of the Earth’s surface for part of the year and its seasonal waxing and vanning in the two hemispheres prescribes one of the largest modulations of the Earth’s surface by virtue of the higher surface albedo of sea ice as compared to open water. There is no unified go-to-point for Arctic, Antarctic or global sea ice data or observational methods. During the

International Geophysical Year (1957-1958) the World Data Center-A for Glaciology (Snow and Ice) (WDC), as one of three international data centres, had been established to facilitate the exchange of cryospheric data including sea ice. The National Snow and Ice Data Centre has taken on management and distribution of cryospheric data, which is being contributed from scientific or operational projects. There are several other data centres managing various streams of sea ice data. Driven from within the scientific sea ice community, a number of observational standards have been developed. These include the Antarctic Sea ice Processes and Climate (ASPeCt) protocols for underway observations (now also adopted for the Arctic in the ASSIST project) and *in situ* measurements (Worby and Allison, 1999); or the field techniques for sea ice research (Eicken et al., 2010). Standards like these form the basis, on which the sea ice chapter of the GCW Best Practices Guide is being built. The aim here is to unify the current observational methods into a single standard for *in situ* observations. However, in light of access issues to near-coastal (fast) ice, plus a new generation of (research) icebreakers being under construction, the GCW sea ice observing guide also implores advances in autonomous observing systems. Furthermore the GCW Guide would be incomplete without reference to satellite-based observing methods: While not taking *in situ* measurements, satellite-based sensors are the only mean to provide a complete picture of the sea ice state.

The advancements in the development of the GCW Best Practices Guide, in parallel with the evolution of the new Measurements and Observations guide managed by the Commission for Instruments and Methods of Observation (CIMO) to include Measurement of Cryospheric Variables (with the 2018 version currently under review by the members), have largely been with the cryospheric components of snow, glaciers, and sea ice, and hence the focus on these components in this document. Ultimately, the guide will also include the cryospheric components of ice sheets, ice shelves, icebergs, lake and river ice, and permafrost and seasonally frozen ground.

3. Content and format

3.1 Introductory chapter

The current and incomplete version of the Guide for the Measurement of Cryospheric Variables begins with a general chapter outlining the scope and contents of the guide. Although still in development, this chapter includes a comprehensive definition of the cryosphere, an introduction to the objectives of GCW, some general characteristics of GCW measurement sites (including siting and exposure requirements), and a brief introduction to measurements and best practices. For each cryospheric component identified by GCW and listed on the GCW website:

https://globalcryospherewatch.org/cryonet/variables/recommended_variables.html.

This document lists the variables for measurement that are recommended or desired by GCW and the required time scale for measurement, whether automated or manual. For snow, as an example, the recommended variables include snow depth, water equivalent of snow cover (SWE), presence of snow on the ground, and specific snow properties (density, grain size, liquid water content, etc.). Recommended variables for glaciers include surface accumulation, surface ablation, surface mass balance, and glacier area. For sea ice, the recommended variables are sea ice thickness, freeboard, stage of melting, class (i.e. pack or fast ice), and sea ice type. For many components, there is often an overlap of recommended and desired variables, depending on the specific application for the measurement. The general focus of the guide is on the recommended variables (although this may evolve over time) so the list of desired variables is not detailed here.

3.2 Snow

As of September 2018, the snow chapter of the guide is the most advanced and comprises the document that was submitted by GCW to CIMO for inclusion in the most recent update of the Guide for the Measurement of Cryospheric Variables. The document describes some of the most common measurement practices for snow, including snow depth (HS), water equivalent of snow cover (SWE), depth of snowfall (HN), presence of snow on the ground (PSG), and snow properties (still incomplete). After introducing common measurement practices, the guide lists best practices for making snow measurements and discusses issues with siting and exposure which have a substantial influence on measurement quality. Because snow is an integral component in the cryosphere, this chapter will present considerations for measuring snow on other cryospheric components, such as glaciers and sea ice. The discussion is organized to offer an explanation of both manual and automated techniques (where available) for measuring snow and the sources and magnitude of errors associated with each.

Using snow depth as an example, the guide illustrates manual (e.g. snow stakes; Fig. 1 Left, semi-automated (e.g. hourly photographed snow stakes; Fig. 1 Middle) and automated (e.g. sonic derived depth; Fig. 1 Right) measurement techniques, discussing the best practices for each. Figure 2 is an illustration showing the best observation technique for snow stakes given different snow characteristics across the face of the stake.

Figure 1: Left: visually observed snow stake; Middle: photographed snow stake; Right: sonic snow depth instrument over artificial target.

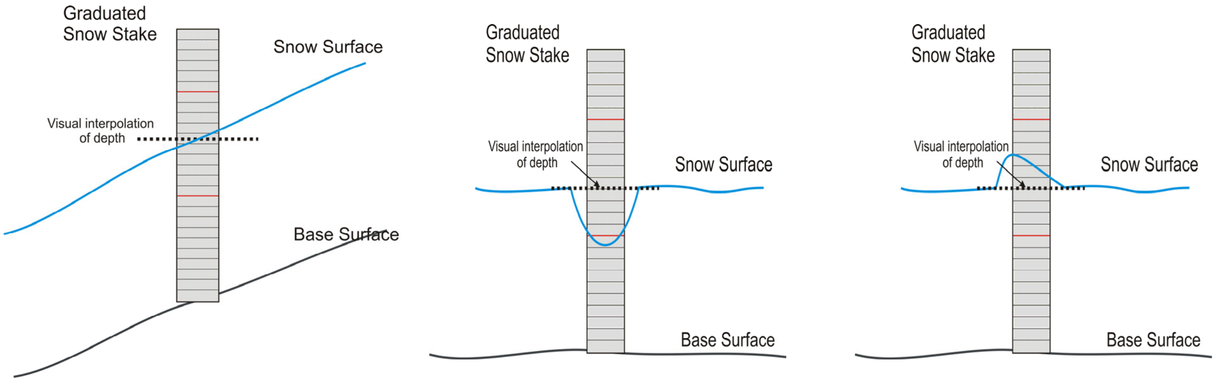

Figure 2: Illustration of the best observation practices for a snow stake showing how to interpolate and observe uneven snow depth across the face of the stake due to a sloping snow surface (left), welling (middle) and mounding (right).

Following SPICE, the most significant addition to the best practices guide for measuring snow are the recommendations on best practices for operating automated instruments. This document will include guidance on instrument selection and limitations, installation and infrastructure, the use and implications of an artificial surface target for snow depth, and automated quality control.

Each of the snow components listed above will include a discussion of the errors associated with each measurement, both manual and automated, and some recommendations on how to mitigate them. For example, the impact and prevention of “over-probing” (where an observer inserts a snow rod through the snow and into the underlying surface, thereby overestimating depth) are discussed as well as errors associated with the misinterpretation of the snow across the face of a snow stake (as in Fig. 2). For automated measurements of snow depth, errors associated with erroneous temperature corrections (for sonic instruments), target heaving/settling, and the obstruction of an instrument from collected snow and ice (e.g. Fig. 3) are all listed as sources of errors with recommendations on how to limit these errors. Similar discussions are (or will be) included for water equivalent of snow cover, depth of snowfall, presence of snow on the ground, and snow properties.

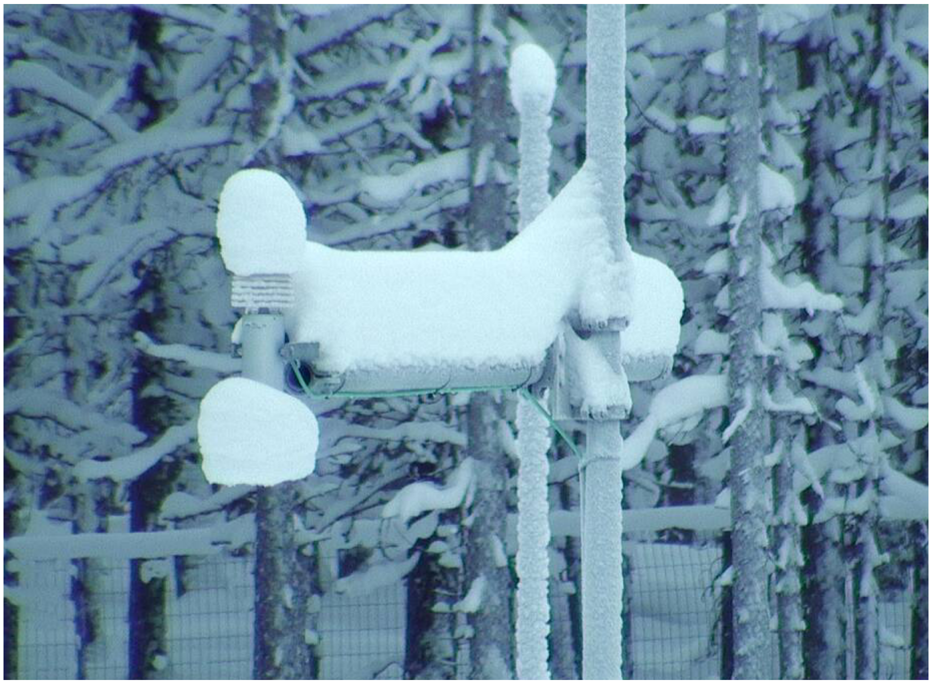

Figure 3: Unheated snow depth instrument and mounting infrastructure collecting snow in a low wind environment. (photo courtesy of FMI).

3.3 Glaciers

The glacier chapter starts with definitions of glaciers and ice caps, outlining physically based definitions as well as those used by the remote sensing communities to delineate individual glaciers on satellite imagery. Classification schemes for glaciers and ice caps are also described. The recommended variables for measurement at CryoNet stations that conduct glacier measurements are surface accumulation, surface ablation, surface mass balance (at point and glacier wide scales), and glacier area.

A separate chapter is devoted to the mapping of glacier outlines, based on reports published by the GLIMS-consortium (Global Land Ice Measurements from Space; https://www.glims.org/MapsAndDocs/guides.html). GLIMS has produced the software GLIMSView which allows a user to generate digitized glacier outlines, add appropriate metadata, and export the whole package into appropriate data transfer format. The GLIMS definition gives clear indications on whether bodies of ice adjacent to the glacier, which may contribute accumulation through avalanching and ice falls, belong to the glacier or not. The same applies to stagnant ice masses, debris covered parts of the glacier and other components.

Methods for determining glacier thickness by radio-echo sounding (RES) are described in the glacier chapter. Due to logistic challenges, radio-echo sounding has only been carried out on a fraction of the world´s 200,000 glaciers. Glaciologists thus apply empirical scaling laws to estimate glacier volumes from glacier areas (Adhikari and Marshall, 2012), allowing estimates of the total volume of glaciers and ice caps on Earth. The section on glacier thicknesses will review progress in the development of such scaling relations. Recent advances in mapping glacier surfaces with airborne and spaceborne laser scanners and radiometers will also be outlined.

Best practices in mass-balance measurements on glaciers and ice caps form an important part of the glacier chapter. Accumulation and ablation processes and their seasonal variation are outlined, as well as different zones on a glacier. Recommendations on the selection of locations for point measurements of winter and summer mass balance are made. Snow measurements will be described in the snow section, emphasizing glacier specific peculiarities and methods (e.g. snow core drilling, Fig. 4). Emphasis is on the importance of density measurements in pits and on snow cores, for the determination of SWE for the winter layer.

The placement of ablation stakes is described and special attention is given to methods that need to be employed at high altitudes, where drilling equipment and ablation stakes must be carried onto the glaciers. Figures 5 a&b illustrate the difference between hot water drilling systems that need to be transported by ski-doos or other vehicles, and lightweight, portable drills that can be carried to inaccessible glacier locations

Figure 4: Left: A snow coring drill powered with a pipe threader in operation. Right: Removing a snow core from the core barrel (Photos: Thorsteinn Thorsteinsson).

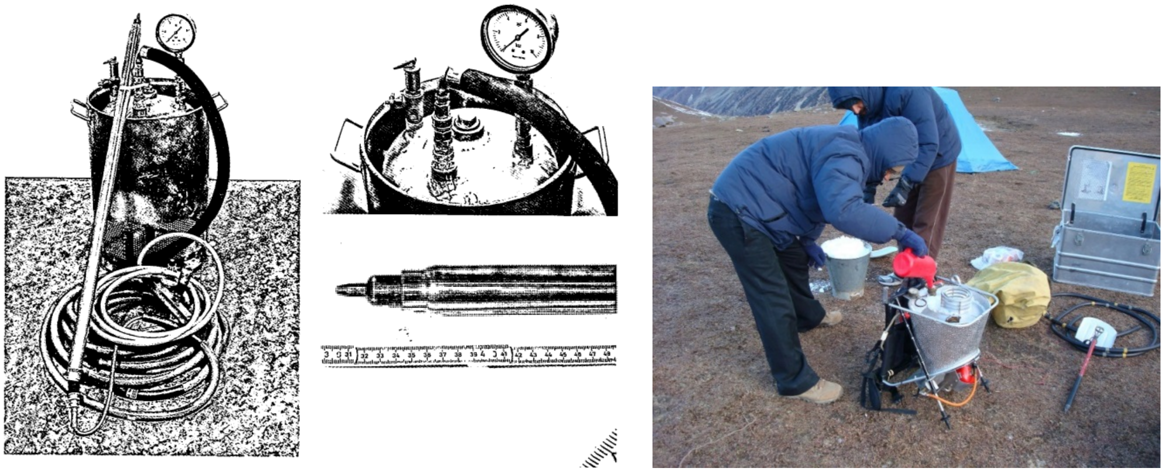

Figure 5: Left: A "hot-point drill" using steam produced in a pressure boiler, heated by propane. An insulated rubber hose, 10-15 m long, delivers steam to the drill stem. At a steam pressure of about 6 atmospheres, this drill penetrates 5-10 metres of ice per hour (Photo from Østrem and Brugman, 1991). Right: A lightweight, portable steam drill, suitable for use on high-altitude glaciers (Photo: Thorsteinn Thorsteinsson).

In September 2018, additional sections on measurement methods to estimate basal ablation on glaciers and calving fluxes are being compiled. The GCW guide will also include sections on measurements of glacial runoff, ice velocity and ice/firn temperatures.

3.4 Sea Ice

Despite its very low thickness (compared to ocean depth or glacial thickness), sea ice is an extremely effective insulator between the ocean and the atmosphere, reducing the exchange of thermal energy, moisture, and particle and momentum fluxes between those. During thermodynamic growth, sea ice releases cold brine into the underlying ocean, increasing the local ocean density. The sinking of this heavy water leads to Bottom Water Formation, presenting one of the drivers for the meridional overturning circulation of the world’s oceans. Changes in the sea ice formation rates directly affect the global climate. Furthermore, sea ice also provides infrastructure to associated ecosystems, e.g., ice algae and krill or macroscopic wildlife including seals or penguins. Last but not least, sea ice enables subsidence hunting and affects marine operations, including shipping, off-shore platforms and near-coastal off-shore travel.

The basis of the sea ice chapter are the recommended and desired variables for sea ice components and the challenge to observe these sufficiently within GCW’s CryoNet framework of in situ stations. With sea ice forming at the ocean-atmosphere interface, access to measure sea ice properties is challenging, hence costly and limited. Consequently, near-coastal sea ice observatories have been established with a focus on shore-fast ice, which provides a relatively stable surface for measurement for much of its lifetime. However, fast ice represents (by area) only a small part of the sea ice, and autonomous measurements (i.e., from drifting buoys) as well as ship-based, aerial and remotely-sensed observations are required to supplement those taken at fixed CryoNet stations. It is a topic of discussion to admit autonomous Lagrangian drifters and ship-based observatories into the list of CryoNet stations, as these are the only efficient means to obtain information on the state of the pack ice, which includes all drifting sea ice.

Sea ice thickness, concentration and ice type lead the list of required parameters. Others are sea ice freeboard, extent, floe size and topography. The Best Practice Guide devotes subsections for the various approaches to measure them, distinguishing automated and manual measurements. Here we note the limited scope of in situ observations of ice concentration and associated sea ice extent, and provide information on remotely-sensed methods. As the Best Practice Guide has been constructed, a consistent description of methodology has been given to each sea ice parameter.

Special attention has also been given to the so-called derived parameters, which are used in operational sea ice analysis. Stage of development, start day of melt, or duration of ice cover, are just a few examples. As part of the Best Practice Guide, it will remain important to clearly identify those variables required, so that the derived parameters can build.

The above mentioned data sparsity for sea ice observations has led to various groups (such as the Norwegian Ice Charting Center) to seek additional observations by permitting non-expert observers. These may be expeditioners or guests on tourist vessels, or ship crews on non-research cruises into the ice-covered ocean. Special training material is included in the Best Practice Guide to assist non-experts in conducting sea ice observations at a consistent quality level.

Last but not least, sea ice occurs in various regions and hence different environmental settings. Each of these brings their own observing challenges, for which the Best Practice Guide aims to provide a suitable approach for observing sea ice variables. An example for this is the presence of platelet ice, which may freely float underneath the sea ice cover or may attach itself to the base of the sea ice and eventually be incorporated into the sea ice matrix. However, the platelets interfere directly with in situ deployed sensors by aggregating to the sensor, resulting in the sensor data being either invalid or requiring specific interpretation.

4. Document evolution and timelines

The current version (September 2018) of the Guide for the Measurement of Cryospheric Variables, which only contains the general chapter and the chapter for snow, is under review by CIMO and WMO members. This version has been frozen pending this review. In the meantime, the GCW Best Practices guide will continue to evolve in parallel with the CIMO version and is currently under review by invited experts from both the operational and research community. Engaging both communities will insure that the guide is functional for both. It is anticipated that all of the recommended cryospheric components will be included in the GCW guide in advance of operationalizing GCW in 2020. As components are added, the CIMO editorial review process will be utilized to allow for the CIMO Guide for the Measurement of Cryospheric Variables to update in parallel with the document required for GCW. This represents a significant collaborative effort between CIMO and the GCW initiative. The guide, as written, is intended to be a living document, updated as often as required as best practices evolve. This is especially important as new automated technologies are continually developed and improved along with the recommendations on the best practices for their use.

References

Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A.A, Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Möller, M., Nicholson, L., Zemp, M. 2011. Glossary of Glacier Mass Balance and Related Terms, IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris, http://unesdoc.unesco.org/images/0019/001925/192525E.pdf

Eicken, H., R. Gradinger, M. Salganek, K. Shirasawa, D. Perovich, and M. Leppäranta (Eds). 2010. Field Techniques for Sea-Ice Research, 368pp., ISBN: 9781602230590.

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A. 2009. The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology N°83, IACS Contribution N°1, UNESCO-IHP, Paris, http://www.cryosphericsciences.org/snowClassification.html;

Gray, D. M. & Male, D. M. (Eds.) 1981. Handbook of Snow: Principles, Processes, Management and Use. Reprint. The Blackburn Press, Caldwell, NJ, USA.

Kaser, G., Fountain, A., Jansson, P. 2003. A Manual for Monitoring the Mass Balance of Mountain Glaciers, IHP-VI Technical Documents in Hydrology No. 59, Paris, http://www.cryosphericsciences.org/glossaryMassBalance.html

Kinar, N. J., and J. W. Pomeroy. 2015. Measurement of the physical properties of the snowpack, Rev. Geophys.,53, doi:10.1002/2015RG000481

Nitu, R., Rasmussen R., Roulet, Y. 2016. WMO SPICE: Intercomparison of instruments and methods for the measurement of solid precipitation and snow on the ground, overall results and recomendations, WMO Technical Conference on meteorological and environmental instruments and methods of observations, pages 1–7, Madrid, Spain, https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-125_TECO_2016/Session_3/K3A_Nitu_SPICE.pdf

Østrem, G., Brugman, M. 1991. Glacier Mass-Balance Measurements, A manual for field and office work, NHRI Science Report No. 4, Environment Canada, Saskatoon, 224 pp, https://wgms.ch/downloads/Oestrem_Brugman_GlacierMassBalanceMeasurements_1991.pdf

WMO. 2008. Guide to Hydrological Practices, 6th edition, WMO-no. 168, Geneva, Switzerland, http://www.whycos.org/hwrp/guide/index.php

WMO. 2014. Guide to Meteorological Instruments and Methods of Observation, 2014 Edition (updated in 2017), WMO-no. 8, Geneva, Switzerland, https://library.wmo.int/index.php?lvl=notice_display&id=12407#.W5A_BronbmF

Worby, A. P. and I. Allison. 1999. A technique for making ship-based observations of Antarctic sea ice thickness and characteristics, Part I: Observational technique and results, *Antarctic CRC Research Report*, 14, pp 1-23.