VOLUME II MEASUREMENT OF CRYOSPHERIC VARIABLES [1]

[1] The preliminary content of this document might change in the future. This new volume should include all GCW components of the cryosphere as enumerated in the definition of the latter, that is snow, glaciers and ice caps, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost, and seasonally frozen ground. For now, only chapters 1 and 2 are included in this Guide, while other chapters are under development and will be added later.
Note that that solid precipitation measurements are covered in Volume I, Chapter 6.

CHAPTER CONTENTS

CHAPTER 1. GENERAL

1.1 OBSERVATION OF THE CRYOSPHERE

1.1.1 General

The cryosphere collectively describes components of the Earth System that may very often contain water in its frozen form; it includes solid precipitation, snow, glaciers and ice caps, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost and seasonally frozen ground. Permafrost, however, can be "dry" and therefore the cryosphere also includes any natural material in frozen form. The cryosphere includes elements that occur on or beneath the Earth's surface or that are measured at the surface in the case of solid precipitation, excluding ice clouds. The cryosphere is global, existing not just in the Arctic, Antarctic and mountain regions, but at various latitudes in approximately one hundred countries. The cryosphere provides some of the most useful indicators of climate change, yet is one the most under-sampled part of the Earth System. Improved cryospheric monitoring and integration of that monitoring is essential to fully assess, predict and adapt to climate variability and change.

1.2 OBSERVING SYSTEMS OF THE CRYOSPHERE

WMO, with the co-operation of other national and international bodies and organizations, and using its global observing and telecommunication capability, is in a position to provide an integrated, authoritative, continuing assessment of the cryosphere – a Global Cryosphere Watch (GCW). The GCW surface observation network is considered as the cryospheric component of the WMO Integrated Global Observing System (WIGOS), contributing to the Global Climate Observing System (GCOS) and the Global Earth Observation System of Systems (GEOSS). As encouraged by GCOS, GCW facilitates the establishment of high-latitude and alpine stations with co-located measurements of key variables, especially permafrost and snow cover, thus enhancing GCOS and Global Terrestrial Observing System (GTOS) networks for Permafrost, Glaciers and Hydrology.

1.3 GENERAL SITING AND EXPOSURE REQUIREMENTS FOR A STATION MEASURING CRYOSPHERIC VARIABLES

The characteristics of the measurement site should be captured in the station metadata. Important siting details for measurements to be listed in the metadata include, but may not be limited to, surface type (mineral soil and/or organic layers, vegetation type, ice, etc.), prevailing wind direction, site layout and exposure to both wind and solar radiation. However, the representativeness of the measurement area to the surrounding landscape needs to be considered. At alpine stations, measurements on areas with higher exposure than the surrounding landscape should be avoided as these exposures may cause unrepresentative measurements.
Finally, siting should take into consideration accessibility and permanence which will ultimately impact the continuity of the record. For automated measurements, considering the source of available power and communications may also be a consideration for siting.

1.4 MEASUREMENT STANDARDS AND BEST PRACTICES

To ensure high quality and consistent observations, measurements of cryospheric variables at GCW stations will be made according to accepted standards. Many measurement standards have been compiled by GCW, or other networks, though the compilation is not exhaustive for several cryospheric measurements. An initial inventory of existing documents describing measurement practices, or in some cases best practices for processing the observations, are found on the GCW website (https://globalcryospherewatch.org/bestpractices/methods.html).

Some existing cryosphere networks have their own standards. It will be a major effort of GCW to establish standards in agreement with the existing ones as well as with guidelines for observations of single cryospheric variables, some of which are routinely used. Thus GCW measurement standards will draw on existing ones, for example the *Guide to Hydrological Practices* (WMO-No. 168), *Snow cover measurements and areal assessment of precipitation and soil moisture* (WMO-No. 749), or the *International Classification for Seasonal Snow on the Ground* (Fierz et al., 2009), and add new ones as necessary. They will be reviewed by the scientific community, modified as needed, and maintained in this Guide that is the GCW standard document for measurements and best practices relating to the cryosphere.

GCW established a list of required, recommended and desired variables that is reproduced below for each component of the cryosphere. Currently, required measurements are listed only for meteorological surface measurements at CryoNet stations and therefore only measurements for recommended cryospheric variables are described in this Guide. Recommended measurements of cryospheric variables may become required at a later stage.

1.4.1 Snow

There is no global, coordinated monitoring of snow on the ground yet. This relates to the fact that network requirements differ from application to application such as avalanche warning, meteorological observations, snow hydrology, etc. Guides to best practices are thus found in various manuals pertaining to each of these applications, often coinciding.

Moreover, best practices that work in an alpine region may not work in extreme conditions as found in East Antarctica, where, for example, “snow depth” is much more difficult to define unequivocally.

Since 1954, there exists an International Classification of Seasonal Snow on the Ground (ICSSG) that covers many but not all aspects of snow monitoring as well as measurements and observations of snow properties. A Working Group of the International Association of Cryospheric Sciences (IACS) has revised ICSSG that is now available online (Fierz et al., 2009).

However, as the number of regular and continuous manual observations diminishes worldwide, there is an urgent need to improve our ability to measure automatically snow on the ground and to validate those measurements against manual observations. One important step in that direction is the WMO Solid Precipitation Intercomparison Experiment (SPICE). Again, requirements are very different depending on the application. While an avalanche forecaster will not be too concerned about an error of ±5 cm in the depth of snowfall, road maintenance may become active as soon as a road is covered by 1 cm of snow.

Table 1.1. List of required, recommended and desired snow variables; where A: automatic, M: manual, S: Snow, G: glaciers, IS: ice sheets, ISV: ice shelves, SI: sea ice, LRI: lake and river ice, P: permafrost, SFG: seasonally frozen ground

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*weekly*	*monthly*	*yearly*
Required	None yet					
Recommended	Snow depth (including stake farms and snow courses)	A(S, G, SI, LRI)	M(S)	M(SI, LRI)*		M(G, IS)
	Water equivalent of snow cover	A(S)		M(S)*		M(G,IS)
	Snow properties (that is density, specific surface area, grain shape and size, hardness, liquid water content, salinity, chemistry, impurities, mechanical)			M(S)*		M(IS)
	Presence of snow (on the ground)		M(S)			
Desired	Snow depth	A(IS, P)	M(P)	M(S)*		
	Snow properties			M(SI, LRI)*		
	Depth of snowfall		M(S)			
	Water equivalent of snowfall		M(S)			
	Snow cover extent	A(SI, LRI)		M(SI, LRI)*		
	Snow surface temperature	A(S, SI)		M(SI, LRI)*		
	Snow temperature	A(S)				
	Drifting snow	A(S)	M(S)			

* bi-weekly

1.4.2 Glaciers and ice caps

The Global Terrestrial Network for Glaciers (GTN-G) is the framework for the internationally coordinated monitoring of glaciers and ice caps in support of the United Nations Framework Convention on Climate Change (UNFCCC). This GCOS/GTOS network is jointly run by the World Glacier Monitoring Service (WGMS, a service of IACS), the US National Snow and Ice Data Center (NSIDC), and the Global Land Ice Measurements from Space initiative (GLIMS).

Beside detailed (index) in situ measurements of mass balance, glacier inventories comprise basic information on physiographic properties of glaciers, including glacier boundaries and surface topography. Efforts are also made to compile standardized data on glacier thickness measurements.

In 2015, WGMS designed the Global Glacier Change Bulletin (GGCB) series with the aim of providing an integrative assessment of worldwide and regional glacier changes at two-year intervals. The basic data, however, can be found on the official websites of the above organizations.

Table 1.2. List of required, recommended and desired glacier and ice cap variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*weekly*	*monthly*	*yearly*[+]
Required	None yet					
Recommended	Surface accumulation (point)	A				M[1]
	Surface ablation (point)	A				M
	Surface mass balance (glacier wide)					M
	Surface mass balance (point)	A				M
	Glacier area (glacier wide)					M[2]
Desired	Surface accumulation (glacier wide)					M
	Surface ablation (glacier wide)					M
	Basal Ablation (point)	A				M
	Glacier thickness (point)					M[2]
	Glacier volume (glacier wide)					M[2]
	Glacial runoff	A				
	Calving flux (point)					A/M
	Ice velocity (point)		A			M
	Ice/firn temperature profile (point)	A				

[+] 1 seasonal; 2 multi-year

1.4.3 Ice sheets

Table 1.3. List of required, recommended and desired ice sheet variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*weekly*	*monthly*	*yearly*$^{+}$
Required	None yet					
Recommended	Surface accumulation (point)		A			
	Surface ablation (point)		A			
	Surface mass balance (point)		A			M
Desired	Ice sheet thickness (point)					M^{2}
	Ice velocity (point)				A	
	Ice/firn temperature profile (point)	A				

$^{+}$ 2 multi-year

1.4.4 Ice shelves

Table 1.4. List of required, recommended and desired ice shelves variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*weekly*	*monthly*	*yearly*
Required	None yet					
Recommended	Basal ablation					A/M
	Ice velocity		A			M

1.4.5 Icebergs

Icebergs largely occur in the Arctic Ocean and adjacent seas, as far south as Newfoundland and Labrador, and in the Southern Ocean. Iceberg monitoring is a crucial safety issue for travelling and offshore ventures in polar seas, as well as providing input for climatological analysis, such as assessing the mass loss from the glacial ice sheets.

Iceberg monitoring is largely based on remotely-sensed imagery. Nevertheless iceberg observations form part of several *in situ* observation programmes, including the ship-based observation (for example, Jacka and Giles, 2007; Romanov et al., 2017).

In situ iceberg observations for both, the Arctic and Antarctic include basic observations of the position, size and distribution density, as well as motion, shape and draft.

Table 1.5. List of required, recommended and desired iceberg variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*weekly*	*monthly*	*yearly*
Required	None yet					
Recommended	Iceberg position			M		
	Iceberg form, size			M		
	Iceberg concentration (distance)			M		
Desired	Iceberg motion		A/M			
	Iceberg height (above water)		A/M			
	Iceberg width and length (at waterline)		A/M			
	Iceberg draft			A*		
	Underwater 3-D form			A*		

* bi-weekly

1.4.6 Sea ice

Sea ice, as well as ice covered lakes and rivers, and icebergs affects large regions of economic, environmental and social importance.

Information on sea-ice conditions is provided by the national ice services conducting continuous monitoring of sea ice, lake and river ice as well as iceberg occurrences. Other bodies involved in this monitoring include the International Ice Patrol as well as the research community on hemispheric, circumpolar or regional scales. For operational purposes many ice properties are displayed as two-dimensional (2D) parameters (polygons) in ice charts. However, it is evident that satellite remote sensing is the primary source of data for sea ice monitoring, though not all of the key parameters can be observed with sufficient accuracy by space-borne measurements. *In situ*, coastal, shipborne and airborne measurements are a vital complementary, and sometimes a primary, source of information. These initiatives, especially ship- and air-borne, are largely in support of scientific research, and using standard observation procedures (such as ASPeCt underway sea-ice observation protocol (Antarctic Sea ice Processes and Climate, www.aspect.aq), or ASSIST (Arctic Shipborne Sea Ice Standardization Tool, http://icewatch.gina.alaska.edu/pages/data_guide)) has been proven crucial to the successful uptake of the data. Recently efforts have been initiated to unify the Antarctic and Arctic observing protocols.

Table 1.6. List of required, recommended and desired sea ice variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*weekly*	*monthly*	*yearly*
Required	None yet					
Recommended	Sea-ice thickness	A		M*		
	Sea-ice freeboard	A		M*		
	Sea-ice stage of melting			M		
	Sea-ice class (pack or fast ice)		M			
Recommended – applicable for pack ice	Sea-ice type (level/rafted/ridged and floe descriptor)		M			
	Form of ice (floe size)			M		
Desired	Sea-ice openings (leads, polynyas, cracks)		A			
	Sea-ice velocity	A	M			
	Sea-ice deformation (divergence/convergence)	A	M			
	Sea ice ridge cover (concentration and height of ice ridges)	A	M			
	Sea-ice draft			M*		
	Sea-ice salinity profile (vertical)			M*		
	Sea-ice stratigraphy			M*		
	Surface temperature (surface-air interface)	A				
	Sea-ice temperature pro-file (vertical)	A		M*		
Satellite-based (non *in situ*)	Sea-ice concentration		A/M			

* bi-weekly

1.4.7 Lake ice

Table 1.7. List of required, recommended and desired lake ice variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*weekly*	*monthly*	*yearly*
Required	None yet					

Recommended	Ice thickness	A		M*		
	Ice concentration		A/M			
	Ice class (pack or fast ice)		M			
	Ice type (level/rafted/ridged and floe descriptor)		M			
	Form of ice (floe size)			M		
	Stage of ice development			M		
	Ice phenomena (dates of freeze-up, fast-ice formation/breakout, melt onset, break up)			A/M		M
	Ice stage of melting		M			
Desired	Areal extent of floating/grounded ice			M		
	Ice surface temperature	A				
	Ice openings (leads, polynyas, cracks)		A			
	Ice velocity	A	M			
	Ice deformation (divergence/convergence)	A	M			
	Ice ridge height	A	M			
	Ice ridge cover (concentration of ice ridges)	A	M			
	Ice stratigraphy			M*		
	Ice temperature profile (vertical)	A		M*		

* bi-weekly

1.4.8 River ice

Table 1.8. List of required, recommended and desired river ice variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*weekly*	*monthly*	*yearly*
Required	None yet					
Recommended	Ice thickness	A		M*		
	Ice concentration		A/M			
	Ice class (pack or fast ice)		M			
	Ice type (level/rafted/ridged and floe descriptor)		M			
	Form of ice (floe size)			M		
	Stage of ice development			M		
	Ice phenomena (dates of freeze-up, fast-ice formation/breakout, melt onset, break up)			A/M		M
	Ice stage of melting		M			
	River ice jams and dams		M			
	Flooding extent caused by jams and dams		M			
	River icings (*Aufeis*)		M			
	Maximum level		M			
Desired	Areal extent of floating/grounded ice			M		
	Ice surface temperature	A				
	Ice openings (leads, polynyas, cracks)		A			
	Ice deformation (divergence/convergence)	A	M			
	Ice ridge height	A	M			
	Ice ridge cover (concentration of ice ridges)	A	M			
	Ice stratigraphy			M*		
	Ice temperature profile (vertical)	A		M*		

* bi-weekly

1.4.9 Permafrost

Changes in permafrost temperatures frequently reflect changes in surface climate over time, and therefore serve as a useful indicator of climate change. The Global Terrestrial Network for Permafrost (GTN-P) was initiated by the International Permafrost Association (IPA) to organize and manage a global network of permafrost observatories for detecting, monitoring, and predicting climate change. Existing local networks focus on monitoring the key thermal state parameters (TSP, ground temperature) and active layer depth. GTN-P provides access to this data. In addition, global monitoring of permafrost extent is required (GCOS Implementation plan).

Table 1.9. List of required, recommended and desired permafrost variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*bi-weekly*	*monthly*	*yearly*
Required	None yet					
Recommended	Ground temperature	A				
	Active layer thickness		A			M
Desired	Rock glacier creep velocity					M[1]
	Rock glacier discharge	M				
	Rock glacier spring temperature	M				
	Seasonal frost heave/subsidence					M
	Surface elevation change					M[2]
	Ground ice volume					M
	coastal retreat					M
	soil moisture		A		M	

+ 1 half-yearly; 2 multi-year

1.4.10 Seasonally frozen ground

Table 1.10. List of required, recommended and desired seasonally frozen ground variables; where A: automatic, M: manual

Measurement Designation	*Variable*	*Timescale*				
		hourly	*daily*	*bi-weekly*	*monthly*	*yearly*
Required	None yet					
Recommended	Ground temperature	A				

1.4.11 Surface meteorology (at CryoNet stations)

Table 1.11. List of required, recommended and desired surface meteorology variables; where A: automatic, M: manual

Measurement	*Variable*	*Timescale*

Designation		*hourly*	*daily*	*bi-weekly*	*monthly*	*yearly*
Required	Air temperature	A				
	Air humidity	A				
	Wind speed	A				
	Wind direction	A				
Recommended	Air pressure	A				
	Incoming shortwave radiation	A				
	Reflected shortwave radiation	A				
Desired	Incoming longwave radiation	A				
	Outgoing longwave radiation	A				
	Precipitation	A				

1.5 UNCERTAINTY OF MEASUREMENTS

Establishing best practices, guidelines and standards for cryospheric measurements will include consideration of data uncertainty, homogeneity, interoperability, and compatibility of observations from all GCW constituent observing and monitoring systems and derived cryospheric products.

Additionally, instrument intercomparison campaigns will regularly be conducted to determine and compare performance characteristics of instruments under field conditions and to link readings of different instruments.

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