Measuring winter precipitation and snow on the ground in northern polar regions

J. R. Janowicz, S. L. Stuefer, K. Sand and L. Leppänen

ABSTRACT

Measuring winter precipitation in cold and windy regions is recognized as a difficult task. Nonetheless, the accurate measurement of solid precipitation provides important input data for predicting snowmelt floods and avalanche danger and for monitoring climate change. The difficulties in measuring solid precipitation are associated with environmental factors and technological issues. Environmental factors that contribute to measurement errors include wind, freezing rain, rime, and a large range of solid particle shapes and sizes. Technological issues include gauge configuration, the need for remote, low-power-consumption operation, and difficult conditions for data transmission and retrieval. The objectives of this study were to review currently used gauges for measuring solid precipitation and snow on the ground, to summarize the positive and negative characteristics of each gauge, and to provide a discussion of best practices and design and performance criteria that might be used to stimulate research on new and/or improved precipitation gauges in Northern Research Basin (NRB) countries.

Key words | Arctic, precipitation gauge, snow depth, snowfall, snow water equivalent, solid precipitation

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INTRODUCTION

It is widely recognized that measuring amounts of winter precipitation is difficult in cold regions. The challenges associated with measuring winter precipitation have been documented in previous studies (Goodison *et al.* 1998; Sevruk *et al.* 2009). While wind-induced undercatch has been identified as the greatest source of error in winter precipitation measurement, other environmental factors contributing to measurement errors include freezing rain, rime, and a large range of solid particle shapes and sizes (Groisman *et al.* 1991; Yang *et al.* 1995, 1998; Peck 1997). Technological issues include the need for remote, low-power-consumption operation, along with difficult conditions for data transmission and retrieval. Nonetheless, the need for measuring precipitation accurately in winter remains. A wide variety of gauges, including several that have been developed or modified since the last comprehensive assessment (Goodison *et al.* 1998), are now in use in cold regions. Each gauge has its strengths and weaknesses, with operations-based activities having a strong bearing on gauge reliability, accuracy, and installation and operation cost (Sevruk & Klem 1989; Yang *et al.* 2001). Yet, none of the gauges accurately measures solid precipitation in windy, treeless environments (Goodison *et al.* 1998).

The first World Meteorological Organization (WMO) intercomparison was conducted from 1987 to 1993, with Canada as its lead and with the following objectives: to assess wind-related errors, to derive standard methods for adjusting solid precipitation measurements, and to introduce a reference method for calibrating precipitation gauges (Goodison *et al.* 1998). Experimental results were obtained

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for 26 sites in 13 countries. The Double Fence Intercomparison Reference (DFIR), consisting of an octagonal double fence shield with a manual Tretyakov gauge, was developed. Errors associated with the measurement of solid precipitation were determined for 20 gauge and shield combinations, and correction equations were developed. The study confirmed that all solid precipitation measurements must be adjusted to account for systematic errors and biases. The Tretyakov, Helmann, Nipher, and NWS 8-in. were determined to be the four most widely used manual gauges. It was acknowledged that shielded gauges catch more precipitation than unshielded gauges; therefore, it was recommended that all gauges should be shielded, either naturally in a forest clearing or artificially with a manufactured shield. Wetting and evaporation losses were also identified as a significant source of error. Because 'trace' amounts of precipitation are significant in some locations, it was recommended that they be treated as non-zero events. It was also recommended that wind speed at gauge height be measured.

A second WMO Solid Precipitation Intercomparison Experiment (SPICE), also led by Canada, was initiated in 2012 (Nitu *et al.* 2012). While the focus of the former study was on manual measurements of winter precipitation, the latter study focused on automated measurements. The specific objectives of SPICE included an intercomparison of automated instrumentation for measuring snowfall and snow on the ground, documentation of sources and magnitude of error, development of methods of adjustment based on environmental factors, assessment of temporal resolution at finer than daily scales, and compilation of a comprehensive dataset for validating remote sensing techniques (Nitu *et al.* 2012). The study included 15 nations and 20 field sites. At many study sites, intercomparison work continues so that the record can be extended and new instrumentation can be adopted as it becomes available. In addition, new sites, while not included within the WMO study, have been established by agencies that have an interest in assessing and comparing instrumentation in specific eco-climatic regions. Canada has three formal study sites within SPICE: Caribou Creek and Bratt's Lake in Saskatchewan and Environment Canada's Centre for Atmospheric Research Experiments in Ontario. Subsequent to the commencement of SPICE, new Canadian study sites have been established or planned in British Columbia (Coquihalla Summit), Newfoundland (Mount Pearl), Nunavut (Iqualuit, Eureka), Alberta (Fortress Mountain), and Yukon (Wolf Creek) and have loosely become part of Canadian-SPICE (C-SPICE) (Wartman 2012). The United States has one formal site within SPICE located at Marshall field station, Colorado (Rasmussen *et al.* 2012). Finland has a formal SPICE site at Sodankylä (Leppänen *et al.* 2016).

In the period between the two WMO studies, at the 2009 meeting of the International Northern Research Basins (NRB) Symposium and Workshop, the continuing issues associated with measuring solid precipitation were noted, and a working group was formed to summarize the state of knowledge around the practice (Young & Brown 2010). The NRB was established in 1975 with the support and guidance of the International Hydrological Program and cooperating agencies. The objectives of the NRB include developing a better understanding of hydrologic processes in cold region environments, exchanging information for the improvement and standardization of measurement techniques, and forming task forces to promote research initiatives. Membership in the NRB is open to countries with land territories north of 60 degrees latitude, which includes Canada, Denmark (Greenland), Finland, Iceland, Norway, Russia, Sweden, and the USA. The scope of the working group included measurement of both solid precipitation and snow on the ground. This paper evolved from the discussions and collaboration between NRB countries on the topic of solid precipitation and snow on the ground measurements.

This paper updates and summarizes measurement techniques across the northern polar countries based on: (1) manual solid precipitation gauges, (2) automatic solid precipitation gauges, and (3) instruments for measuring snow on the ground. We use this information to review gauge performance and to discuss strengths and weaknesses of the measurement practices across NRB countries.

INSTRUMENTATION FOR MEASURING SOLID PRECIPITATION

Instrumentation for measuring solid precipitation has two categories. The first category includes non-recording or manual gauges, where the observer has to be present to make a measurement. The second category of gauges includes automated or recording gauges commonly used by NRB countries.

Manual gauges

Numerous manual precipitation gauges are in use worldwide for measuring winter precipitation. Table 1 provides an inventory of manual precipitation gauges currently in use by NRB nations, with a summary of gauge characteristics and windshield type. The types of precipitation gauge and windshield configuration differ significantly among the NRB countries. Generally, the transition from manual to automatic gauges occurred in the last decades of the 20th century with evolving technology.

Automatic gauges

One of the earliest recording precipitation gauges was developed in England for the measurement of rain in the late 1830s. The weight-activated gauge with a clock-driven drum recorded rainfall amount on a rotating strip chart (Strangeways 2006). Accuracy improved significantly with earlier versions of modern weighing all-season precipitation gauges in the mid-20th century (Metcalfe & Goodison 1993). Recording precipitation data on punched paper tapes or a chart recorder, the earliest gauges were the Belfort and Fischer Porter. Modern weighing gauges (Table 2) use either vibrating wire transducers or solid-state load cells (Larson 1993).

Mechanical tipping bucket rain gauges were developed in the late 19th century and are still widely used. These gauges were adapted to record snowfall by enlarging the orifice opening, removing the funnel, and incorporating a large collection bucket. The first electronic tipping bucket rainfall gauges were developed in the 1960s and were fitted with heating apparatus to accommodate snowfall. A further refinement was made by adding antifreeze and an oil layer to minimize evaporation.

Non-catchment automatic gauges include a variety of optical gauges and the total precipitation sensor (TPS), also referred to as ‘hotplate’. Optical precipitation gauges have evolved recently from visibility measurement instruments and are primarily used for detecting existing weather conditions (Strangeways 2006). These gauges operate by detecting precipitation particles passing through a light beam and can convert the signal into a precipitation intensity rate, which in turn can be converted into precipitation amount. They are also capable of differentiating the form of precipitation by analyzing the wavelength spectrum. An experiment with precipitation measurement in polar regions using the TPS was conducted at the Atmospheric Radiation Measurement site in Barrow, Alaska, USA. The TPS consists of two 12.7 cm diameter plates, warmed by electric heaters to maintain each plate at a constant temperature (Yankee Environmental Systems 2016). The TPS measures the amount of solid precipitation by accounting for the power required to evaporate the precipitation from the top plate (TPS Handbook, Cherry 2011). The results of

Table 1 | Manual solid precipitation gauges used by NRB counties (Sevruk & Klem 1989)

Country of use	Country of origin	Gauge name	Orifice area (cm^2)	Length (cm)	Material	Windshield
Canada	Canada	Nipher	127	56	Copper	Nipher
Finland	Finland	H&H-90	200	40	Aluminum (Teflon coated)	Tretyakov
Greenland	Denmark	Hellman	200	43	Galvanized iron	Nipher
Iceland	Denmark	Hellman	200	43	Galvanized iron	Nipher
Norway	Norway	Norwegian	225	25	Copper	Nipher
Russia	Russia	Tretyakov	200	40	Galvanized iron	Tretyakov
Sweden	Sweden	SMHI	200	35	Aluminum	Nipher, modified Nipher, Wyoming
USA	USA	NWS 8-in.	324	68	Copper/Steel	Alter, Wyoming

Table 2 | Automatic solid precipitation gauges

Gauge name	Country of origin	Manufacturer	Instrument name	Orifice area (cm^2)	Capacity (mm)
Gauges with weighing-strain and vibrating wire					
Belfort	USA	Belfort Instrument Company	AEPG II 200	200	1,220
Geonor	Norway	Geonor AS	T-200B	200	600, 1,000, 1,500
MPS	Slovakia	MPS System	TRwS204/504/205/405	200, 400, 500	230, 400, 500
Gauges with weighing-load cell and pressure transducer					
Meteoservis	Czech Republic	Meteoservis v.o.s.	MRW500	500	1,400
NOAH	USA	ETI Instrument Systems	NOAH	324, 729	305, 508, 762
Ott Pluvio & AWPAG[a]	Germany	Ott Messtechnik	Pluvio^2	200, 400	750, 1,500
MG-24	Russia	Gidrometpribor	MG-24	200	100
Standpipe	Canada	Geo Scientific	PG-4	1,134	
Sutron	USA	Sutron Corp.	TPG	200	914–1,829
Gauges with tipping bucket					
CAE	Italy	CAE S.P.A.	PMB2/R	1,000	CAE
EML	UK	Environmental Measurements Ltd.	UPG1000	1,000	EML
HSA	USA/Australia	Hydrological Services America	TBH-LP	729	HSA
Meteoservis	Czech Republic	Meteoservis v.o.s.	MR2H	200	Meteoservis
MTX	Italy	MTX s.r.l.	FAK030AA	200	MTX
			FAK001AC	400	
			FAK010AA	1,000	
Omega	USA	Omega Engineering Co.	RG-2500E	324	Omega
			RG-2500E-12	729	
Thies	Germany	Adolf Thies GmbH & Co.	Precipitation transmitter	200	Thies
Young	USA	R.M. Young	52202	200	Young
Heated rain gage	USA	Campbell Scientific	CS700H	314	Heated rain gage

[a] AWPAG stands for the All Weather Precipitation Accumulation gauge. It is installed at the ASOS stations across the USA.

the TPS tests in Barrow remained inconclusive, and the experiment was discontinued in 2014.

SNOW ON THE GROUND

Snow on the ground (units of water equivalent) is often used as a proxy for cumulative winter precipitation less sublimation. Snow water equivalent (SWE) can be measured manually with snow tubes and automatic gauges (Dixon & Boon 2012). Alternatively, snow depth can be used to develop SWE estimates if snow density information is available.

SNOW DEPTH

Manual devices

Snow depth is the most basic snow cover measurement parameter and likely the earliest to be measured. At meteorological stations, newly fallen snow is measured daily using a snow board, which is cleared on a daily basis and reported as 'snowfall'. Snow depth accumulated on the ground is measured in a variety of ways (Table 3). Graduated markers or stakes placed vertically in the ground surface can be read from a distance using binoculars or photography. Aerial markers provide a simple means of measuring snow depth from aircraft. A portable snow depth probe (MagnaProbe) fitted with a GPS and data logger was developed in the late 1990s (Sturm & Holmgren 1999).

Automatic instrumentation

Developed in the 1980s, ultrasonic snow depth sensors automatically record snow depth evolution over the winter season (Table 3). An ultrasonic pulse is emitted from a downward-facing transmitter/receiver, which is placed in a fixed position above the snow cover surface. The timing of the rebounded signal is recorded, which with air temperature is used to determine the speed of the ultrasonic pulse and the distance between the receiver and the snow surface (Goodison *et al.* 1984).

SNOW WATER EQUIVALENT

Manual instrumentation

Snow pit

The use of snow pits may have been the earliest means of determining snow density (Table 4). A pit is excavated to the ground surface, and a known volume of the pit cross section is extracted and weighed, which provides a value for snowpack density. For a precise SWE measurement, the snowpack profile is stratified into layers of varying density, and SWE is determined for each layer. SWE can be obtained based on integrated snow density and snow depth for the profile.

Snow tube

The earliest snow surveys were carried out in Europe, likely associated with the study of avalanches. This technology was brought to North America by James Church in 1906, who performed the first formal snow surveys in 1908 on Mount Rose, on the eastern slopes of the Sierra Nevada

Table 3 | Instrumentation for snowfall and depth measurements

Gauge name	Country of origin	Manufacturer	Model name
Manual measurements			
Snow board[a]	Canada	Weaver	2000
Ruler or avalanche probe	Multiple	Multiple	Multiple
Snow stake	Multiple	Multiple	Multiple
Snow depth probe	USA	Snow-Hydro	MagnaProbe[b]
Automatic measurements			
Snow depth sensor	Canada	Campbell Scientific	SR-50
Felix	India/UK/Canada	Felix Technology Inc.	SL300
Jenoptik	Germany	Jenoptik ESW GmbH	SHM 30
Sommer	Austria	Sommer Messtechnik	USH-8
Meteoservis	Czech Republic	Meteoservis v.o.s.	MR2H
MTX	Italy	MTX s.r.l.	FAK030AA, FAK001AC, FAK010AA
Omega	USA	Omega Engineering Co	RG-2500E, RG-2500E-12
Thies	Germany	Adolf Thies GmbH & Co	Precipitation transmitter
Young	USA	R.M. Young	52202

[a] Snowfall measurements.

[b] Portable data logger and GPS-equipped probe that records location and snow depth.

Table 4 | Instruments for measuring SWE and snow density

Gauge name	Country of origin	Description/Manufacture
Snow tubes for manual SWE and snow density (Goodison *et al.* 1987; Dixon & Boon 2012; Laudon & Lofvenius 2016)		
Mount Rose	USA	Cutter area (A) is 11.4 cm^2, tube material is aluminum
1980 Metric	Canada	$A = 10.0\ cm^2$, aluminum
1981 Metric	Canada	$A = 10.4\ cm^2$, aluminum
Standard Federal	USA	$A = 11.2\ cm^2$, aluminum
Sharpened Federal	USA	$A = 11.2\ cm^2$, aluminum
Bowman	USA	$A = 11.2\ cm^2$, plastic
McCall	USA	$A = 11.2\ cm^2$, aluminum
Rosen	USA	$A = 11.2\ cm^2$, aluminum
Utah	USA	$A = 11.2\ cm^2$, aluminum
Svartberget	Sweden	$A = 12.6\ cm^2$, plastic
ESC 30	Canada	$A = 30.0\ cm^2$, plastic
SnowHydro	USA	$A = 30.0\ cm^2$, plastic
Adirondack	USA	$A = 35.7\ cm^2$, fiberglass
MSC	Canada	$A = 39.1\ cm^2$, plastic and aluminum
WS-43	Russia	$A = 50\ cm^2$, aluminum
Aluminum Tubing	Canada	$A = 77.1\ cm^2$, aluminum
Songa	Norway	$A = 79\ cm^2$, stainless steel
Glacier	USA	$A = 81.9\ cm^2$, plastic
Korhonen-Melander sampler	Finland	$A = 100\ cm^2$, black plastic
Manual snow density measurements		
Snow density cutter	USA	250/1,000 cm^3 wedge cutter by Snowmetrics
Density cutter	USA	100/250 cm^3 (custom volumes available) box cutter by SnowHydro
Automatic SWE measurements		
Snotel snow pillow	USA	Snow pillow by Rickly Hydrological
SSG	Austria	Snow scale by Sommer Messtechnik
SWE sensor	USA	Solid-state SWE sensor by CRREL
SSC300	USA	2KR Snow scale
CS725	USA	CS SWE Sensor by Campbell Scientific
SPA	Austria	SPA by Sommer Messtechnik
Gamma Water Instrument	Finland	Gamma SWE sensor by Astrock
Lysimeter	Several	Weighing lysimeter

Mountains in Nevada (Helms *et al.* 2008). Church realized that using snow depth alone provided insufficient data for runoff forecasting. His early core samples were obtained using stovepipe sections, with SWE values determined by melting the snow over a woodstove (Helms *et al.* 2008). Church developed the Mount Rose Snow Sampler during the winter of 1908–09, which provided a measure of the water content in a column of snow. The second-generation sampler consisted of sections of 5 cm diameter steel pipe, but due to the weight was soon replaced with aluminum. A standardized diameter of 1.485 in. (3.77 cm) was adopted, so 1 in. (2.54 cm) of SWE was equal to 1 oz (26 g) of water, allowing the tube and snow core to be weighed together instead of weighing the snow separately. Formal snow surveys were not carried out until the 1930s in Europe, and then they quickly spread to other continents. The technique became widely accepted to provide data for flood forecasting in the 1960s. A variety of samplers with various characteristics was developed over time (Table 4). A metrification committee established in 1978 by the Western Snow Conference (WSC) (Goodison *et al.* 1987) recommended that two metric samplers be adopted to accommodate both shallow and deep snow. The 1981 metric sampler with a cutter area of 10.6 cm^2 was proposed for deep snowpacks. The ESC 30 with a cutter diameter of 30 cm^2 was recommended for shallow snowpacks less than 1 m. As a component of the metrification process, Farnes *et al.* (1982) assessed snow sampling tubes to determine the variation of SWE between samplers; they used the 81.9 cm^2 Glacier tube as the reference standard. Farnes *et al.* (1982) determined that small-diameter snow tubes (10–12 cm^2 cutter area) overestimate SWE by up to 10%, while large-diameter snow tubes are within 1% of the reference standard.

Automatic instrumentation

The oldest automatic instrumentation for measuring SWE is the weighing lysimeter, which consists of a 1 m square or circular pan. Typically, the pan is filled with soil, which may support grass or other vegetation and represent a natural soil column. When used for energy or water balance studies, lysimeters must be closed systems, with snowmelt amounts contained within the pan (Tarboton 1994). The pan is supported by one or more load cells that monitor the weight associated with energy and water balance fluxes including sublimation and ablation amounts. To determine snowmelt volumes and rates, meltwater must be accumulated and weighed in separate containers.

Snow pillows are the oldest practical devices for measuring SWE directly. They were developed during the 1970s in the USA for operational purposes to provide data for flood forecasting and volume runoff assessments for irrigation purposes (Table 4). Snow pillows are fluid-filled bladders containing equal proportions of water and ethanol; they are typically circular or octagonal, are approximately 2–3.5 m in diameter, and are made from various materials (butyl rubber, sheet metal, stainless steel) (Pomeroy & Gray 1995). As snow accumulates on the pillow, an equal weight of fluid is displaced to a connected standpipe where the pressure change can be measured with a pressure transducer yielding a value for SWE. Measurement errors may occur as a result of bridging associated with the formation of hard snow or ice layers or during the transition from subfreezing snow temperatures to an isothermal snow cover with a temperature of 0 °C (Johnson & Schaefer 2002). Snow pillows require little maintenance and are popular for placement in remote locations; however, occasional damage may occur due to curious wildlife.

Weighing snow scales, which use load cells to measure SWE, thus negating the need for glycol solution (Table 4), have become popular recently. The Cold Regions Research and Engineering Laboratory (CRREL) and Natural Resources Conservation Service (NRCS) conducted a series of experiments to develop the square modular SWE sensor, which is able to accommodate loads of 1,780 mm. The SWE sensor consists of eight aluminum panels (0.9 × 1.2 m) and a center panel (1.2 × 1.2 m), supported by the load cell (Johnson & Schaefer 2002); the sensor has a surface area of 9 m^2. Of a similar design is the rectangular Sommer snow scale (SSG) that consists of seven 0.8 × 1.2 m aluminum panels with a total measuring surface of 6.7 m^2 (Table 4). The measurement is carried out solely by the center panel, with the outer panels acting to stabilize the snowpack and minimize bridging. The panels are perforated allowing for meltwater drainage and thermal stability between the sensor and ground surface. The SSG is relatively easy to assemble. Various load cells are available to accommodate 200, 500, 1,000, 2,000, and 3,000 mm SWE. Using similar technology, the 2KR Systems SSC300 snow scale is triangular, but has three strain gauges, one in each apex of the triangle for redundancy purposes (Table 4). The approximately 2 m^2 sensor is constructed of aluminum, with an outer skirt to minimize snow bridging. The sensor has a capacity of 300 mm SWE and has the potential to expand.

The Campbell Scientific CS725 water equivalency sensor measures SWE by passively monitoring the attenuation of naturally occurring electromagnetic radiation associated with potassium and thallium decay (Table 4). As snowpack increases, the emission of radioactive waves decreases, with the sensor monitoring the attenuation of the radiation. The attenuation is directly proportional to

SWE. The sensor is mounted approximately 3 m above the ground surface and has a measurement area of 50–100 m^2. The performance of the sensor is not affected by adverse weather conditions, but is dependent on suitable amounts of potassium and thallium, and, as such, is site-specific. The sensor outputs attenuation data associated with both elements, with the premise that one may be superior for determining SWE.

The Sommer Snow Pack Analyser (SPA) is an automatic *in situ* measurement system capable of determining snow depth, density, water equivalent, as well as ice and liquid water content (Table 4). The SPA system measures the dielectric constant of the snowpack by appraising the frequencies of water, ice, and air within. The system can operate with up to four sensors, which are mounted on bands, either installed sloping through the complete snow cover or arranged horizontally at the ground or defined levels. The bands are connected to an impedance analyzer that determines the various properties of the snowpack. The system must be used in conjunction with an ultrasonic snow depth sensor.

INSTRUMENTATION INVENTORY AND NETWORK AND GAUGE PERFORMANCE FOR NRB NATIONS

This section provides an inventory of solid precipitation and snow on the ground instrumentation and a discussion of network and gauge performance for several NRB countries.

Canada

Inventory

Manual solid precipitation measurements in Canada are almost exclusively carried out with the standard (56 cm long, 127 cm^2 collection area) copper gauge, fitted with the Nipher shield (Table 1). For automatic measurements, the Belfort and Fischer Porter weighing-strain gauge (324 cm^2 collection area; 600 mm capacity), fitted with the Alter or Nipher shield, has been phased out. For a time, these gauges were being replaced by the Campbell Scientific CS700 rainfall gauge with the CS705 snowfall adapter package; however, problems occurred with congealing of the antifreeze solution and these gauges have largely been replaced with Geonor and OTT Pluvio (Table 2). Early versions of the Geonor gauge had only one vibrating wire; however, because of potential problems with a single sensor, two additional sensors were added for redundancy purposes. Both the Geonor and Pluvio gauges have several models with a range of collection areas and capacities and are equipped with Alter shields. Environment Canada's (EC) Meteorological Service of Canada (MSC) operates the national climate network with both staffed and automatic stations, largely within communities at relatively low elevations. In the 1970s and 1980s, MSC operated a remote higher elevation network in mountainous regions to provide data more representative of the typical elevation profile. The staffed stations have manual Nipher gauges, which are emptied daily, while both staffed and automatic stations primarily use the Geonor gauge. Testing of the Ott Pluvio has been done with an emphasis on mountainous regions. Provincial agencies, university and government research groups, and private companies operate a variety of instrumentation.

Snow depth of newly fallen snow is measured at staffed stations using the Weaver board 2000 snowfall measurement board (0.5 m × 0.5 m white plywood board) on a daily basis with a snow ruler. Campbell Scientific SR-50 acoustic distance sensors are used by MSC with various other instruments used by other agencies. Environment Canada's Water Resources Branch (WRB) began routine snow surveys in 1922 (Goodison *et al.* 1987). In 1962, snow surveys were added to the data collection protocols at principal meteorological stations, but this practice stopped in the early 1990s, with provincial and territorial agencies continuing with the operation of the snow survey network. Typical snow surveys include manual measurements of snow depth and SWE, providing information for flood forecasting and summer volume runoff estimates that are used for developing irrigation and forest fire indices. The provincial agencies in western Canada have an alliance with the WSC, consisting of the western USA, to coordinate snow survey activities with common sampling equipment and protocols. A standard WSC snow survey consists of a ten-point snow course, which is sampled using a Mount Rose (Federal) snow tube (Table 4). Snow surveys are conducted within a small window near the beginning of each month during late winter and spring. Over time, snow pillows and other instrumentation have been added.

Network and gauge performance

The MSC meteorological network has decreased since the 1990s, with the loss of secondary networks and remote stations. There are also staffing issues associated with third-party stations, which have resulted in some data loss and inaccuracies with precipitation measurements. Other agencies, such as Yukon's Wildland Fire Program, are collecting data, which fills the gap, but these programs use different protocols and standards. The snow survey programs continue to operate and even expand in some areas, with flood forecasting having a higher profile because of increasing flooding frequency and severity associated with climate warming.

Intercomparison studies at Wolf Creek, Yukon, in northwestern Canada have been carried out by the Yukon WRB since 2013. Figure 1 illustrates cumulative corrected precipitation plots for the February to May 2013 period for the unshielded Pluvio 200, Standpipe, shielded Pluvio 400, and Geonor gauges, with the standard Nipher gauge, which was sampled monthly, as a reference. Pluvio gauge data were corrected internally by instrument programming to remove negative and very small positive numbers. Manual corrections were performed on the Geonor data to remove 'noise', which was generally identified by daily totals that were less than 0.1 mm. Corrections were applied to the standpipe data to 'smooth' the data only. It was assumed that there were no evaporation losses.

The unshielded gauges track closely, even with significantly different catchment areas. While the shielded gauges catch approximately 55% more precipitation by the end of the accumulation season, the Geonor records approximately 10% more precipitation than the Pluvio 400. The Geonor tracks closely to the reference Nipher over the season.

Figure 2 provides a SWE comparison of the traditional butyl rubber snow pillow, SSG, and Campbell Scientific CS725 gamma radiation sensor (CS725) for the winter of 2014–15 at Wolf Creek, with manual snow survey measurements used as a reference. A significant portion of the winter SSG record is missing; however, the late winter accumulation and spring melt periods are available. The snow pillow tracked the manual snow survey measurements closely during the early accumulation period, but under-recorded from March onwards for the remainder of the accumulation (13%) and melt (24%) periods, likely due to snow or ice bridging. While much of the record was unavailable, the SSG tracked closely to the snow pillow during the accumulation period, but was approximately 25% above during the melt period. The CS725 tracked well above (approximately 20%) during the early accumulation period, but was close during the late (February/March) accumulation and melt periods.

Finland

This section provides a summary of the practices for measuring solid precipitation and snow on the ground in Finland. It includes an overview and history of precipitation gauges and

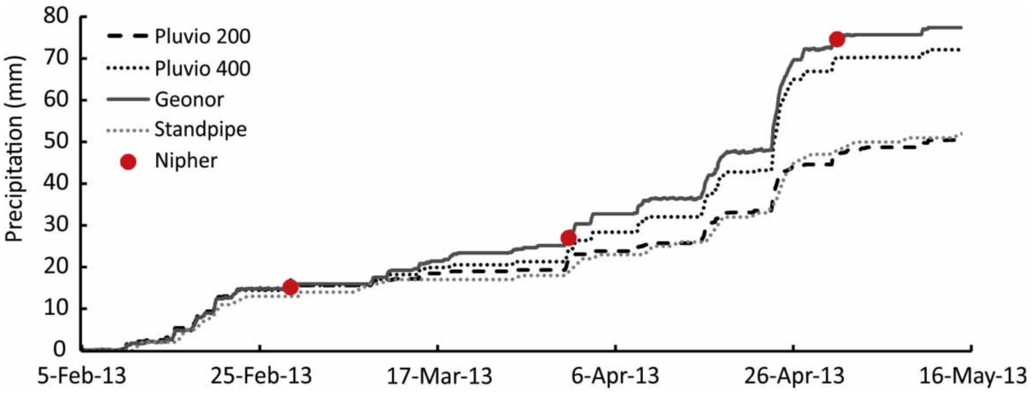

Figure 1 | Cumulative corrected precipitation for Wolf Creek subalpine taiga meteorological station February–May 2013.

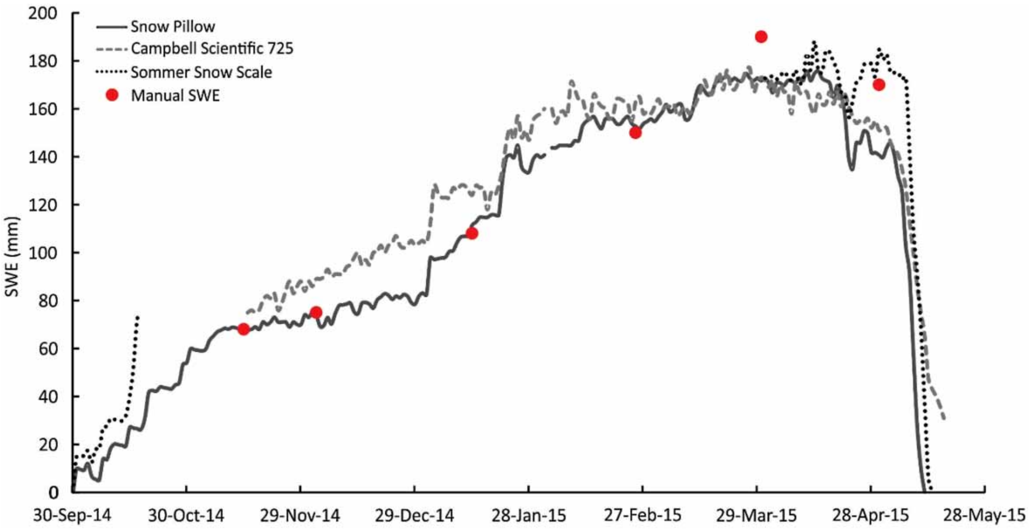

Figure 2 | SWE for Wolf Creek subalpine taiga meteorological station 2014–15.

techniques for measuring snow depth and SWE. An overview of the Finnish Meteorological Institute's Arctic Research Centre (FMI-ARC) measurement sites and SPICE site in Sodankylä is also provided.

Inventory

Only manual precipitation gauges were used in Finland before 2005. The precipitation gauge used from 1893 to 1907 was a 1.5 m high cylinder container with a 250 cm^2 collection area mounted on top of a tripod. The Wild precipitation gauge, which was made from 0.5 mm thick brass plating and was fitted with a Nipher shield made from galvanized iron, was used from 1908 to 1981. It had a collection area of 500 cm^2. The Tretyakov precipitation gauge, made of galvanized iron and fitted with a Tretyakov shield, was used from 1982 to 1992 (Table 1). Since 1992, the H&H-90 precipitation gauge, fitted with a Tretyakov shield, has been in use (Table 1). Ninety-five manual gauges are still in operational use in Finland. Automatic precipitation gauges have been used since 2005. The VRG101 (Vaisala, Finland) with Alter shield was used from 2005 to 2013. The FMI has two VRG101 instruments at the Sodankylä SPICE site. The Pluvio^2 with Alter shield has been used operationally since 2008 at automatic weather stations (AWS) in Finland, and 102 AWS had Pluvio^2 in 2016. The collection area of the operational gauges is 400 cm_2. The Sodankylä SPICE site has two Pluvio^2 gauges (200 cm^2) as well as two Pluvio^2 (400 cm^2) gauges.

Snow depth was measured manually before the 1990s. Manual measurements were made daily using fixed stakes, which were generally replaced with automatic instruments between the 1990s and 2000s; however, some manual snow depth measurements with fixed stakes and manual probes are still made for research purposes. The SPICE site in Sodankylä has four manual stakes, which are read using a web camera image. As of 2016, 179 AWS have SR50 (Table 3) sensors for snow depth measurement. In addition, the FMI-ARC has four SR50 sensors for research purposes. The SPICE site has two SR50, two USH-8, and one SHM-30 for snow depth measurements (Table 3).

SWE has been measured manually with a Finnish standard snow tube, Korhonen-Melander snow sampler (Korhonen 1923), since 1922. The snow tube is 50 cm high, and the collecting area is 100 cm^2 (Table 4). Before 1922, the measurement was made with a similar cylinder by melting the snow. SWE is measured automatically with snow pillows, experimental Gamma Water Instruments (Astrock, Finland), and the SGG scale (Table 4).

Network and gauge performance

The FMI is responsible for operational weather data in Finland, including solid precipitation and snow depth. The first systematic snow depth measurements in Finland were made during 1750–60, as described in Kuusisto (1984). Snow depth measurements started in 1890, and in 1909, the number of stations was over 100. The FMI made manual SWE measurements from 1909 until the 1950s. The first snow course measurements including SWE and snow depth measurements were made in the 1920s. Precipitation has been measured since the 1890s. The FMI started AWS installations in the 1990s to replace manual measurements; it currently has 179 AWS. The FMI also collects additional data for research use. The FMI-ARC in Sodankylä maintains an extensive manual and automatic snow measurement network for research purposes. For example, the WMO SPICE site is located in Sodankylä at FMI-ARC facilities.

The SPICE site is located in the FMI-ARC area in a forest opening of a coniferous pine forest. On average, Sodankylä has snow cover from October to mid-May; average annual precipitation is 527 mm (Pirinen *et al.* 2012). The average wind speed at the site at 1.5 m high was 2.22 m/s in 2014–15 (Leppänen *et al.* 2016). Low wind conditions promote snow accumulation on the instruments and supporting structures. The installation of the SPICE site was started in 2012 and was completed in the summer of 2013. Nine manufacturers provided their instruments for the site. The WMO SPICE measurement campaign was held during the winters of 2013–14 and 2014–15. Some of the instruments were still in place during the winter of 2015–16. The Sodankylä SPICE site focused on snow on the ground. An example of precipitation measured in Sodankylä with two automatic instruments (Pluvio^2 and VRG101 with Alter shield) and a manual instrument (H&H-90 with Tretyakov shield) is presented in Figure 3. Manual observations were made every morning; automatic observations were made every day.

The Finnish Environment Institute (SYKE) also collects snow data for hydrological monitoring. SYKE started manual SWE measurements in 1912. Snow course measurements have been made manually by SYKE since 1935. Currently, SYKE has 150 snow courses around Finland close to drainage basins. A typical snow survey consists of 40–80 snow depth measurements, made at regular intervals along a 4 km course; eight of those are chosen for SWE measurements so that all land cover types have at least one SWE measurement (Leppänen *et al.* 2016). SYKE also has some automatic instrumentation for SWE observations (Kuusisto 1984).

Norway

The Norwegian Meteorological Institute (NMI) is responsible for operating and maintaining observational networks, which consist of automated weather stations, radiosondes, and weather radar. The NMI also carries out quality control measures and archives and disseminates the data. The network of meteorological observations includes Norway, adjacent sea areas, and the Svalbard

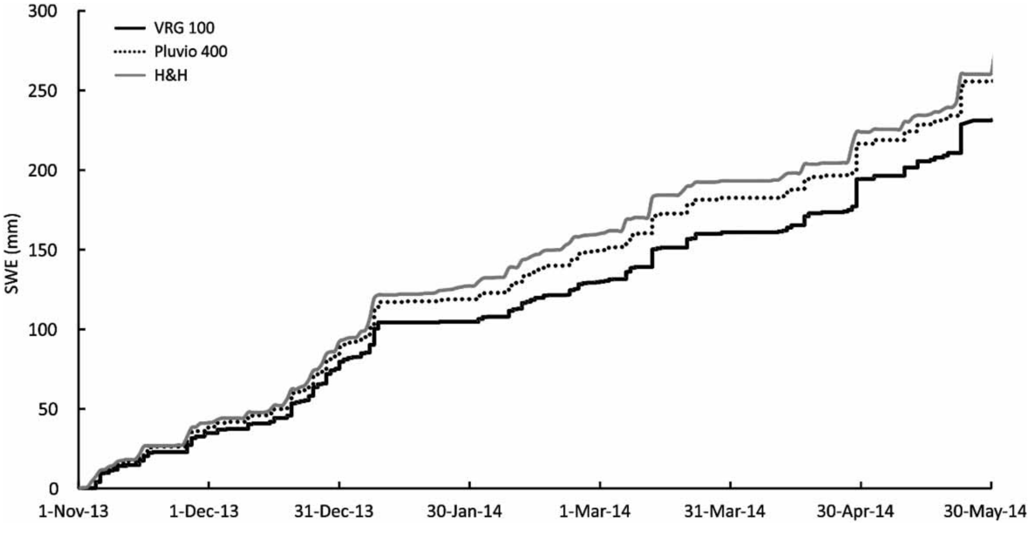

Figure 3 | Cumulative precipitation Sodankylä, Finland, 2013–14 accumulation period.

area. The NMI currently operates 324 and 125 manual and automatic precipitation gauges, respectively; it also issues weather forecasts, assesses national climatological conditions, and produces climatological reports. In addition to the NMI-operated meteorological stations, there are precipitation measurement sites operated by public hydroelectric utilities, private companies, and research groups.

Inventory

The manual precipitation gauge standard used by NMI is the Norwegian standard gauge; it has a 200 cm^2 collection area and is fitted with a Nipher shield (older stations, some 100 years old, are not fitted with a windshield for continuity purposes). Since 1982, the Norwegian standard gauge has been slowly phased out, replaced with the Swedish standard gauge as the national standard. The Swedish SHMI gauge is made of anodized aluminum; it is 35 cm high, has a collection area of 200 cm^2, and is fitted with a Nipher shield (Table 1).

The automatic precipitation gauge in use in Norway is the weighing Geonor T-200 which has a collection area of 200 cm^2, a capacity of 600 mm (newer models have a capacity of 1,000 mm), and is manufactured by Geonor of Norway (Table 2). It is fitted with a single Alter shield. The Lambrecht 15188H heated tipping bucket gauge is also used at some locations. It has a 0.1 mm bucket capacity and a 200 cm^2 collection area; some of the gauges are fitted with an Alter shield (Table 2).

Network and gauge performance

Catch deficiency routines have been developed for most instruments used in Norway (Goodison *et al.* 1998). Several Norwegian hydroelectric companies use these corrections on a regular basis, while NMI does not perform corrections of solid precipitation. To improve the methodology for operational correction of solid precipitation gauge deficiency, a mountainous test site was established and became fully functional in 2012. Possible options for reducing measurement error include improving the current gauge design and site locations, optimizing procedures for operational correction, and developing new measurement techniques.

The Norwegian power company Statkraft Energy tested a SPA system for measuring SWE from 2010 to 2014 (Table 4). During the snow cover periods, manual control measurements of snow depth and snow density were made, and SWE was calculated. The SPA measurements significantly deviated from the manual control measurements.

The data shown in Figure 4 are raw and uncorrected. The numerous spikes are not real values, but are due to

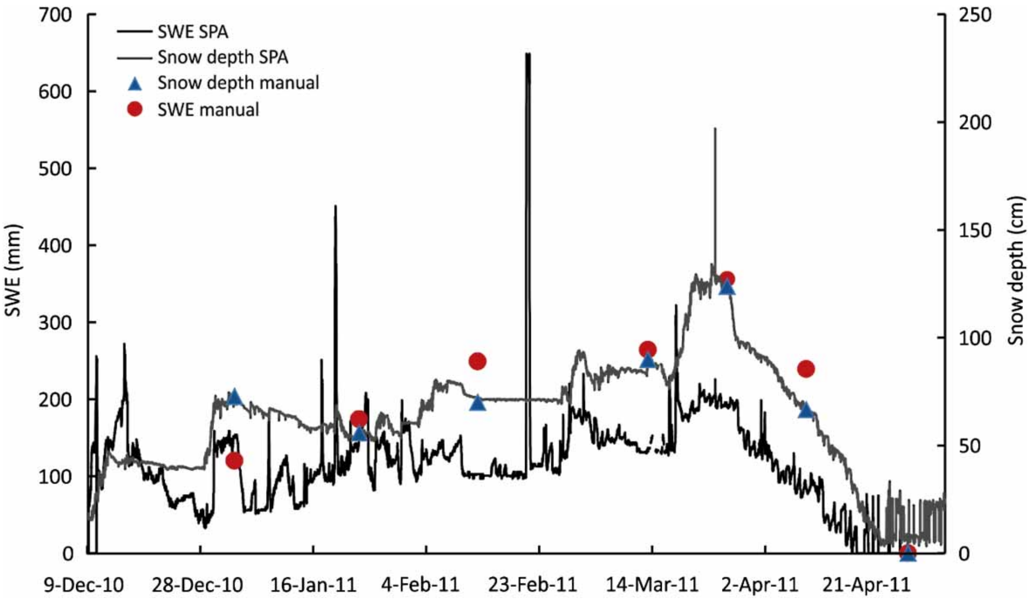

Figure 4 | Snow depth and SWE measured by the SPA during winter 2010–2011. Snow depth was measured accurately, while SWE was highly underestimated.

instrument malfunction or insufficient data processing. The robustness of the sloping band was insufficient, as during the five-year test period, the band broke three times. It is assumed that the band broke due to the vibration caused by winds, since the nearby weather station recorded strong winds during periods when the band breakages occurred. The overall conclusion from the test period was that the instrument is not suitable for use at sites with strong winds.

During the test period, some observations were made that may explain some of the shortcomings of this instrument. Every winter, observations showed that an air space developed around the sloping band at the snow surface. In order to obtain a valid determination of the dielectric constant of the snow, the band must be completely surrounded by snow. When air space develops around the band, the measurement of the dielectric constant will not be correct, as the volume of influence now is partly air space and partly snow. Consequently, estimates of snow density and liquid water content will be erroneous. The assumption is that the main reason for the development of air space is that the band vibrates during windy periods. However, this problem was observed at both forested and mountainous test sites. Most of the mountainous areas in western Norway experience 'rain on snow' events during the winter period. During rain events, water droplets have been observed traveling downward on the sloping band and infiltrating the snowpack. This water provides energy input to the snow, which contributes to snowmelt and hence increases the volume of the air space mentioned, and this water will be part of the volume of influence for the measurement of the dielectric constant. Both concerns introduce sources of error in SPA measurements. To obtain accurate measurements of liquid water content, snow density, and SWE from a sloping SPA sensor, an accurate snow depth measurement is required. Ideally, the snow depth should be measured exactly at the point where the sloping band penetrates the snow. Because the sloping band interferes with the ultrasonic snow depth sensor, the snow depth measurements must be made away from the band. Normally at an exposed mountainous site, the snowpack is unevenly distributed; hence, snow depth measurements 2 or 3 m to the side of the band may not represent the snow depth where the band penetrates the snow surface. This introduces errors in snow depth measurements and, consequently, erroneous determination of liquid water content, snow density, and SWE.

United States

This section provides a summary of the practices for measuring solid precipitation and snow on the ground in the state of Alaska. The Alaska network mainly differs from the continental USA because the density of stations is extremely low. For example, the area of the entire state of Alaska is approximately 1,480,000 km^2, and the number of precipitation stations is 1,653 (as of 2012) or approximately one station per 895 km^2. This count of 1,653 includes both total and rainfall-only precipitation gauges. For comparison, the state of California (423,970 km^2) has 8,278 precipitation stations (as of 2014) or one station per 51 km^2.

Inventory

Solid precipitation is measured with a variety of precipitation gauges with an orifice diameter of 20.3 cm (8 in.). These gauges vary from manual or non-recording types, to unheated or heated automatic weighing or tipping bucket (Table 1). Currently precipitation data are collected by several agencies, research groups, and private companies that concurrently use different gauge types, listed in Tables 1, 2 and 4. The largest agencies that collect and report solid precipitation data in Alaska are (1) the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS), (2) the NRCS Snow Telemetry (SNOTEL), and (3) the United States Geological Survey (USGS).

Precipitation gauge types and shield configuration vary between data collection agencies. For example, the NWS cooperative network primarily uses standard NWS 8-in. non-recording precipitation gauges; some of these gauges are equipped with windshields (Table 1). First-order NWS stations were modified to fit the Automated Surface Observing System (ASOS) standards. Those stations are equipped with recording weighing-type All Weather Precipitation Accumulation gauges (AWPAG) and Alter shields to reduce wind field distortion above the gauge orifice (Table 1). The NRCS operates automated recording weighing-type precipitation gauges. Most of the NRCS sites in Alaska are equipped with a standard NWS 8-in.

precipitation gauge, antifreeze, and the Wyoming shield. Propylene glycol antifreeze is often used to prevent collected precipitation from freezing. The USGS maintains several automated recording weighing-type precipitation gauges, equipped with the Alter shield, at remote glacier locations across Alaska. Most of the NWS observations are located along the road system and in population centers, whereas the NRCS SNOTEL and USGS networks represent solid precipitation measurements at high elevations.

The NOAA/NWS sites have a protocol for measuring snow depth on the ground once a day at the scheduled time of observation. Total depth of snow is measured at a permanently mounted snow stake or by taking the average of several depth readings with a measuring stick (Table 3). Snow depth, snow density, and SWE are measured once a month by NRCS professionals at the designated snow course locations across Alaska. The NRCS SNOTEL sites are often equipped with automatic snow depth sensors such as the Campbell Scientific SR50 (Table 3).

The NRCS measures SWE on the ground using antifreeze solution-filled snow pillows at selected sites across Alaska (Table 4). At research sites, automated SWE measurements on the ground are being performed with electronic SWE pressure sensors (Johnson & Schaefer 2002). Several SWE sensors have been tested in the USA (Alaska) and northern Canada at the SnowNet experimental field sites (National Science Foundation, Arctic Observing Network project). An example from the Imnavait Creek SnowNet site, located in the northern foothills of the Brooks Range, shows that the SWE sensor measurement agrees well with the manual SWE measurements (Figure 5).

Network and gauge performance

The major strength of the precipitation network in northern Alaska is that a measurement program was initiated around 1900 in several locations. This precipitation record has been maintained to the present.

The major weakness of the precipitation network is that the density of the stations in the entire state is quite low; most of the stations are located at low elevations and most of them are distributed along the road system or near the coast (Kane & Stuefer 2015). Although the density and spatial cover of the precipitation network have improved during the last century, large areas in northern and western Alaska are still without gauge coverage. Kane & Stuefer (2015) analyzed precipitation records used to update the intensity–duration–frequency curves for Alaska. The authors reported that the number of gauges at higher elevations is insufficient, but that this number has improved with the number of stations above 305 m, increasing from 26 gauges in 1963 to 134 gauges in 2012.

Solid precipitation is still difficult to quantify at unattended sites in the Arctic. The effect of snow transport on precipitation and SWE measurements can be illustrated with the example shown in Figure 5. Cumulative

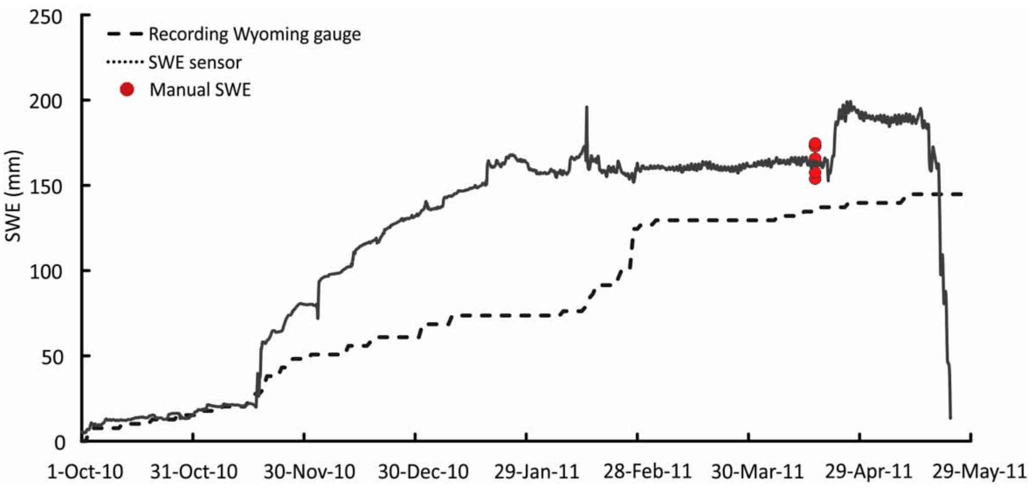

Figure 5 | Cumulative winter snowfall measured by the NRCS recording precipitation gauge equipped with a Wyoming shield, SWE on the ground measured by the SWE sensor (grey line), and manual snow survey measured at the SWE sensor.

precipitation matches the SWE record closely during the first two months. This changes after the first snow transport event during 17–18 November 2010, when maximum hourly averaged wind speed (V) at the 10 m height was recorded at 13.7 m/s and the snow transport rate was calculated at 0.62 m^3/hr/m (Sturm & Stuefer 2013). During this event, the precipitation gauge record departed from the SWE sensor record due to two factors: (1) additional deposition of snow transported by wind at the SWE sensor and (2) decreased accumulation at the precipitation gauge due to wind undercatch. This pattern reverses during the snow transport event on 23 February 2011, when V was 23.3 m/s and snow transport rate was calculated at 5.98 m^3/hr/m (Stuefer & Sturm 2012; Sturm & Stuefer 2013). Strong winds and favorable snow conditions on 23 February 2011 resulted in an accumulation of drifted snow at the precipitation gauge and snow erosion at the SWE sensor (Figure 5). This example illustrates common difficulties with automatic precipitation measurements and interpretations in treeless, windy environments. Corrections for gauge undercatch need to be made to the historical precipitation data (Goodison *et al.* 1998), but too often information on the shield status of precipitation gauges and wind speed is lacking (Kane & Stuefer 2015).

CONCLUSION

This paper provides a summary of current instrumentation and common practices used for measuring solid precipitation and snow on the ground across the northern polar countries that are members of the NRB Working Group. Manual and automatic gauges used for solid precipitation measurements, as well as instrumentation and measurement techniques used for measuring snow on the ground, were reviewed and updated. The information in this paper is directed toward practitioners planning to develop or upgrade polar observing networks, researchers wishing to assess the possible accuracy of data from a specific or worldwide network, and program managers engaged in promoting polar climatological and hydrological research and precipitation gauge development.

Most NRB countries use the Nipher shield. The Tretyakov shield is widely used in Finland and Russia. The USA uses the Alter and Wyoming shields. Catch performance varies among different gauges used by NRB countries because of gauge and windshield configurations. These differences in catch performance result in inconsistencies of solid precipitation data across borders, for example the Alaska–Yukon border (Scaff *et al.* 2015).

The use of automatic gauges has become common practice and complements manual precipitation gauge measurements. Unlike manual precipitation gauges, automatic gauges developed in one country are being adopted in several NRB countries. The favored type of automatic gauges among NRB countries is the weighing gauge (as opposed to the tipping bucket).

This review, which has been undertaken within the NRB group, is synergistic to ongoing, more formal and comprehensive international intercomparison projects, such as the WMO SPICE initiative. Several NRB countries are carrying out their own intercomparison studies. One of these studies has taken place at Wolf Creek in northwest Canada with the unshielded Pluvio 200 (200 cm^2) and Standpipe (1,134 cm^2), and the shielded Pluvio 400 (400 cm^2) and Geonor (200 cm^2) gauges, with the standard Nipher gauge used as a reference. Intercomparison results show that the unshielded gauges agree well, even with significantly different catchment areas. Shielded gauges record approximately 55% more precipitation than unshielded gauges by the end of an accumulation season. The Geonor records approximately 10% more precipitation than the Pluvio 400. The Geonor agrees well with the reference Nipher over the season.

A study was conducted at Sodankylä in northern Finland during the 2013–14 snow accumulation period, comparing the VRG101, the $Pluvio^2$ 400, and the manual H&H. Study results indicated that the VRG101 and $Pluvio^2$ recorded 20% and 5% less precipitation, respectively, than the manual H&H-90.

As with the assessment of solid precipitation gauge performance, some NRB countries have carried out intercomparison studies of instrumentation for measuring SWE. Studies in northwest Canada included the traditional butyl rubber snow pillow, SSG, and Campbell Scientific CS725 gamma radiation sensor (CS725) for the winter of 2014–15 at Wolf Creek, with manual snow survey measurements used as a reference. The snow pillow approximated manual snow survey measurements closely during the early accumulation period, but under-recorded during the late accumulation (March) and melt periods by 13% and 24%, respectively due to ablation associated with the relatively large instrument footprint. The SSG approximated the snow pillow during the accumulation period, but recorded approximately 25% higher during the melt period. The CS725 tracked well above (approximately 20%) during the early accumulation period, but was very close during the late (February/March) accumulation and melt periods.

The Norwegian experience with the SPA for automated snow density measurements was not encouraging in windy alpine environments. During the five-year test period, control measurements of snow depth, snow density, and calculated SWE did not agree well with the SPA data. In addition, the robustness of the sloping cable was questionable, as the cable broke three times during the test period because of strong winds. Observations indicated that air spaces had developed around the sloping cable, likely due to vibration that occurred during wind events. These spaces affected the calculation of the dielectric constant, resulting in erroneous readings. Rain events were also common during the study period. Drainage along the sloping cable likely affected the calculation of the dielectric constant. The conclusion of the study was that the instrument is not suitable for locations with strong winds and frequent winter rain events.

A study conducted at Imnavait Creek in the Alaska Arctic to evaluate an electronic SWE pressure sensor (Johnson & Schaefer 2002) showed that the SWE sensor measurement approximated the corresponding manual SWE measurements. Cumulative records of SWE on the ground and SWE captured in wind-shielded precipitation gauges diverged during strong wind events. Current practices of solid precipitation measurements work well in protected environments, such as subarctic sites in Sodankylä and Wolf Creek, and remain challenging in treeless, windy locations such as Imnavait.

As technology evolves and new instrumentation becomes available, gauges are upgraded or replaced. Several different gauges are used within and between individual NRB countries, because data collection agencies and standards vary within and between these countries. In terms of best practices, precipitation gauge heating should be used where possible to minimize capping; however, power is frequently an issue in remote areas, and some effort could be expended in improving heating capability by minimizing power requirements. Windshields should be used to minimize undercatch, and measurements should be adjusted for undercatch accordingly. Snowfall and snow on the ground should be measured simultaneously.

International initiatives such as SPICE are a critical step for the integration, communication, and future improvement in programs designed for solid precipitation and snow on the ground data collection across the NRB countries.

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