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Northern Hemisphere in situ snow water equivalent dataset (NorSWE, 1979-2021)

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Abstract. In situ observations of snow water equivalent (SWE) are critical for climate applications and resource management yet there is no global database of in situ SWE observations. We present a dataset the Northern Hemisphere in situ snow water equivalent dataset (NorSWE) consisting of over 11.5 million SWE observations from more than 10 thousand different locations across the Northern Hemisphere spanning the modern satellite era (1979–2021). NorSWE builds on an existing framework applied to Canadian data (CanSWE; Vionnet et al., 2021) and includes SWE observations from manual snow courses covering Canada, the United States, Finland and Russia. Snow pillows, automated passive gamma radiation sensors, and airborne passive gamma SWE estimates provide additional coverage over North America. In addition to SWE, snow depth (SD) and derived bulk snow density are included when available. A consistent quality control is applied to all records and the final dataset delivered as a single NetCDF file that is publicly available at https://doi.org/10.5281/zenodo.14503592 (Mortimer and Vionnet, 2024).

1 Introduction

Accurate knowledge of the amount of water stored in the seasonal snowpack is critical for risk and resource management including flood and drought forecasting (e.g. Barnett et al., 2005; Fyfe et al., 2017; Huning et al., 2020; Vionnet et al., 2020), water supply for agriculture (Biemans et al., 2019; Qin et al., 2020) and human consumption (Foster et al., 2011, Sturm et al., 2017; National Academies of Sciences, Engineering, and Medicine, 2018), hydropower operations (Magnusson et al., 2020), as well as for ecosystems and climate monitoring (National Academies of Sciences, Engineering, and Medicine, 2018; GCOS, 2022). It is quantified by the snow water equivalent (SWE), or water equivalent of the snow cover, which is *'the vertical depth of water that would be obtained if the snow cover melted completely, which equates to the snow-cover mass per unit area'* (WMO, 2018). At global scales, SWE can be estimated from global climate models, reanalyses (Mudryk et al., 2024 and references therein) and, to some extent, from passive microwave satellite observations (Pulliainen et al., 2020) but these methods usually produce SWE estimates at medium to coarse spatial resolutions (5–25km) and their accuracy must be verified against ground-based measurements. In situ, SWE can be measured manually from snow pits or using a snow tube (WMO, 2018), from automated sensors such as snow pillows (Beaumont, 1965), snow scales (Johnson, 2004a; Smith et al., 2017),

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passive gamma radiation sensors (Kodama et al., 1979; Paquet et al., 2008), or the analysis of GNSS signals (Henkel et al., 2018; Steiner et al., 2022). SWE can be estimated from in situ snow depth (SD) measurements using snow density models relating SD to SWE, as in the Northern Hemispheric dataset NH-SWE (Fontrodona-Bach et al., 2023) and the airborne lidar-based Airborne Snow Observatory (ASO, Painter et al.; 2016); however, these are not direct observations of SWE. Rather, they rely on ancillary data and direct in situ observations such as those provided in our dataset for their development.

Snow cover varies spatially, influenced by landcover and microclimates, so SWE measured at a single point or from automated sensors, which have footprints ~< 100 m^2, may not be representative of a larger area (López-Moreno et al. 2020; Meromy et al., 2013). Therefore, for manual SWE observation, it is common practice to collect multiple SWE and SD measurements along a predefined route, referred to as a multi-point gravimetric snow survey, a snow course, or a snow transect (WMO, 2018). These multiple measurements are averaged together to provide a single SWE value for the area of interest. At larger scales still, SWE is estimated from airborne surveys of passive gamma radiation by relating the attenuation of gamma radiation emitted from the upper layers of the soil by the intervening water mass (solid or liquid) after accounting for the background soil moisture (Carrol, 2001). This principle, also employed by automated gamma radiation sensors (e.g. Choquette et al. 2013), has been used operationally in the United States (NOHRSC) since 1979. Direct comparisons of airborne gamma and snow course measurements showed reasonable correspondence (correlation > 0.7) in non-mountain areas up to distances of at least 50 km (Mortimer et al., 2024).

Although manual in situ SWE measurements have been conducted for nearly a century (USDA, 2008; Bulygina et al., 2011) there is no standard global database to archive these observations, nor is there a standard approach to measuring SWE (cf. Pirazzini et al., 2018 for Europe). Some national agencies such as the All-Russia Research Institute of Hydrometeorological Information – World Data Center (RIHMI-WDC) and the Finish Environmental Institute (SYKE) maintain a comprehensive national network of repeated manual snow surveys whose data are archived and searchable. Elsewhere, such as Canada and the United States, SWE is measured separately by various agencies, government departments, and hydropower companies, some of which are consolidated into larger databases for example the Canadian historical Snow Water Equivalent dataset (CanSWE) (Vionnet et al., 2021) and by the Natural Resources Conservation Service (NRCS) through its regional data collection offices (Fleming et al., 2023). It is under this fragmented landscape that we compiled available in situ SWE measurements spanning North America, Finland and Russia. Our dataset, the Northern Hemisphere in situ snow water equivalent dataset (NorSWE), includes observations from manual snow surveys, automated snow pillows and passive gamma radiation sensors, and airborne gamma SWE measurements for the period 1979–2021. It was initially compiled to support the evaluation of gridded SWE products (Elias Chereque et al., 2024; Mortimer et al., 2024; Mudryk et al., 2024) so we concentrated on compiling snow courses and airborne gamma SWE which are more spatially representative than automated instruments. To support evaluation of hydrological models (Arnal et al., 2024) which requires a higher temporal frequency than available from the snow courses, we added automated SWE measurements over North America. NorSWE is available as a single NetCDF file following the conventions of CanSWE (Vionnet et al., 2021). Dataset development generally followed Vionnet et al. (2021), with additional procedures and data attributes to support the non-Canadian data sources described herein.

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This paper is organized as follows: Section 2 describes the types of measurements included in the dataset, Sections 3 through 5 outline the data processing and quality control (QC) procedures, Sections 6 summarizes the published dataset, Sections 7 and 8 discuss its usage and limitations, and a brief conclusion is given in Section 9.

2 SWE measurement methods included

NorSWE includes SWE observations from manual gravimetric snow surveys, airborne gamma SWE, automated snow pillows and automated passive gamma radiation sensors from the sources listed in **Table 1**. The measurement type codes (**Table 2**) follow the WMO BUFR table (WMO, 2019) except for airborne gamma which we assign code 64 to differentiate it from passive gamma radiation sensors (**Table 3**).

Table 1: Data sources included in NH in situ SWE.

Data provider or dataset	Station ID prefix	Geographic domain	Measurement method(s)	Variables	Data access
CanSWEv6 [Environment and Climate Change Canada and partners]	CanSWE	Canada	Snow course, snow pillows, passive gamma radiation sensors, acoustic SD sensors*	SWE, SD. Bulk density derived from SWE and SD	https://doi.org/10.5281/zenodo.10835278
U. S. Department of Agriculture Natural Resources Conservation Service (NRCS) – snow survey	NRCS	Western US and Alaska	Snow course. Aerial markers excluded.	SWE, SD. Bulk density derived from SWE and SD	https://www.nrcs.usda.gov/wps/portal/wcc/home/snowClimateMonitoring/snowpack/ accessed February 2022
U. S. Department of Agriculture Natural Resources Conservation – SNOTEL	SNOTEL	Western US and Alaska	Automated snow pillows (SWE); acoustic SD sensors*.	SWE, SD. Bulk density derived from SWE and SD	Direct download using soilDB (Beaudette et al., 2024) https://CRAN.R-project.org/package=soilDB accessed April 2024.
Maine Geological Survey: Maine Cooperative Snow Survey Program	MGS	Maine, New Hampshire and transboundary Canadian watersheds	Snow course	SWE, SD. Bulk density is derived from SWE and SD	https://mgs-maine.opendata.arcgis.com/datasets/maine-snow-survey-data/explore accessed January 2021
Northeast Regional Climate Centre	NRCC	New York, Vermont	Snow course	SWE, SD. Bulk density derived from SWE and SD	https://www.nrcc.cornell.edu Data received via direct email January 2021
New Hampshire Department of Environmental Services (DES) – Dams	NHDES	New Hampshire	Snow course	SWE, SD.	https://www.des.nh.gov/ Data for 1950–2020 received via direct email January 2021

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				Bulk density derived from SWE and SD	2019-present available from: https://nhdes.rtiamanzi.org/snow_data
National Operational Hydrologic Remote Sensing Center (NOHRSC)	NOHRSC	US and southern Canadian prairies	Airborne gamma radiation	SWE	https://www.nohrsc.noaa.gov/snowsurvey/ accessed January 2022.
Finish Environmental Institute – SYKE	SYKE	Finland	Snow course	SWE	https://www.syke.fi/en-US/Open_information/Open_web_services/Environmental_data_API#Hydrology
All-Russia Research Institute of Hydrometeorological Information – World Data Center – RIHMI-WDC	RIHMI	Russia	Snow course	SWE, SD and bulk snow density.	https://meteo.ru/english/climate/snow1.php accessed June 2021

*SD measurements from acoustic sensors are included when co-located with a snow pillow or GMON sensor.

Table 2: Description of variables in the NH in situ SWE NetCDF file. Adapted from Vionnet et al. (2021).

Type of variable	Variable name	Description	Dimension	Units
Dimension	station_id	Station identification code	station_id	(-)
	time	Time	time	Day
Observational metadata	lat	Station latitude	station_id	°North
	lon	Station longitude	station_id	°
	elevation	Station elevation	station_id	m
	source	Data provider	station_id	(-)
	station_name	Station name	station_id	(-)
	type_mes	Method of measurement for SWE[1]	station_id	(-)
Data	snw	Water equivalent of snow cover (SWE)	station_id, time	kg m^{-2}
	snd	Snow depth (SD)	station_id, time	m
	den	Bulk snow density	station_id, time	kg m^{-3}
Quality control flags	data_flag_snw	Agency data quality flag for SWE[2]	station_id, time	(-)
	data_flag_snd	Agency data quality flag for SWE[2]	station_id, time	(-)
	qc_flag_snw	CanSWE quality control flag for SWE[3]	station_id, time	(-)
	qc_flag_snd	CanSWE quality control flag for SD[3]	station_id, time	(-)

Table 3: WMO SWE measurement codes (WMO, 2019) and new (non-WMO) codes 64 for airborne gamma SWE.

Code	Method of SWE measurement
0	Multi-point manual snow survey
1	Single-point manual snow water equivalent measurement
2	Snow pillow or snow scale
3	Passive gamma
4	GNSS/GPS methods
5	Cosmic ray attenuation
6	Time domain reflectometry

64	Airborne gamma SWE
63	Missing value
7 – 62	Reserved

Table 4: Manual snow survey sampling protocol and equipment. Precise sampling protocols may differ from those described below, especially where multiple entities contribute data to a single agency.

Agency or dataset	Survey design	Snow sampler	References
CanSWE	5–10 snow cylinders and SD along a 150–300 m line representative of the surrounding landcover. (Environment Canada, 2004; Brown et al., 2019; Vionnet et al., 2021). Snow cylinders are usually supplemented by 10–15 ruler SD measurements between SWE samples (e.g. double sampling, WMO, 2018). Saskatchewan: 3–5 snow cylinders surrounding a single point; measurement location may vary from one measurement date to the next (see data QC flag).	Federal Sampler, ESC-30 Sampler, Prairie sampler (Saskatchewan)	Vionnet et al. (2021) Environment Canada (2004)
Northeast Regional Climate Center (NRCC) contributing partners	3–5 snow cylinders surrounding a single small general location. Varies by contributing partner organization.	Primarily Adirondak sampler. Federal sampler also used.	Engel et al. (2022); Samantha Borisoff personal communication March 2022
New Hampshire DES	10 cylinders per site.	Federal Sampler	Engel et al. (2022); Nancy Baillargeon personal communication June 2024
Maine Geological Survey	10 snow cylinders and SD along a 100 yard (91.44 m) course.	Primarily Federal Sampler, Adirondack sampler also used.	Maine Geological Survey (2016)
Finland-SYKE	8 density (snow tube) and 80 snow depth along a 2 km – 4 km transect. Measurements are distributed according to landcover type. Mean SWE computed by weighted average according to areal land cover percentages.	Korhonen-Melander sampler: 100 cm^2 cross sectional area (70 cm long, 10 cm diameter)	Kuusisto (1984); Leppänen et al., (2016); Vershinina (1971, 1974)
Russia ROSHYDROMET	Double sampling (WMO, 2018) along a 1 km and 500 m course in open and forested areas, respectively. Open (forest): cores every 200 m (100 m) and SD every 20 m (10 m) in between.	VS-43: graduated iron snow cylinder A = 0.005 m^2 x 0.6 m long	Bulygina et al. (2011); Haberkorn (2019)
NRCS	5–10 evenly spaced samples along a transect marked by standard snow course markers.	Federal Sampler, McCall cutter	USDA (2012); Fleming et al. (2023)

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2.1 Manual gravimetric snow surveys

Gravimetric snow surveys, also known as snow courses or snow transects, consist of multiple depth and density measurements collected along a predefined route that are averaged to obtain a single representative SWE value for the entire route (WMO 2018; **Table 4** and references therein). In general, a double sampling technique is employed where SD and SWE measurements are collected at multiple points (n = ~5–15) along the route with additional SD measurements (n = ~10) collected between these SWE sampling locations (WMO, 2018). We gathered snow course data from multiple agencies in Canada (consolidated in CanSWE cf. Vionnet et al., 2021), the United States, Finland, and Russia (**Table 1**). **Table 4** provides general sampling procedures for the contributing datasets; however, even within a given contributing agency, protocols may vary and differ from those listed. Measurement uncertainty for various snow samplers ranges from ~3% to 13% (Table 2 in Dixon and Boon, 2012 and references therein; USDA, 2012; López-Moreno et al., 2020). **Figure 1** shows the location of the manual snow survey contained in NorSWE.

NorSWE includes SWE estimates from NOAA's National Operational Hydrologic Remote Sensing Center (NOHRSC) snow survey program (https://www.nohrsc.noaa.gov/snowsurvey/; Carroll, 2001). This network consists of approximately 2,400 flight lines in 25 US states and seven Canadian provinces (Carroll, 2001) as shown in **Fig. 1**. Flight lines are 10–15 km long and 300 m wide. Surveys are conducted once per year near peak SWE, with occasional flights added to capture hydrologically important conditions. The method, which is limited to ~ < 1000 mm SWE, relates the attenuation of gamma radiation emitted from the upper ~20 cm of the soil by the water mass of the snowpack (liquid or solid phase) after accounting for the background soil moisture (Carroll, 2001). Snow-free radiation and soil moisture conditions are obtained from a snow-free flight, usually conducted in the fall. In the absence of a fall flight, subjective estimates (SE), a default value (DV, typically 35%), or other ground-based measurements (GM of GI) of soil moisture content is used. SWE accuracy, determined from comparisons with coincident ground-based observations, ranges from 4% to 10% for prairie SWE 20–150 mm (Carroll and Schaake, 1983) and 23 mm in forested areas for SWE between 20 and 480 mm (Carroll and Vose, 1984). The airborne gamma SWE data does not include coincident observations of snow depth.

2.3 Automated measurements – North America

The automated SWE observations in NorSWE cover Canada and the US. When available, we also include snow depth measurements from co-located snow depth sensors. Measurements from automated passive gamma radiation sensors (GMON, Choquette et al., 2013) deployed in central and eastern Canada by Hydro-Québec, the Government of Newfoundland and Labrador, and Manitoba Hydro were taken directly from CanSWE v6. GMON sensors relate the attenuation of naturally emitted gamma radiation from the upper layers of the soil to SWE after accounting for the background soil moisture. Measurement footprint is ~50–100m^2 and measurement range is 0–600 mm; readings are taken every 6 hrs (distributed hourly). The stated accuracy of common automated passive gamma instruments is ± 15 mm up to 300 mm and 15% from 300 mm to 600 mm (Campbell Scientific, 2017). However, the measurement uncertainty when deployed in the field can much larger

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(Smith et al., 2017). The GMON sensors deployed by Hydro Québec also have a co-located hourly-recording sonic snow depth sensor.

The snow pillow data cover western North America (**Fig. 1**) and were obtained from CanSWE v6 and from the US SNOTEL network (**Table 1**). Snow pillows measure SWE from the overlying hydrostatic pressure on a bladder filled with anti-freeze (Beaumont, 1965). Measurement footprint is 9 m^2; instrument accuracy is ~ ± 4% (USDA, 2011). SNOTEL sites (USDA,

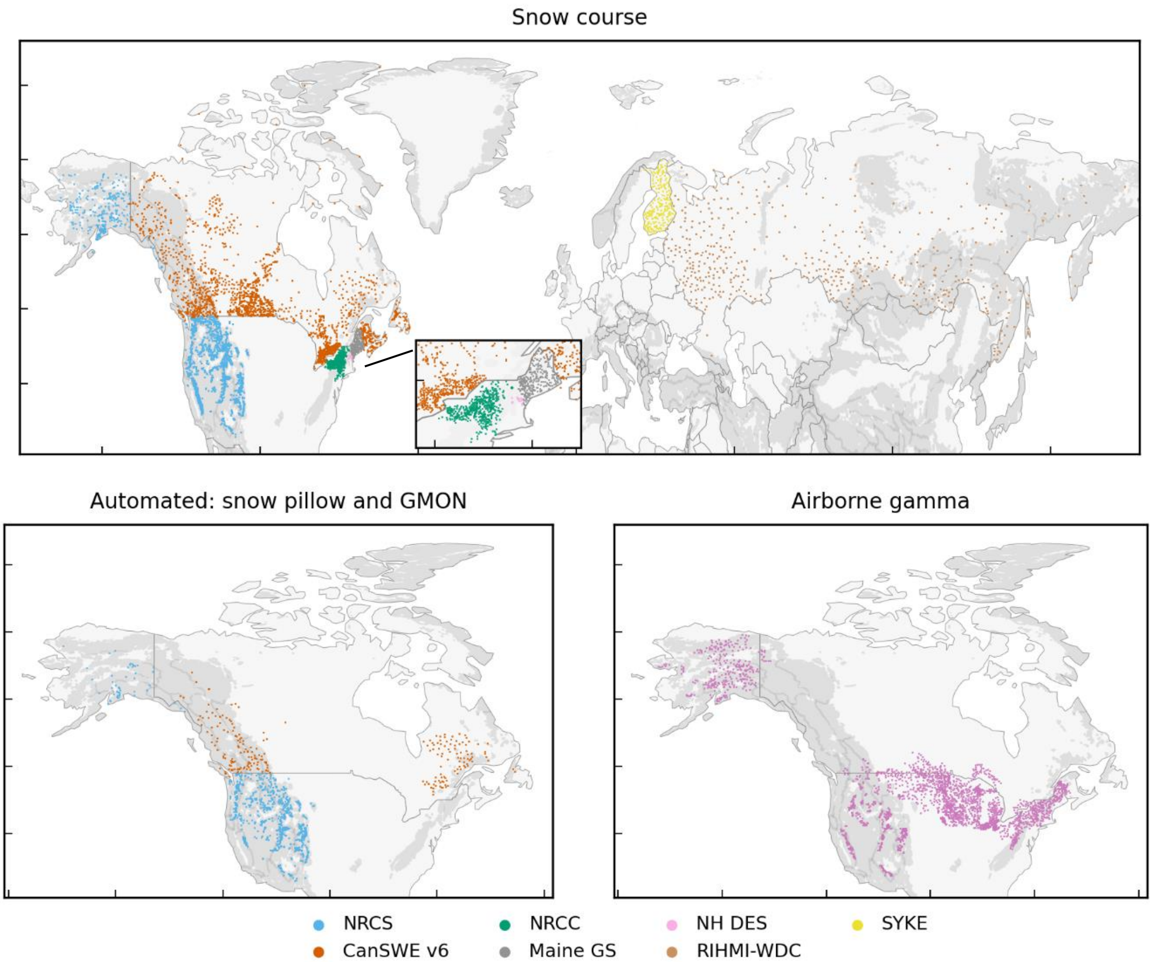

Figure 1: Spatial distribution of NorSWE sites by measurement type (snow course, automated, airborne) and data source. Grey shading indicates mountain mask as detailed in Sect. 3.

2012; Fleming et al., 2023) and roughly half of the Canadian snow pillow sites are equipped with a co-located acoustic snow depth sensor. Compiled and quality-controlled snow pillow data over western North America are available elsewhere (e.g. Yan et al., 2018; Sun et al., 2019; Musselman, 2021). Due to differing QC procedures (see **Sect. 4**) the snow pillow data in NorSWE may differ slightly from those contained in these other datasets. In many regions, snow pillows are gradually being replaced with the more environmentally friendly snow scales. NorSWE does not differentiate between these two instruments.

3 Data cleaning and formatting

Data from each of source listed in **Table 1** were obtained either through direct download or email exchange. Data processing followed the steps shown in **Figure 2**. Data cleaning involved removing duplicate stations and observations, correcting obvious errors in measurement dates and removing records flagged as erroneous, adding a mountain classification, and finally converting to a standard netCDF format. Sites intersecting either a 2° slope mask derived from the GETASSE30 DEM or with the Global Mountain Biodiversity Assessment (GMBA) Mountain Inventory v2 (Snethlage et al., 2022; 2023; https://www.earthenv.org/mountains) with a 25 km buffer were flagged as mountain. This broad mountain classification, which is used during quality control (**Sect. 4**), is consistent with that applied in Mortimer et al. (2024) and Mudryk et al. (2024). Data harmonization involved converting imperial units to metric, harmonizing agency-specific quality flags, applying a consistent quality control, checking for duplicate sites between agencies, and finally merging the datasets into a single NetCDF file.

Data for the agencies listed in **Table 1** were cleaned and reformatted to a modified version of the CanSWE NetCDF (**Table 2**) using unique agency-specific Python scripts. Station metadata includes a unique station ID, station name, coordinate consisting of a single latitude, longitude, and elevation, the data source, measurement method and mountain flag (**Table 2**). Station IDs were constructed by prepending the source abbreviation listed in **Table 1** to the original station ID, Russia excepted (see **Sect. 3.2** and **Table 6**). Where elevations were not provided for a given site or network (e.g. Russia, Finland) they were obtained from the USGS' National Elevation Dataset (Gesch et al., 2002). The primary snow variable of interest is SWE. SD and derived bulk snow density, calculated from SD and SWE, are provided when available. Each site, identified by a unique station ID, is permitted only one set of snow observations (snw/snd/den) per day; duplicate observations are removed during data processing. Where possible, data quality and flag information contained in the original data are included in the harmonized 'agency_data_flag' variables (**Table 5**). Agency-specific processing steps are described below except for SYKE (Finland) which did not require any additional processing beyond the general steps described herein.

Table 5: Data flags in NH in situ SWE. Not all data flags are used by all data sources.

Data flag	Definition	Comment
A	Sampling problems	
B	Manual snow survey conducted outside the nominal sampling period	
C	Combination of A and B	
E	Estimate	
G	Measurement location > 1 km from station coordinate.	Specific to Saskatchewan Water Security Agency housed in CanSWE beginning in 2011.
M	Missing	
P	Patches	
R	Revised data	
T	Trace	

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Y	Precise sampling date not available. CanSWE: NWT set to 1 April, within 1 week for Government of Manitoba, research sites (UU) approximate date. NRCS: set to nominal survey date.	
AI	Soil moisture – airborne	Data flags for airborne gamma are used to store the soil moisture estimation method.
AM	Soil moisture – airborne	
GI	Soil moisture – ground-based information	
SE	Soil moisture - subjective estimate	
MM-avgX	Average of 'X' SWE observations using soil moisture method 'MM' where 'MM' is the soil moisture method AI, AM, GI or SE.	Specific to airborne gamma SWE Lines with >1 observation on a given date, see Section 3.5.

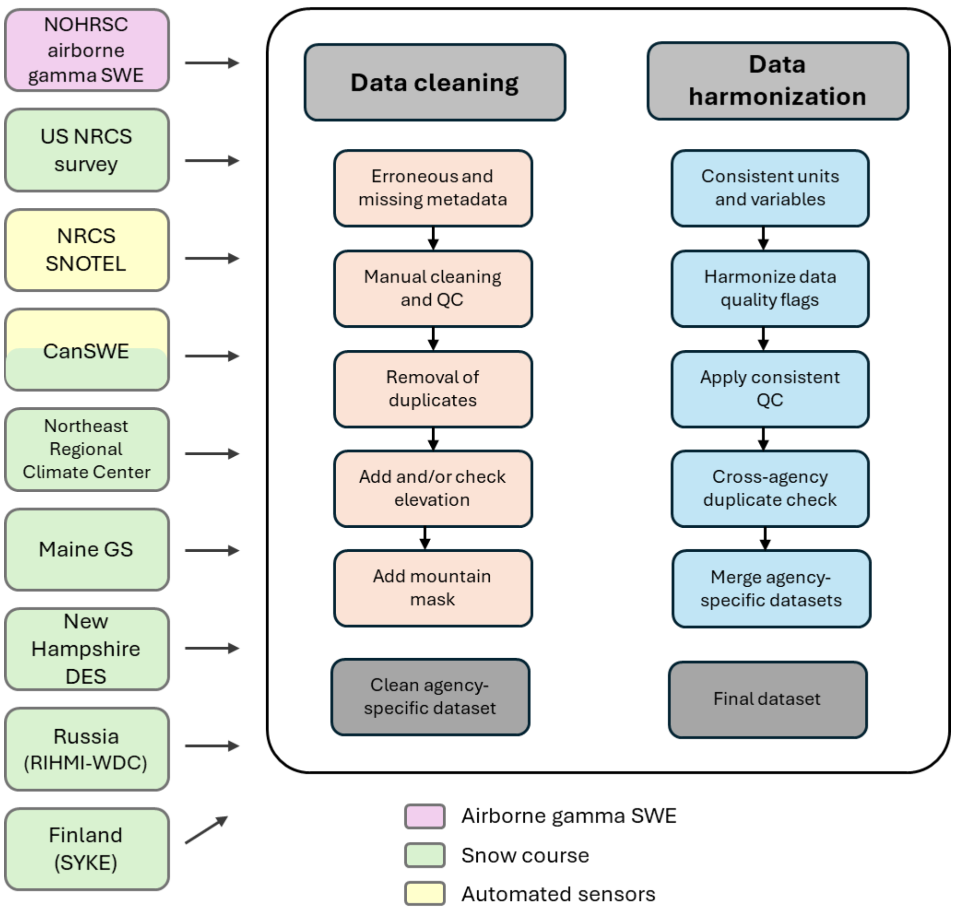

Figure 2: Schematic of data processing steps. See tables 1 and 2 for information on the contributing datasets listed on the left-hand side.

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3.1 CanSWE (Canada)

The CanSWE v6 dataset is included *'as is'* except that we removed the secondary and tertiary station names and IDs to simplify the dataset. We also added a mountain variable (see **Sect. 4**) and prepended CanSWE to the original station ID and CanSWEv6 to the original source variable. In CanSWE, only one automated observation per day corresponding to 18:00 UTC is included. As described in Vionnet et al. (2021), a 24-hour median filter (Stone, 1995) is applied to the hourly data from British Columbia Ministry of Environment and Hydro-Québec and then the record corresponding to 18:00 UTC is extracted. When daily automated data are provided (e.g. Alberta Environment and Parks), these observations are assigned a timestamp of 18:00 UTC.

3.2 RIHMI-WDC (Russia)

RIHMI-WDC assigns the same WMO ID to up to three unique snow courses covering different land covers (field/open – 1, forest – 2, and 3 gulley – 3; Bulygina et al., 2011). These distinct snow courses have different sampling frequencies depending on the land cover. Prior to the spring melt period, sampling of field/open sites is conducted every 10 days when at least half of the visible area is snow covered; forest sites are sampled once per month prior to 20 January and every 10 days thereafter (**Table 4**, Bulygina et al., 2011). Measurement frequency is every 5 days during spring snowmelt regardless of land cover type. Land cover type is provided by RIHMI-WDC as a separate variable which is not supported by our NetCDF format (**Table 2**). To maintain these distinct snow courses while conforming to our NetCDF format we generated new station IDs by appending the landcover flag to the WMO ID as demonstrated in **Table 6**.

Table 6. Station ID construction for RIHMI-WDC (Russia) for example site 22127 (Lovozero). Not all sites have all three transect types. Station coordinates as the same for each transect although transects and sampling frequencies differ (Sect. 3.2).

Agency prefix (see Table 1)	**WMO ID** (RIHMI-WDC)	**Landcover code**	**Landcover definition**	**New NorSWE ID** (RIHMI + WMO ID + Type code)
RHIMI	22127	1	Field/open	RIHMI-22127_1
RHIMI	22127	2	Forest	RIHMI-22127_2
RHIMI	22127	3	Gulley	RIHMI-22127_3

3.3 Northeast US

Data covering the US northeast were obtained from three sources: Maine Geological Survey (Maine GS), New Hampshire Department of Environmental Services (NH-DES), and the Northeast Regional Climate Centre (NRCC). Each required substantive manual cleaning to remove duplicate records, inaccurate dates, and to correct errors in the metadata. Sites with missing coordinates were dropped as were records flagged as erroneous by the providing agency. For Maine specifically, records with confidence level marked as '*questionable'* (n = 302) or '*dummy site'* (n = 852) were removed as were those with error codes '*inconsistent or duplicate data within 1, 2, or 3 days*' (n = 156). To avoid creating duplicate records, we removed all sites from Maine GS with source or station IDs containing Québec, New Brunswick or variations thereof (n = 1392). Quality flags accompanying the original data were retained and harmonized to **Table 5**.

3.4 US Natural Resource Conservation Service

Snow survey data from the US Natural Resources Conservation Service covering the US were obtained directly using the GitHub repository https://github.com/CH-Earth/snowcourse. Records missing exact dates were assigned the date of the nominal survey period and a Y quality flag assigned. In some remote areas of the western US that are challenging to access the NRCS uses aerial markers instead of snow courses The marker consists of a large vertical mast (typically a pipe) with horizontal cross bars that can be seen from a survey aircraft. SD is observed during flyover and SWE is calculated using an estimated snow density. As these are not direct observations of SWE, we exclude them from NorSWE. Aerial markers were identified as sites with IDs ending in AM or containing AERIAL. This approach, which removed 127 sites, does not account for changes in measurement method over time – sites classified as being aerial markers may include some snow course observations and vice versa.

Automated data from the SNOTEL network were obtained using https://ncss-tech.github.io/AQP/soilDB/fetchSCAN-demo.html (Beaudette et al., 2024). Daily SD and SWE downloaded separately and merged by the station ID. For consistency with the automated data from CanSWE, the daily values are assigned to 18:00 UTC (**Sect. 3.1**).

3.5 Airborne gamma SWE

Metadata for the airborne gamma SWE flight lines were derived from the GIS shapefile *'https://www.nohrsc.noaa.gov/gisdatasets/NOHRSC Flight Lines.shp'* as detailed in **Table 7**. LINE became the station ID and station names were constructed from the LINE and River Basin variables. For coordinates, we used the flight line midpoints provided in the file. We calculated missing midpoint coordinates from the flight line endpoints. NOHRSC assigns SWE estimates at or above the method detection limit of 1000 mm a value of 999.0 mm. We excluded these records (n = 32) from our dataset. Finally, we include information about the soil moisture measurement method in the data_flag_snw variable. Typically, NOHRSC provides two separate SWE estimates: one based on the measured or estimated soil moisture conditions and one using a soil moisture value of 35% (Carroll, 2001). We only included SWE calculated using either a measured or an estimated soil moisture. In some cases, multiple SWE values are provided for the same date as updated or new soil moisture conditions become available. When this was the case, we averaged these multiple measurements because last upload or modification dates were not consistently available. These averaged records make up <1% of the airborne gamma SWE records and are identified by '-avgX' appended to the soil moisture estimation code, where X is the number of records averaged which ranged from two to three. There were no instances of different measurement methods being averaged together.

Table 7. Derivation of variables in this dataset from the NOHRSC flight index (https://www.nohrsc.noaa.gov/snowsurvey/fline_index.html). The first two letters of the station ID refer to the state or region.

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NH in situ SWE NetCDF	NOHRSC flights.shp
station_id	NAME (Flight line index 'LINE')
station_name	RIVER_BASI-NAME
lat*	LAT_MIDPNT
lon*	LON_MIDPNT
data_flag_snw	METHOD

*if LAT_MID and LON_MID were missing, latitude and longitude were calculated from the flight line endpoints.

4 Quality control

The level of internal quality control of the included datasets differs by agency. Some agencies apply their own quality checks prior to data distribution (e.g. Snotel, Fleming et al., 2023) while others share their data *'as is'*. Even when quality control is applied by the collecting agency the methodology is rarely published, often relies on expert judgement, and may not have been applied consistently throughout the time series. This limits our ability to standardize existing QC approaches across constituent datasets and necessitates the application of our own procedure for the merged dataset.

To ensure reproducibility of the quality control, we chose not to implement procedures that rely on ancillary data such as precipitation and temperature (e.g. Johnson and Marks, 2004b; Yan et al., 2018; Brown et al., 2021) and instead apply only self-contained methods. Ancillary data are not always consistently available and can be subject to version changes and updates. We encourage users to conduct additional QC using locally available ancillary data when possible.

Data from each source were subjected to the quality control described in Vionnet et al. (2021), which itself was adopted from Bratten et al. (1998). The QC consists of range thresholding and, for automated sites, an automated outlier detection. The infrequency of snow course and airborne gamma observations render QC methods that require near-continuous time series, such as spike checks and automated outlier detection, useless so only range thresholding is applied. Ranges for SD, SWE and bulk density are 0–3 m (0–8 m for mountain sites), 0–3000 kg m^{-2} (0–8000 kg m^{-2} for mountain sites), and 25–700 kg m^{-3}. This approach differs slightly from that of CanSWE which applies the higher thresholds to sites west of 113°W. This change had no impact on the CanSWE data so, metadata aside (see **Sect. 3.1**), the CanSWE records contained in NH in situ SWE are the same as the original (CanSWE v6). Observations outside of these ranges were set to null and a QC flag assigned according to **Table 7**. Thresholds were applied to SD and SWE separately. For example, if a record fell outside the SD range but inside the SWE range only the SD record was set to null and the SD QC flag assigned 'H'. If a record failed the snow density test, both SWE and SD were set to null and a 'D' flag assigned to both the SD and SWE QC flags.

The automated data were subject to an additional QC step, following Hill et al. (2019) (as described in Vionnet et al., 2021). Spurious SD-SWE pairs were identified via the robust sample Mahalanobis distance (Leys et al., 2018) which is the distance of a point from mean of a multivariate distribution using the minimum covariance determinant. Further details are provided in Leys et al. (2018), Hill et al. (2019), Vionnet et al. (2021), and references therein. The test requires a multivariate dataset so is only applicable to automated sites with both SD and SWE. We required sites to have at least 20 records (SD-SWE pairs) to run this test. Outliers, defined as the upper 0.001 quantile of a chi-squared distribution with p degrees of freedom, were set to null and a QC flag 'V' assigned to both *qc_flad_snd* and *qc_flag_snw*. This method is reasonable at removing extreme outliers but it has a tendency to also remove valid data during the snow onset and melt periods.

5 Merging the datasets

The cleaned and quality-controlled NetCDFs from each contributing agency were merged into a single file after removing duplicate sites and observations between networks (**Fig. 2**, right-hand column). Duplication of records often occurs when a watershed spans multiple jurisdictions (for example southern Canada and northern USA), and data are shared between agencies who each assign their own station IDs.

Duplicate sites were defined as those with similar coordinates, elevations, and snow observations, as well as sites with similar station names or IDs. Sites from neighbouring agencies with matching station names were checked for proximity and similarity of snow observations. First, we identified all sites from neighbouring agencies with matching station names and inspected those matched sites within 5 km of each other. If the matched sites had similar coordinates and snow records, we retained the site from the agency whose jurisdiction it intersects. The duplicated site, along with its complete snow record was dropped. For example, if a site in New Hampshire was found in both the NH-DES and Maine databases, we kept the record from NH-DES and dropped the site and its complete record from the Maine GS database. Next, from the remaining sites we identified all sites (same measurement type) within 2 km of any site from a neighbouring agency (e.g. all snow course sites in CanSWE within 2 km of an NRCS snow course site). The records and station metadata from the matched sites were inspected (compared coordinates, elevations, names, IDs, snow observations) and duplicate sites were dropped. This step removed 63 sites: 62 from CanSWE and 7 from Maine GS (**Table S1**).

The CanSWE v6 dataset with duplicate sites removed and modified metadata (**Sect. 3.1**) was used as the base dataset. The cleaned datasets from the other eight agencies were added to this base dataset and the time period restricted to 1979–2021.

6 Dataset summary

The final dataset contains > 11.5 million SWE observations from more than 10 thousand different sites. There are nearly one million observations from almost seven thousand snow courses across North America, Finland and Russia. Together, over two thousand airborne gamma flight lines provide more than 30 thousand SWE observations over the US and southern Canada. The automated data are restricted to North America, but owing to a higher sampling frequency, account for the majority of observations in NorSWE. There are over 10 million observations from nearly one thousand (983) snow pillows in western North America and an additional ~100,00 observations from 112 GMON sensors in Québec and Newfoundland and Labrador, Canada.

Spatially, sites are well distributed across Russia, northern tundra regions excepted, and there is dense coverage over Finland (**Fig.1**). In North America, sites are concentrated around populated regions and in the mountain-west but are sparse in the

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north. This is reflected in the distribution of sites by global seasonal-snow classification (**Fig. 4,** Sturm and Liston, 2021) where there is an over-representation of montane forest, which covers most of the southern populated areas (**Fig. 4**), and an under representation of the tundra and boreal forest snow classes whether analysed for North America (Canada and US only, **Fig. S1**) or the complete Northern Hemisphere (**Fig. 3**). Over half of the sites in North America intersect with our mountain mask (**Sect. 3**) compared to less than 15% of Eurasian sites.

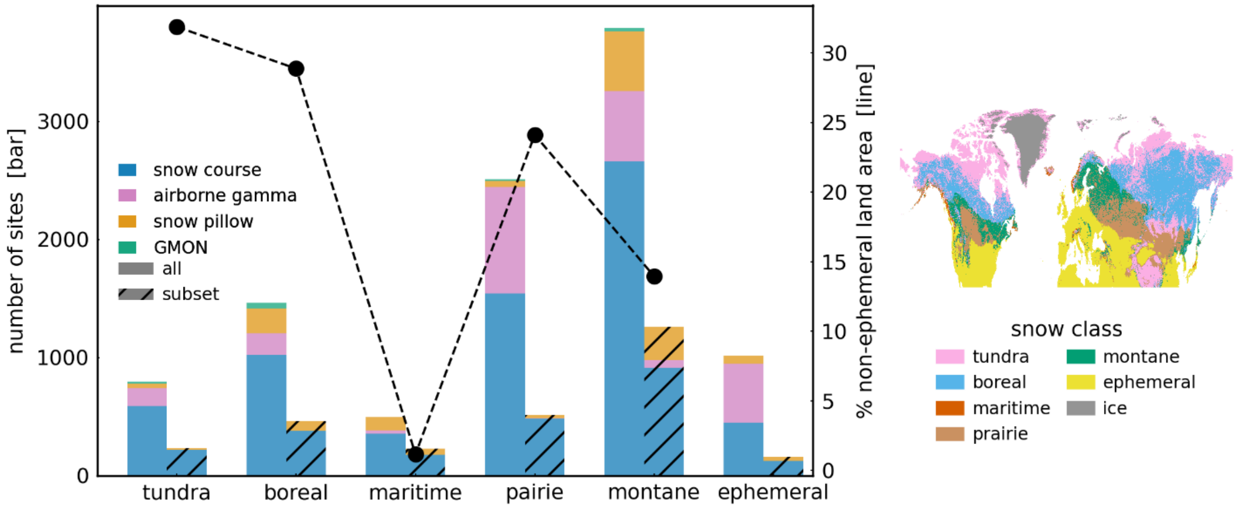

Figure 3. Left: NorSWE site distribution by Sturm and Liston (2021) snow class (Right) for the complete dataset and for a subset of sites with at least one measurement in each pentad starting in 1980 and having measurements in at least 30 different years between 1979 and 2021 (hatched) versus the proportional land area by snow class (dashed black line). The ephemeral snow class is excluded from the land area calculations because it does not differentiate between no snow and ephemeral. Permanent land ice is also excluded. Montane: montane forest, Boreal: boreal forest.

The number of manual observations in NorSWE has decreased over its time span while the number of automated measurements has increased (**Fig. 4**). While automated instruments provide an alternative to the labour-intensive manual snow courses which can be challenging and costly to conduct in remote locations (Pomeroy and Gray, 1995), the shift away from manual observations can be problematic for the continuity of long-term records without thorough site-specific intercomparisons (e.g. Smith et al., 2017). Further, not all sites in our dataset are sampled consistently throughout its time span. In a given year there are between 3689 and 5336 different sites with at least one SWE measurement (**Fig. 4** sum of top row).

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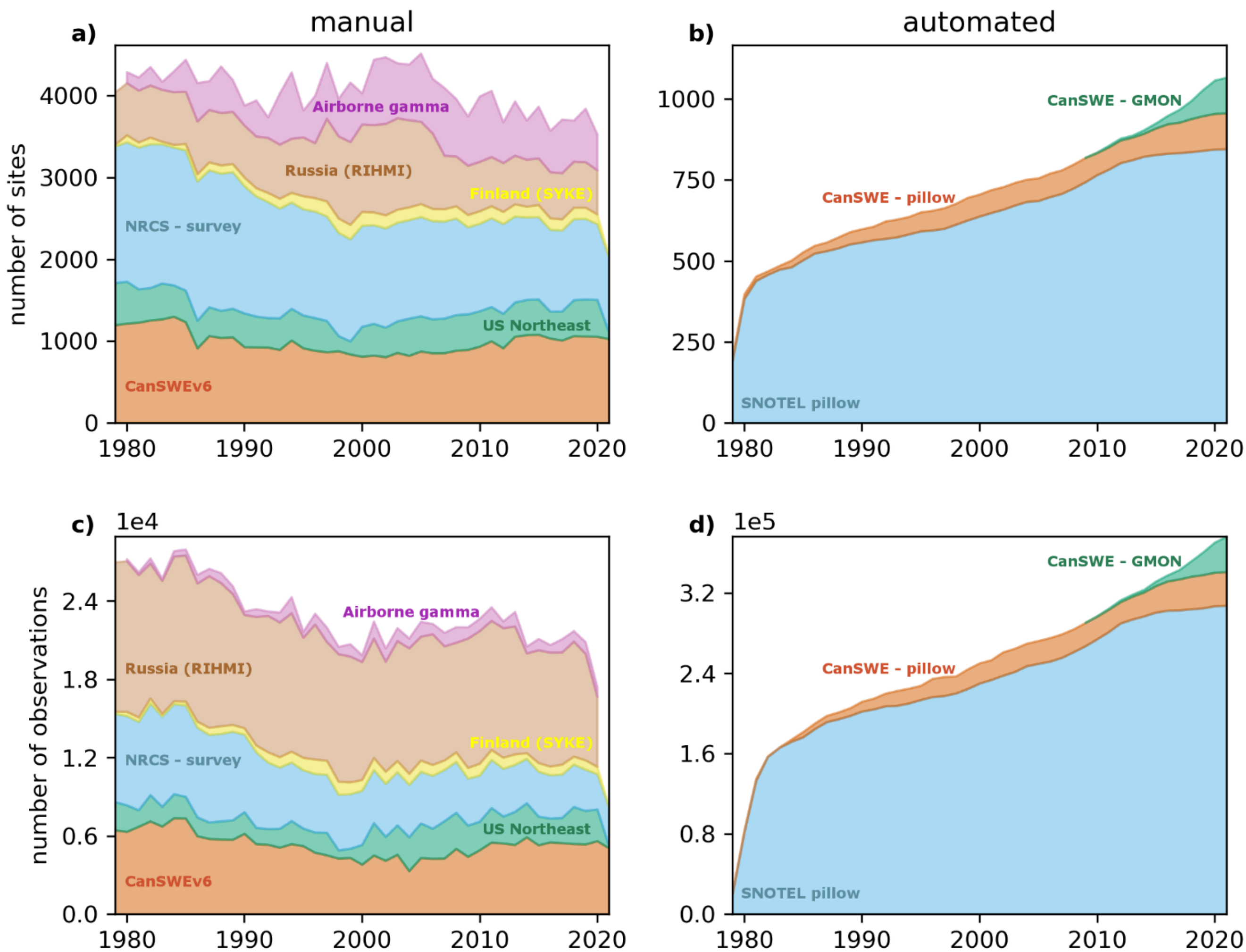

Figure 4. Number of manual (left) and automated (right) observations contained in NorSWE. Maine, NH-DES and NRCC combined for display. Russia typically has 1-3 snow courses for a given site covering different landcovers which are counted separately in NorSWE (Sect. 3.2). Approximately half of the SNOTEL and <~1/3 of the CanSWE automated SWE values are 0 mm.

To understand the distribution of consistently sampled sites in NorSWE we identified sites with at least one measurement in each pentad starting in 1980 and having measurements in at least 30 different years between 1979 and 2021 (**Fig. 5**). The SNOTEL and RIHMI-WDC, NRCS survey, and NH-DES networks are the most consistent over time with at least 40% of their sites retained. Similar to the full suite of sites, the temporally consistent subset has well distributed coverage over Finland and Russia, northern regions excepted. In North America, although density of the temporally consistent sites is lower compared to the full complement, coverage remains good in the east and west, maritime Canada excepted. Critically, however, there are almost no sites with consistent long-term (> 30 yrs) records in the central prairies resulting in an increased underrepresentation

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of the prairie snow class (**Fig. 3 hatched bars, Fig. S2)**. The lack of North American prairie sites is largely attributed to the curtailment of Canada's ground observing networks starting in the 1980s and to the cessation of the Meteorological Survey of Canada (MSC) annual Snow Cover Data (SCD) summaries program in 1985 (Brown et al., 2000), combined with inconsistent airborne gamma surveys (**Fig. S2**). The end of the MSC SCD program, which compiled coordinated SWE observations from agencies across Canada, resulted in the loss of historical data collected after this date and before CanSWE's precursor the Canadian Historical Snow Survey Dataset (Brown et al., 2019). The airborne gamma SWE network has the smallest proportion of long-term consistent sites with only 3% of flight lines meeting our criteria. Airborne gamma observations in Alaska only began in 2003 and flights in much of the western US mountains ceased in the late 2000s and early 2010s (**Fig. S2**).

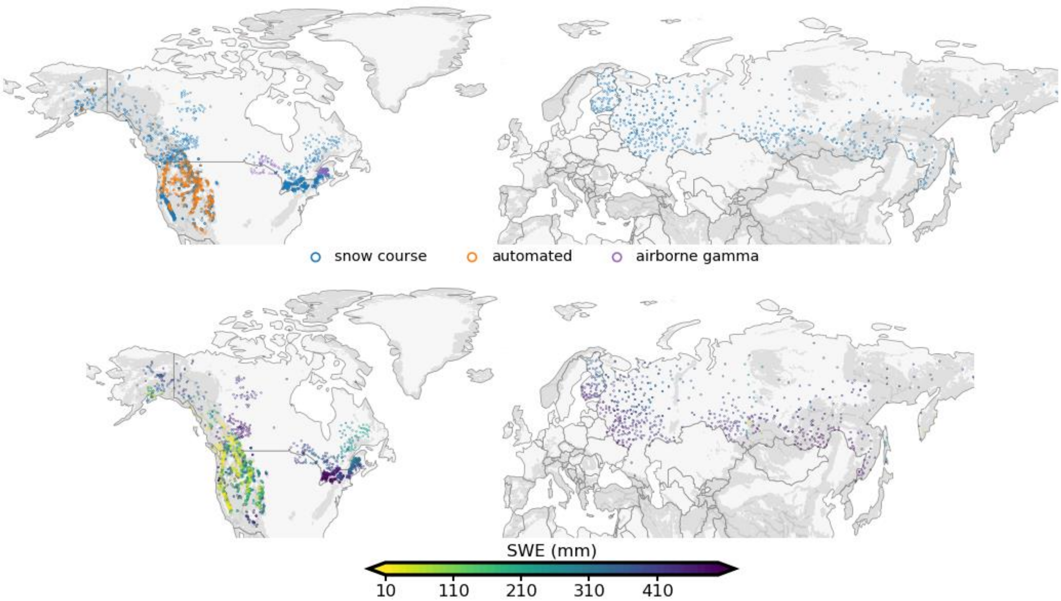

Figure 5. Sites in NorSWE with at least 30 years of observations and at least 1 year in each pentad starting in 1980 by measurement type (top). Bottom: Mean March SWE for sites the sites in top row.

Lastly, to understand the station representativity according to elevation, we compare site elevations with snow class (ephemeral excluded) as well as mountain and non-mountain landmass hypsometries (**Fig. 6**). The ephemeral snow class is excluded because it includes both ephemeral and no-snow areas. The hypsometries were derived by intersecting the Global Seasonal-Snow Classification, v1 30 arc second, (Liston and Sturm, 2021) reprojected to EASE2 Grid with 1 km spacing, with the Copernicus GLO-30 DEM (https://doi.org/10.5270/ESA-c5d3d65). The elevation distribution of non-mountain sites (**Fig. 6** bottom right) matches that of the terrain, but the elevation distribution of the mountain sites is biased high. The latter reflects that sites in mountain areas tend to be located in the upper reaches of headwater catchments to provide the necessary information for various operational activities. Despite the mountain sites being biased high compared to the mountain area hypsometry, they still miss the highest elevation terrain.

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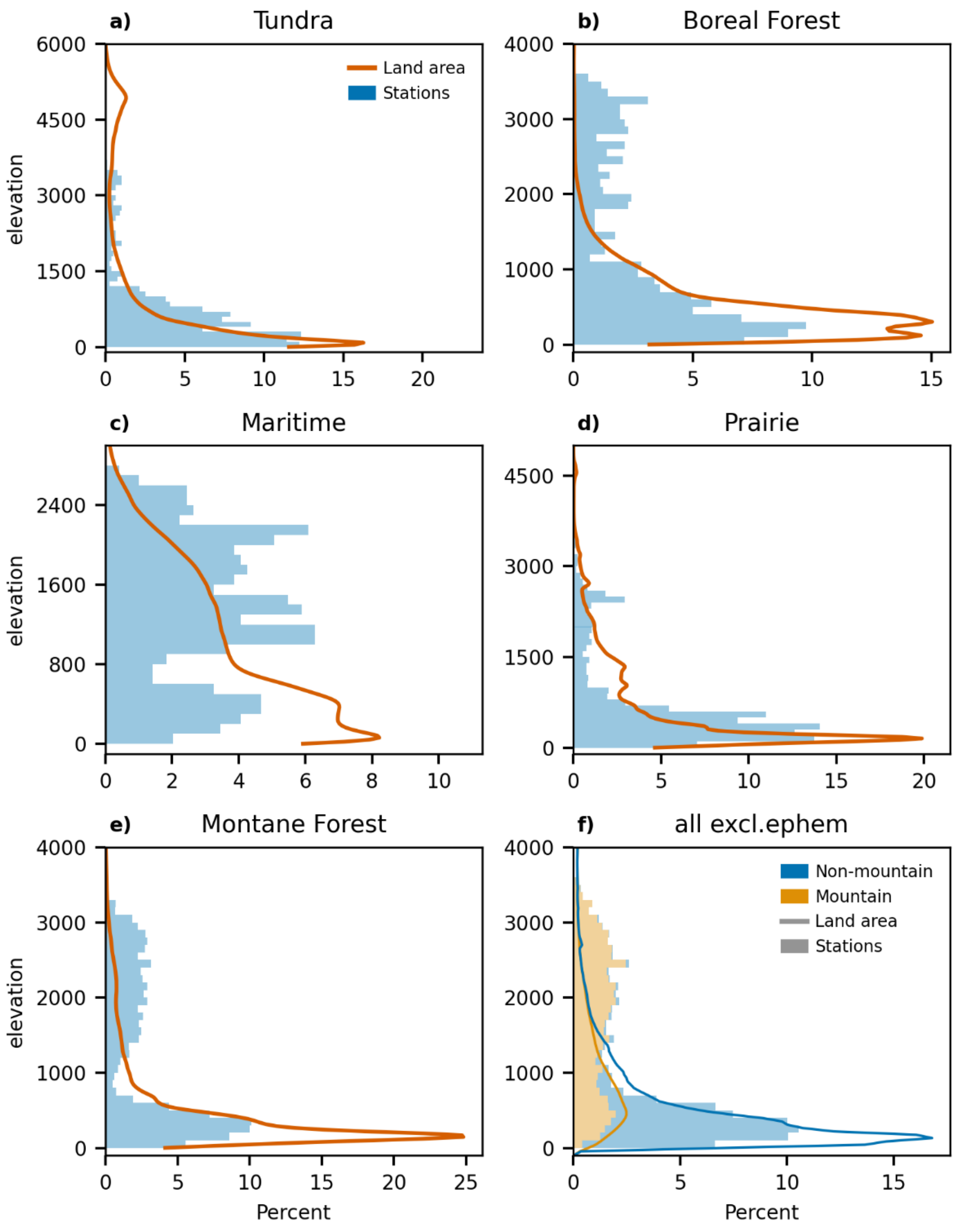

325 **Figure 6. Elevation distribution of NorSWE sites (blue bars) and land area north of 30°N (orange line) by Sturm and Liston (2021) snow class (a-e). f shows the distribution of sites (bars) and land area north of 30°N (lines) of the five snow classes shown in a-e separated into mountain and non-mountain (Sect. 3).**

By snow class, there is representative elevation sampling of the prairie and tundra snow classes, except for the highest elevations of the tundra class. Much of the unsampled high elevation tundra snow is found in High Mountain Asia and in the

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mountains of the Canadian Arctic Archipelago where publicly available in situ snow information is lacking. The elevation distributions of sites in the boreal forest, montane forest, and maritime snow classes are biased high compared to the average terrain. In these snow classes there are generally two peaks: a larger one centred around 200–500 m which aligns with the snow class and is consistent with the non-mountain hypsometry and site distribution (**Fig. 6f**) and a smaller one between 2000 and 3500 m. The second peak, which does not align with the snow class elevation distribution, mirrors the distribution of mountain sites (e.g. **Fig. 6f**). This pattern is reversed for maritime snow.

7 Dataset usage

Repeated in situ SWE measurements, such as those contained in our dataset, are critical for understanding current climate, state and trends. Briefly, SWE time series from manual snow courses (see **Table A1** for uses of CanSWE), such as those contained in our dataset, have been used to quantify changes in snow water storage and SWE both regionally (e.g. Bulygina et al., 2011; Hale et al., 2023) and on a hemispheric scale (e.g. Gottlieb and Mankin, 2024) and to tie model-based trends to a ground truth (Mudryk et al., 2024). They have also been used to benchmark SWE and/or density estimates from satellite data (Luojus et al., 2021; Mortimer et al., 2020; 2022; Gao et al., 2023), reanalysis products and climate models (Mortimer et al. 2020; Elias Chereque et al., 2024; Mudryk et al., 2024), and to understand their uncertainties (Pokorny et al., 2023). Snow density information from a version of our dataset is used parameterize spatially and temporally varying snow densities applied within the satellite-based GlobSnow and SnowCCI SWE algorithms (Venäläinen et al. 2021, 2023). Automated data from the well-known and easily accessible SNOTEL network is used extensively as detailed in Fleming et al. (2023). Beyond those data, automated CanSWE data have been used to evaluate hydrological and snowpack models (e.g. Garnaud et al., 2022; Vionnet et al. 2022; Arnal et al., 2024; Marsh et al., 2024), and to validate SWE reconstructions (Sun et al. 2024).

Further, paired SWE-SD measurements are needed to train and validate snow density models used to convert the more plentiful SD observations to SWE (e.g. Sturm et al., 2010; Hill et al., 2019; Sturm and Liston, 2021; Fontrodona-Bach et al., 2023). Such models, detailed elsewhere (see Avanzi et al., 2015 and references therein; Fontrodona-Bach et al., 2023 and references therein), can fill data gaps by providing estimates of water content when only height is available but they require in situ SWE information for their formulation and evaluation, and the quality of these models is strongly tied to the representativeness of available in situ data. For example, density information from CanSWE and SNOTEL were used to train the snow density model used in NH-SWE (Fontrodona-Bach et al., 2023). However, comparisons of their model with that from Hill et al. (2019) which also included in situ data from the US Northeast suggests that the inclusion of more data (e.g. NorSWE) would likely improve NH-SWE especially over northeast US. Finally, beyond the snow science community, readily available in situ SWE, SD and snow density information is often required to parameterize physical models (e.g. Dulfer et al., 2022) or as training data for various machine learning applications (Tian et al., 2024).

8 Gaps and limitations

NorSWE was initially created to evaluate medium and coarse resolution gridded SWE products (~5–50 km) over the modern satellite period. As such, we focused on snow courses and airborne gamma SWE measurements which are more representative of the surrounding landcover than single point measurements (Meromy et al., 2013). Although automated point data over North America were later added to support specific studies (e.g. Arnal et al., 2024), this criterion excluded many networks in Europe that rely primarily on single point measurements (Haberkorn, 2019). The restricted time period (1979–2021) omits historical data collected before 1979 from NorSWE and it does not extend to present day. Older observations are available from some of the constituent datasets and can be accessed through the links in **Table 1**. Extending our dataset to present day is challenging because, for some agencies, there can be lag of a year or more between data collection and distribution. Another limitation of our dataset is the crude quality control procedure applied to the manual SWE data which relies on common SWE ranges for Canada (Braaten et al., 1998) which may not be appropriate globally. Further, the infrequent nature of snow course and airborne gamma SWE measurements makes it difficult to apply spike checks and similar procedures to identify erroneous data. Machine learning approaches could be explored to develop improved self-contained QC methods for less frequent observations.

To our knowledge, NorSWE is the most comprehensive in situ SWE dataset for North America covering the modern satellite era. The inclusion of snow surveys from Finland and Russia provides coverage of most Northern Hemisphere snow conditions but there are considerable data gaps in Europe and south-central Asia. Importantly, however, these gaps do not necessarily represent an absence of observations. We are aware of networks and sites (see for example Haberkorn et. al., 2019 for Europe, Engel et al., 2022 for the Northeastern U.S.) that were either not made available to the authors or did not meet our initial criteria of long-term snow courses (i.e. they were only operational for a short time period, provide snow depth and not SWE, or were automated point measurements outside of North America). Recent initiatives such as the WMO Joint Body for the Status of Mountain Snow Cover may uncover additional sources that could be included in a future version of NorSWE.

9 Conclusion

NorSWE is a first step towards consolidation and dissemination of in situ SWE data over the Northern Hemisphere. It combines data from nine different sources into a single NetCDF file and with a consistent quality control applied to provide comprehensive coverage of North America as well as Finland and Russia over the period 1979–2021. It includes both manual and automated observations from four different methods: snow courses, airborne gamma, snow pillows, and GMON sensors. Altogether, it includes >10 million observations from >10 thousand different locations. Precursors to this dataset have been used in climate monitoring and research, the development and evaluation of snow products, hydrological modelling, and other activities requiring snow information. NorSWE was possible thanks to the cooperation of individual agencies and to an increase in open data policies. We hope that this dataset will motivate additional agencies to engage in similar data aggregation initiatives.

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10 Dataset availability

NorSWE is distributed as a single NetCDF file following the Climate and Forecasts (CF) metadata conventions. The NetCDF is distributed as a compressed zipped file (NorSWE-NorEEN_1979-2021_v2.zip) available at https://doi.org/10.5281/zenodo.14503592.

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Appendix A: Uses of CanSWE and NorSWE v1

Table A1. Uses of in situ SWE data from CanSWE and/or NorSWE v1. See Fleming et al. 2023 for uses of SNOETL data. Uses specific to Finland and Russia not included.

Benchmarking gridded SWE products	
Mortimer et al. 2022 https://doi.org/10.1016/j.rse.2022.112988	Benchmarking EO SWE product (Snow CCI+)
Luojus et al. 2021 https://doi.org/10.1038/s41597-021-00939-2	Validation of GlobSnow v3 product and older CHSSD dataset (Brown et al., 2019) used as input to monthly bias correction.
Gao et al. 2023. https://doi.org/10.3390/rs15082065	Evaluation of snow densities derived from SMOS over Quebec, Canada.
Mortimer et al. 2024 https://doi.org/10.5194/tc-18-5619-2024	Impact of in situ method on benchmarking gridded SWE products.
Mudryk et al. 2024 https://doi.org/10.5194/egusphere-2023-3014	Benchmarking of 23 gridded products from the SnowPex+ intercomparison project.
Elias Chereque et al. 2024 https://doi.org/10.5194/tc-18-4955-2024	Evaluation of simple temperature index model with different meteorological forcings.
Sun et al. 2024 https://doi.org/10.5194/egusphere-2024-3213	Evaluation of a mountain SWE reanalysis with snow cover fraction data assimilation.
Hydrological model development and evaluation	
Garnaud et al. 2021 https://doi.org/10.3390/rs13245022	Evaluation of snow analyses in hydrological models for forecasting.
Arnal et al. 2024 https://doi.org/10.5194/hess-28-4127-2024	Seasonal hydrological forecasting.
Mai et al. 2022 https://doi.org/10.5194/hess-26-3537-2022	Evaluation and selection of reference datasets for Great Lakes Runoff Intercomparison Project.
Marsh et al. 2024 https://doi.org/10.1029/2023WR036948	Evaluation of simulated snow drifting patterns with the Canadian Hydrological Model across the Canadian cordillera and adjacent regions.
Shrestha et al. 2022 https://doi.org/10.3389/frwa.2022.801134	Evaluation of a functional hydrological model of the Great Lakes Basin.
Vionnet et al. 2022 https://doi.org/10.1029/2021WR031778	Evaluation of the ability of precipitation phase information to improve mountain snowpack prediction.
Model input, parameterization, retrieval schemes	
Fontrodona-Bach et al. 2023 https://doi.org/10.5194/essd-15-2577-2023	CanSWE (and Snotel) data used to develop snow density model to go from SD to SWE. (NH-SWE).

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Venäläinen et al. 2023 https://doi.org/10.5194/tc-17-719-2023	Interpolated snow density information from CanSWE (and others) for use in GlobSnow SWE retrieval.
Dulfer et al. 2022 https://doi.org/10.1016/j.quascirev.2022.107465	CanSWE (SD and density) used to calculate snow shielding factors.
Tian et al. 2024 https://doi.org/10.1016/j.scs.2024.105660	Training data for machine learning model to investigate the reliability of rapid public transit in the Toronto region under various climate change scenarios.
Snow status and trends	
Gottlieb and Mankin 2024 https://doi.org/10.1038/s41586-023-06794-y	Observational data (CanSWE) used to in attribution study of impact of human influence on NH snow loss.
Hale et al. 2023 https://doi.org/10.1038/s43247-023-00751-3	Changes in snow water storage. CanSWE data from 1 April used to evaluate snow storage index output from Snow Storage Index.
Other	
Pokorny et al 2023 https://doi.org/10.1061/JHYEFF.HEENG-5833	Uncertainty analysis – model uncertainties

Competing interests

The contact author has declared that none of the authors has any competing interests.

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