Global Snow Monitoring for Climate Research

Preliminary SWE validation report

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1 INTRODUCTION

1.1 Purpose of the Document

The purpose of this document is to present the validation activities carried out for the GlobSnow-2 SWE prototype product, applying the new HUT Snow emission model and the variable density consideration within the SWE retrieval.

1.2 Structure of the Document

Chapter 2 describes the processing of weather station data for SWE retrieval. Chapter 3 presents the reference data used. Chapter 4 describes the validation methods. Chapter 5 presents the assessment of the new SWE retrieval method. Chapter 6 provides conclusions of the assessment.

1.3 Acronyms

AATSR	Advanced Along-Track Scanning Radiometer (instrument of Envisat)
ATSR	Along-Track Scanning Radiometer (instrument of Envisat)
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BEAM	Basic ERS and Envisat (A)ATSR and MERIS Toolbox
CC	Cloud Cover
DDF	Design Definition File
DEM	Digital Elevation Model
ECMWF	European Centre for Middle Range Weather Forecasts
ENVEO	Environmental Earth Observation IT GmbH
ENVISAT	Environmental Satellite of ESA
EO	Earth Observation
EOS	Earth Observing System
ERS	European Remote Sensing Satellite of ESA
ESA	European Space Agency
FCDR	Fundamental Climate Data Record
FMI	Finnish Meteorological Institute
FPS	Full Product Set
FSC	Fractional Snow Cover
MODIS	Moderate Resolution Imaging Spectro-radiometer (instrument of Terra)
MERIS	Medium Resolution Imaging Spectrometer (instrument of Envisat)
NDSI	Normalized Difference Snow Index
NLR	Norwegian Linear Reflectance Algorithm
NR	Norwegian Computing Center
NRT	Near Real Time
OLCI	Ocean and Land Colour Instrument
RMS	Root Mean Square
RMSE	Root Mean Square Error
SAT	Satellite
SCA	Snow Covered Area
SCDA	SYKE's Cloud Detection Algorithm

SCE	Snow Cover Extent
SD	Snow Depth
SE	Snow Extent
SLSTR	Sea and Land Surface Temperature Radiometer
SMAC	Simplified Method for Atmospheric Correction
SoW	Statement of Work
SWE	Snow Water Equivalent
SYKE	Finnish Environment Institute
TOA	Top of Atmosphere
TS	Technical Specification

1.4 Applicable Documents

[RD-1] EOEP-DUEP-EOPS-SW-08-0006. Statement of Work - DUE *GlobSnow*.
[RD-2] GlobSnow Proposal - Technical Annex. Proposed by FMI et al., 2008.
[D 1.4] Requirement Baseline Document (RB), GlobSnow team, 2009.
[D 1.5] Ground Data Documentation (GDD), GlobSnow team, 2009.
[D 1.6] Description of the Diagnostic Data Set (DDS), GlobSnow team, 2009.
[D 1.7] Design Justification File, Version 1 (DJF), GlobSnow team, 2009.
[D 1.8] Technical Specifications (TS), GlobSnow team, 2009.
[D 1.9] Design Justification File, Version 2 (DJF), GlobSnow team, 2009.
[D 1.10]Acceptance and Test Document (ATD), GlobSnow team, 2009.
[D 1.11]Design Definition File (DDF), GlobSnow team, 2009.
[D 1.12]Qualification Review Report (QRR), GlobSnow team, 2009.
[D 1.13]Prototype Validation and Assessment Report (PVAR), GlobSnow team, 2009.
[D 2.3] Acceptance Review Report (ARR), GlobSnow team, 2010.
[D 2.5] Design Justification File 3 (DJF-v3), GlobSnow team 2011
[D 2.6] Production and Validation Report (PVR), GlobSnow team, 2011.
[D 3.1] Service Evolution Report (SER) v1, GlobSnow team, 2011.
[D 3.2] Service Evolution Report (SER-v2) v2, GlobSnow team, 2011.
[D 3.5] Final Report (FR), GlobSnow team, 2011.

[RD-3] Statement of Work for GlobSnow-2 EOEP-STRI-EOPS-SW-11-0003, issue 1 revision 0.
[RD-4] GlobSnow-2 Consolidated Proposal. Proposed by FMI et al., 2012.

[GS2 DEL-6] Algorithm Theoretical Basis Document for SWE

2 SNOW WATER EQUIVALENT ALGORITHM

2.1 General overview

The GlobSnow SWE algorithm combines information from satellite based microwave radiometer and ground based weather station snow depth measurements into hemispherical scale SWE estimates accompanied by uncertainty estimates for each calculation element. The algorithm is described in detail in GS-2 DEL-6 “Algorithm Theoretical Basis Document for SWE”. However, the processing of weather station data is explained in this section as it’s not part of the retrieval algorithm.

2.2 Weather station data

Four different sources for weather station snow depth data are used. Synoptic weather station data from ECMWF for both Eurasia and North America has been extended with additional datasets for Russian, North American and Canadan sources.

2.2.1 Data from different sources

Synoptic weather station data is downloaded from the operational archive of the ECMWF. The data is downloaded using mars scripts in ECMWF BUFR format. It covers the Northern hemisphere from 1979 to 2012. Total snow depth is extracted from the BUFR files in to ascii files which are then formatted into CSV format. The northern hemisphere CSV files are then cut into smaller regions, namely North America and Eurasia.

ECMWF dataset for Eurasia in version 1.3 includes 5638 stations , showin in Figure 2.2.1. New version of Eurasia dataset that extends the geographical domain to longitude -15 in west and to latitude 20 in south includes 7248 stations, shown in Figure 2.2.2. North America dataset from ECMWF includes 955 stations shown in Figure 2.2.3.

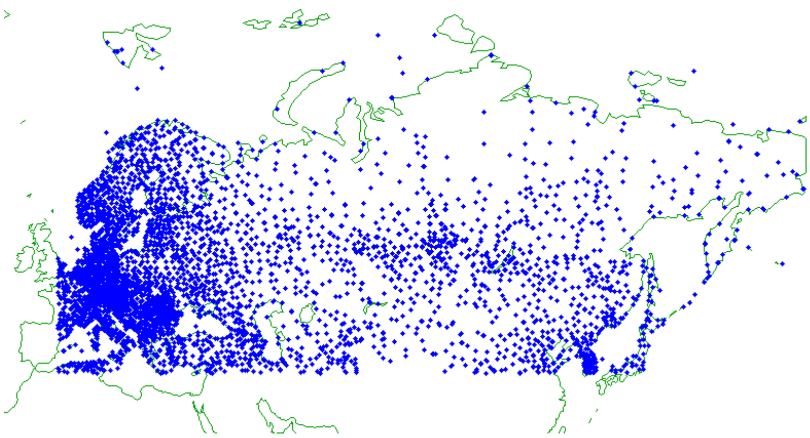

Figure 2.2.1, ECMWF synoptic weather station data over Eurasia v. 1.3.

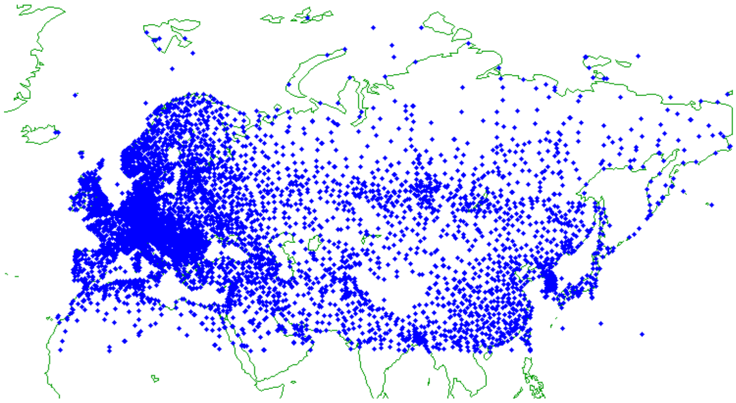

Figure 2.2.2, ECMWF data for Eurasia new, extended spatial domain.

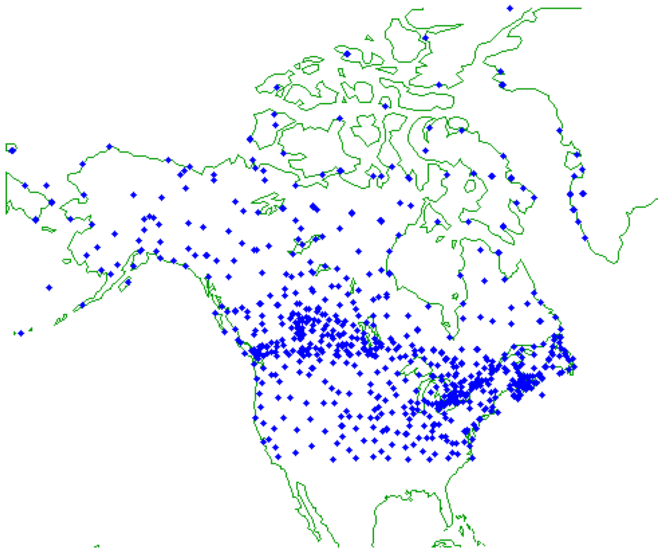

Figure 2.2.3, ECMWF data for North America.

Bulygina et al. ('Description of data set "Snow cover characteristics from Russian meteorological stations and from some meteorological stations over the former USSR territory"' http://meteo.ru/english/climate/descrip2.htm) was used as an additional dataset for Russian region. It spans years from 1978 to 2008 and includes 231 weather stations for that period. The locations of the additional Russian stations are shown in Figure 2.2.4.

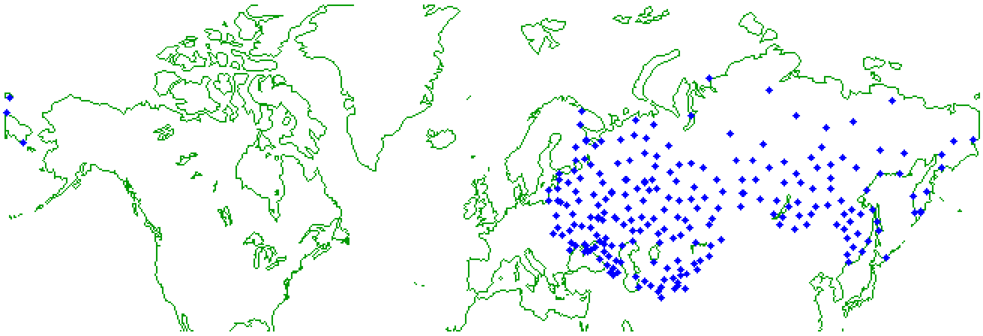

Figure 2.2.4, Russian meteorological stations

Mote et al. ("Daily Gridded North American Snow, Temperature and Precipitation Dataset" http://climate.rutgers.edu/snowcover/) was used as an additional dataset for North America. It covers years from 1952 to 2009 (only years from 1979 to 2009 were used) and includes 14 617 stations spanning years 1979-2009, shown in Figure 2.2.5.

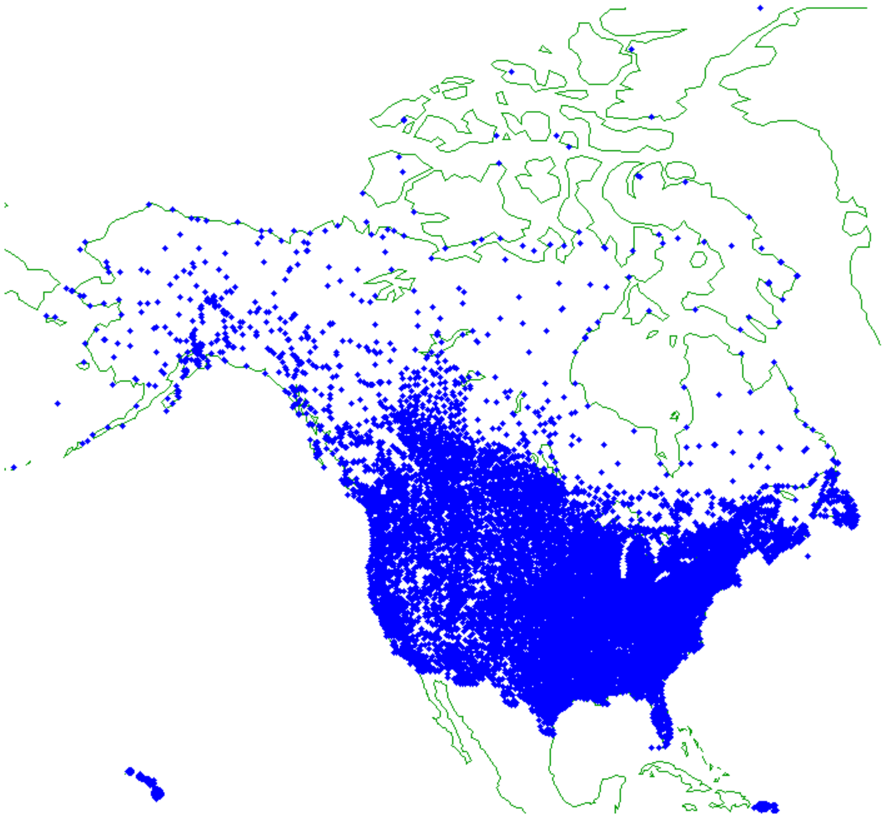

Figure 2.2.5, North America data from (Dave Robinson and Thomas Mote)

Updated version of Canadian Snow Data CD-ROM from Meteorological Service of Canada ("Update of Daily Snow Depth Database on Snow CD",
ftp://ccrp.tor.ec.gc.ca/pub/RBrown/Cdn%20Daily%20Snow%20Depth%20Data/, original MSC, 2000: Canadian Snow Data CD-ROM. CRYSYS Project, Climate Processes and Earth Observation Division, Meteorological Service of Canada, Downsview, Ontario, January, 2000 (CD image file available for downloading from: http://www.socc.ca –

data, search data, snow datasets) and Brown, R.D. and R.O. Braaten, 1998: Spatial and temporal variability of Canadian monthly snow depths, 1946-1995. Atmosphere-Ocean, 36: 37-45.) was used as an additional source of data for Canada. It covers years from 1971 to 2003 (only years from 1979 to 2003 were used) and includes 4 700 stations for the period 1979-2003, shown in Figure 2.2.5.

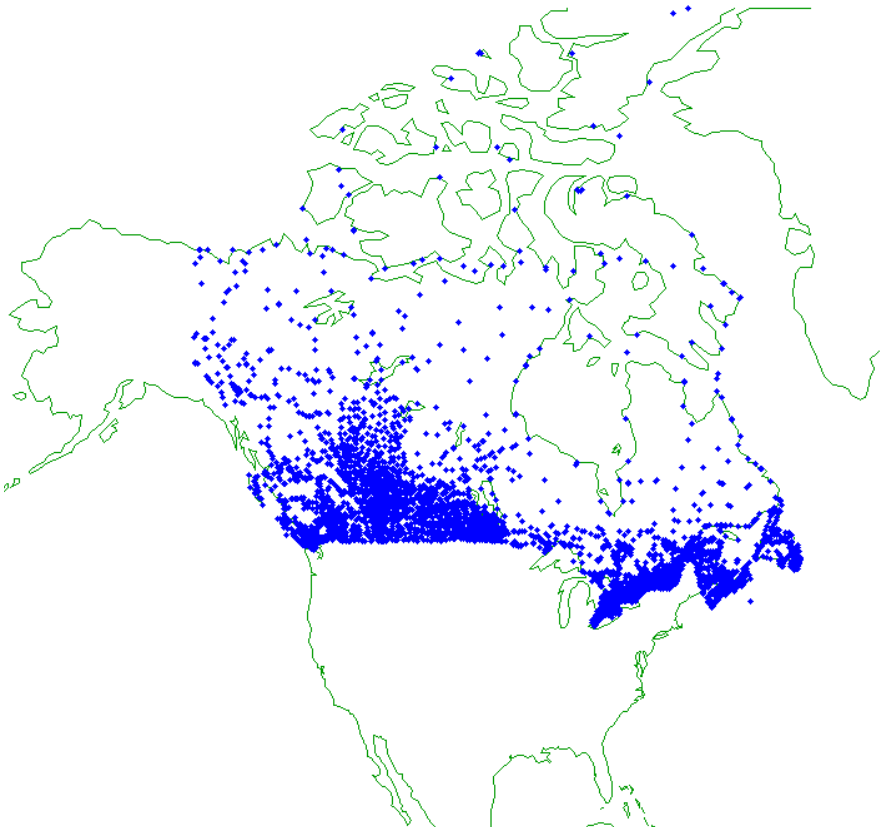

Figure 2.2.6, Canadian stations

2.2.2 Combining and filtering of weather station data

Synop data from different sources are combined and filtered from duplicate observations (difference in latitude and longitude less than 0.02 degrees and difference in snow depth less than one centimeter). Then the data set is filtered from erroneus large snow depth values (over 300 centimeters). A median filtering is applied by removing values that differ more than 50 cm from the median of 11 days' time frame for each station. After that only stations with at least 20 measurements for at least 5 separate years are kept. Then stations with unusually deep snow conditions (mean of March over 150 cm) are found and filtered out if the deep snow conditions have occurred at least 50% of the years that the station has had at least 20 measurements. Lastly snow depth values more than 200 centimeters are filtered out. Flowchart of this routine is presented in Figure 2.2.7.

Combined and filtered dataset for the GlobSnow SWE v1.3 dataset contains data from 4 349 stations in Eurasia (Figure 2.2.8) and 10 550 stations in North America (Figure 2.2.9). The new version of the dataset contains 4 975 stations in Eurasia (Figure 2.2.10) and 10 648 stations in North America (Figure 2.2.11).

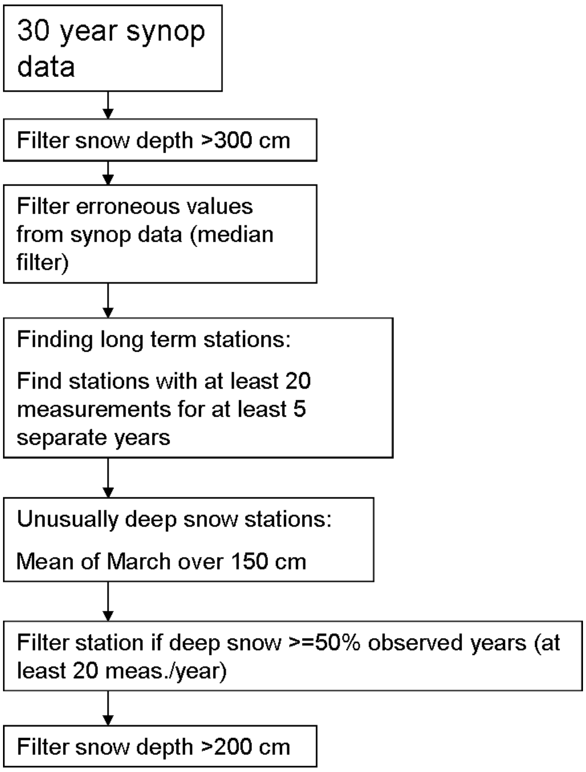

Figure 2.2.7, Flowchart of the filtering routine for weather station data.

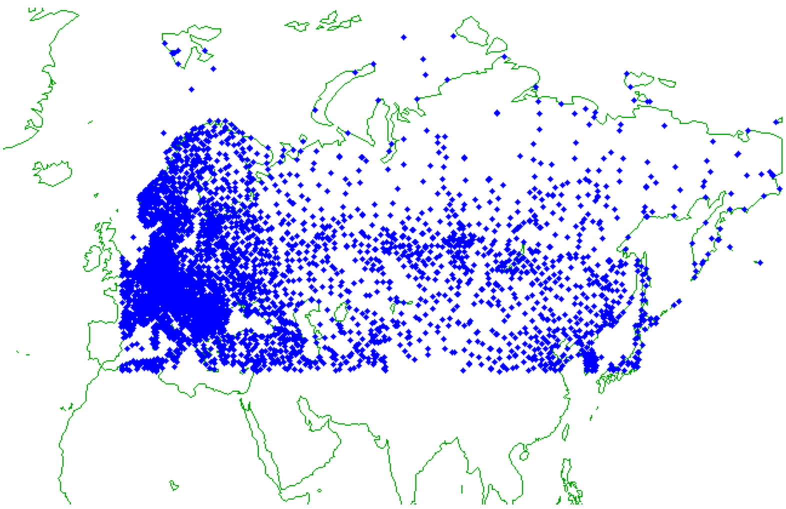

Figure 2.2.8, Eurasia stations combined and filtered, version 1.3, 4 349 stations

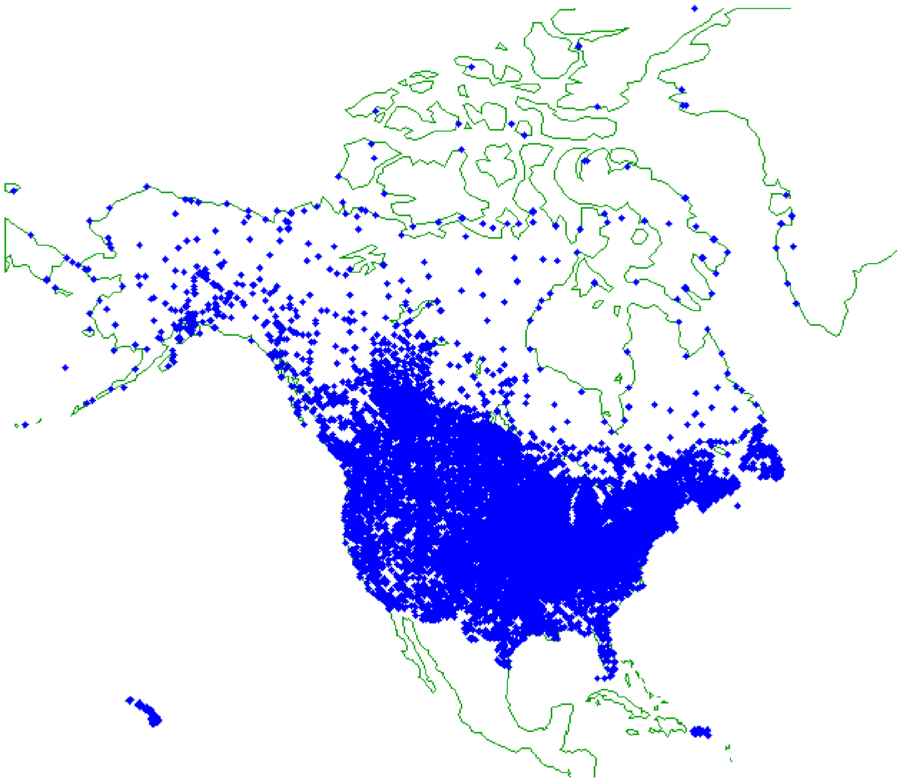

Figure 2.2.9, North America stations combined and filtered, version 1.3, 10 550 stations

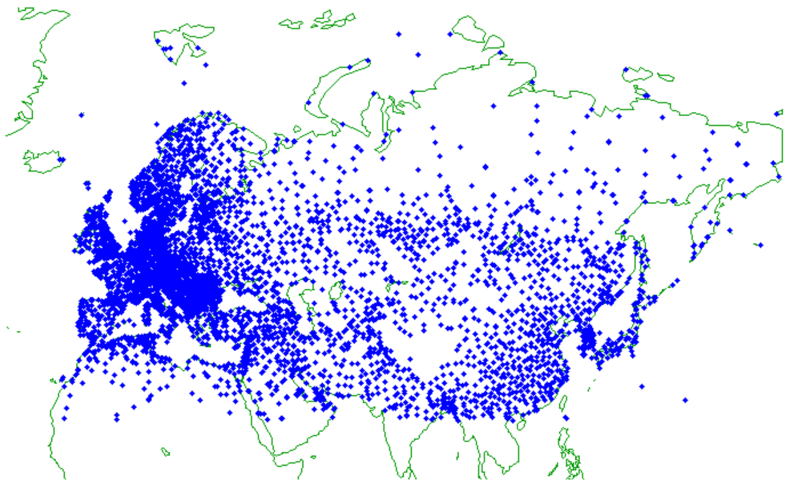

Figure 2.2.10, Eurasia stations combined and filtered, new version, 4 975 stations

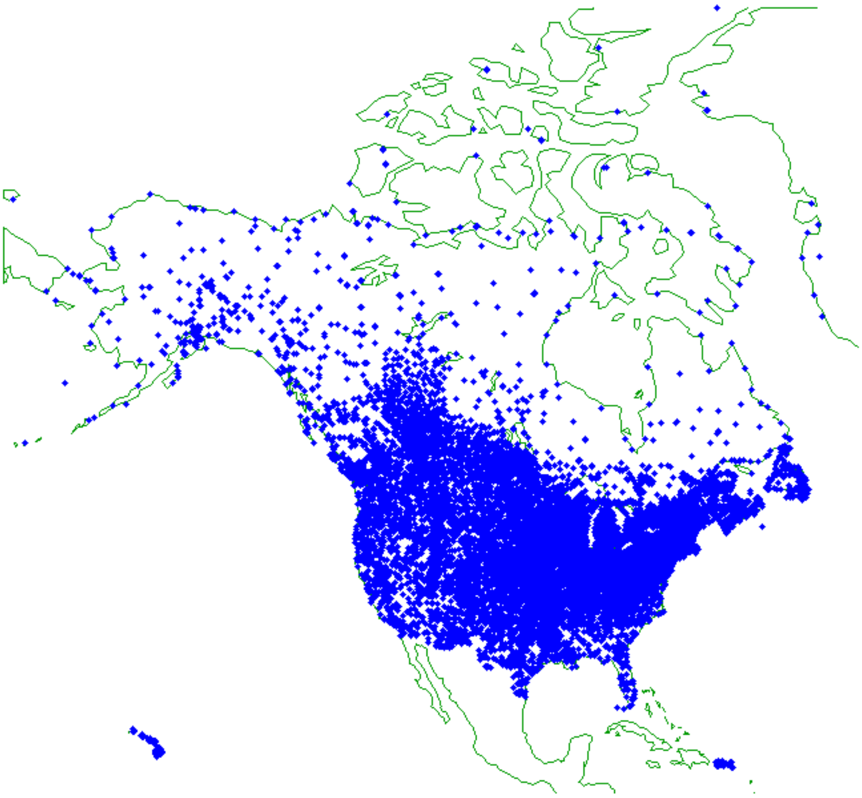

Figure 2.2.11, North America stations combined and filtered, new version, 10 648 stations

2.3 Additional information on weather station data

Additional weather station data for Canada was added to improve the coverage for 1979 to 2003. The greatest influence were seen in the early 1980's and especially for the winters 1980 and 1981. Figure 2.2.12 shows added Canadian observations from January to March for the winter 1980 and Figure 2.2.13 for the winter 1981.

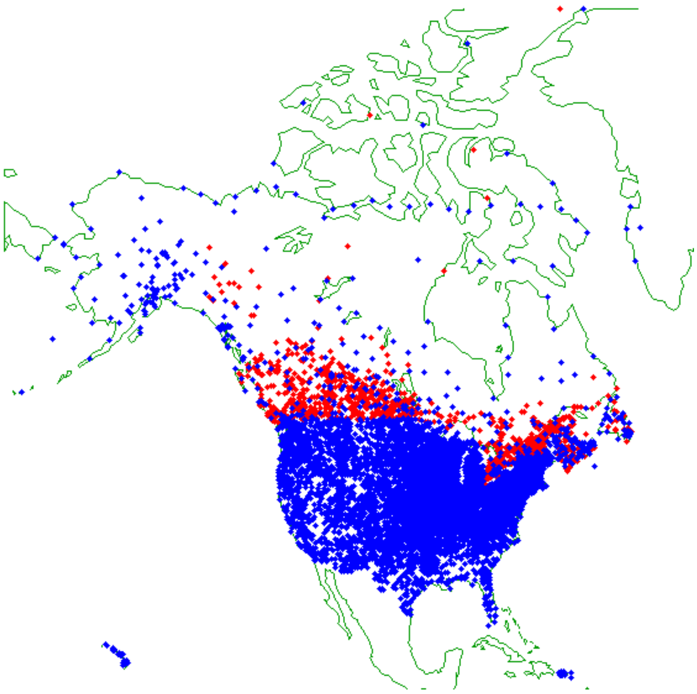

Figure 2.2.12, Added Canadian observations for Jan-Mar 1980 (shown in red)

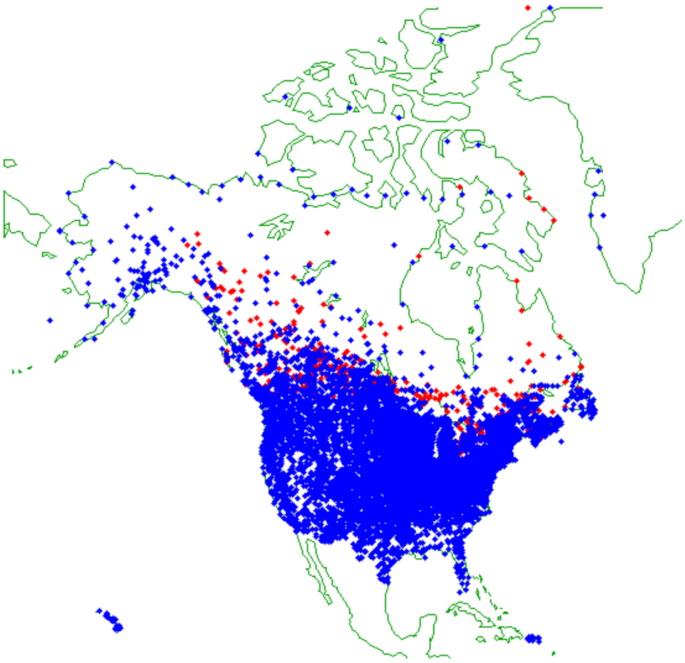

Figure 2.2.13, Added Canadian observations for Jan-Mar 1981 (shown in red)

3 VALIDATION DATA

3.1 INTAS SCCONE data from Russia

The former Soviet Union operated an extensive network of snow observation sites, covering most of the Eurasian landmass. The snow transect data used for SWE validation are available via the website of All-Russian Research Institute of Hydrometeorological Information - World Data Center (RIHMI-WDC) on the following website: (http://meteo.ru/english/climate/snow1.php). The data has been freely available for all interested users, containing data from 517 snow transect locations shown in Figure 3.1.1, spanning year 1966 to 2009. The snow transect sites are concentrated strongly south of the 70°N parallel. Distances between individual snow survey sites can be up to hundreds of kilometres. Data from snow survey sites are typically available several times per month, depending on the year and site.

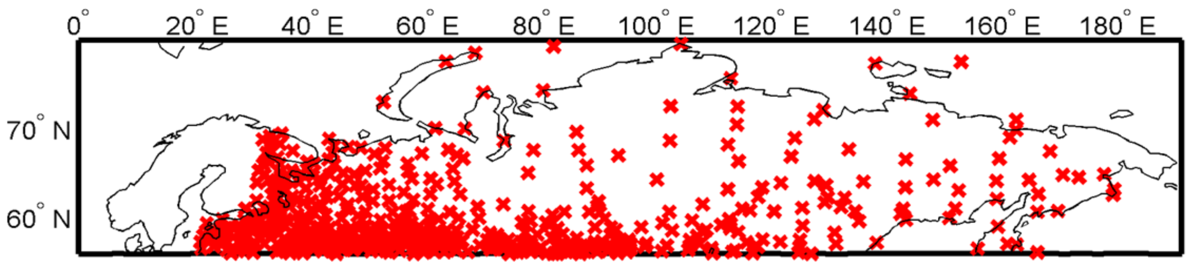

Figure 3.1.1, Locations of the Russian snow transect sites

The snow transect sites consist of averages of snow path observations on depth, density, SWE and general water amount. The snow survey data is available in ASCII files. Data for each site/observation consists of

- WMO index
- Year, Month, Day of observations
- Path Type (field, forest or ravine)
- Snow cover depth average, Snow density, SWE (derived)
- General Water amount
- Flag for snow cover depth and density

There are 3 types of snow transects depending on the landscape. In forests, the length of snow path is 500 m. Snow depth is measured every 10 m, and snow density every 100 m. In forested regions with openings the length of snow path is 1000m. In steppes, the length of snow path is 2000m. In these snow paths, snow depth is measured every 20 m, and snow density every 200 m (in some cases every 100m). Obtained snow depths and snow densities are then averaged along the path and snow water equivalent is calculated from these.

3.2 Finnish snow course data

Ground truth data feasible for validation of snow water equivalent retrievals is relatively difficult to obtain. Snow depth and SWE typically vary relatively much in space and time, so single point observations are typically not valid for coarse resolution satellite instruments. The observations should be conducted over an area corresponding to the pixel size of the applied satellite sensor, and the timing should match the satellite overpass at least so that no considerably changes in snow cover do not occur. The snow course network governed by the Finnish Environment Institute (SYKE) has a heritage from the beginning of 20th century. The network consists of ~160 courses which are monthly visited. A snow course is a 2-4km long transect going through different landscapes; the observer registers the snow information typically at 80 locations along the transect. The observations include snow depth (SD, measured with a stick), snow density (measured with a snow tube) and fraction (%) of snow-free ground (visually estimated for an area within 25m radius from the observer's location). Hence, FSC=100% - Fraction of snow-free ground.

Proper *in-situ* observations are particularly difficult to have when only trace amounts of snow are present. In a scale of a pixel, these easily remain unnoticed by human observer if only several samples are taken at ground-level. The route of each snow course by SYKE is individually planned so that it should represent the locality of few square kilometers. The trail goes through different landscapes in order to catch the differences in snow conditions; the information of prevailing landscape is assigned to each measurement location. The landscapes are: pine forest, spruce forest, mixed forest, broad-leaf forest, forest opening and open bog. The map of the Finnish snow courses and the trail of an arbitrary snow course plotted over a digital photograph are shown in Figure 3.2.1.

In the validation work within GlobSnow-2, a snow course SWE value refers to the average value of all SWE observations along that transect.

Figure 3.2.1, Left: Snow courses and weather stations of Finland. Right: the route of a typical snow course, visiting different landscapes within the ground track.

Snow courses are visited once a month, the typical observation day is 16th of each month during the snow season (November – May). The currently available snow course dataset spanned the years 2006-2011, while the SWE DDS available for validations spanned 2003-2008, the overlapping years of 2006, 2007 and 2008 were utilized for the assessment of retrieval accuracy.

3.3 Canadian reference data

Canada is a relatively large country with a sparse network of snow measurement sites composed mainly of automated single point snow depth measurements. A lack of conventional measurements is a particular problem across vast northern regions of the country (northern boreal forest and subarctic tundra). Care must be taken when using station snow depth measurements for validating satellite scale SWE retrievals because measurement site locations may not represent the regional land cover. This is a particular problem for forested regions because station locations are typically adjacent to airports in large open areas (Derksen et al., 2003). In the context of satellite or model derived data, a single point ground measurement is not appropriate for validating a SWE estimate for a grid cell with 25 km dimensions. In order to evaluate coarse resolution satellite retrievals and climate model simulations, Environment Canada has augmented the sparse national weather station network with field measurement campaigns designed to provide regionally representative snow measurements across data poor regions. In addition, the Boreal Ecosystem Monitoring and Modelling Sites (BERMS) is a long term experiment with a monitoring component that provides consistent snow measurements for an intensively observed 'super-site' in the boreal forest (1997 onwards). Collectively, the field campaign measurements and observations from BERMS sites are suitable datasets for GlobSnow SWE validation.

Measurements of snow physical properties were made at a network of sites across northern Manitoba during late winter 2004 through 2007, and the Northwest Territories from 2005 through 2008. The timing of sampling varied from year to year, but occurred in all cases near peak SWE but before any spring melt events. Site locations were selected to capture the transition from closed to open canopy forest. Some open tundra sites were also sampled. Snow cores were taken for direct measurement of SWE and bulk density. Snow depth measurements were made to characterize local variability. A snow-pit was excavated at each site for snowpack stratigraphy measurements including density profiles, the identification of layering, and mean grain size for each layer. When possible, lakes adjacent to the terrestrial sites were also sampled following the same protocol. SWE values at these sites ranged from 100 to 300 mm. These measurements are described further in Derksen (2008).

Intensive tundra snow surveys (snow water equivalent, depth, density, and stratigraphy) were performed in the Daring-Exeter-Yamba watershed of the Upper Coppermine River Basin in the Northwest Territories Canada at the timing of peak SWE, April 2004 through 2007. Because of a high degree of sub-grid heterogeneity in tundra snow distribution due to topographic controls, a stratified sampling approach was utilized to determine slope, aspect, and land cover controls on snow properties. The measurements were then scaled up to the resolution of satellite passive microwave measurements using landscape weighted means. During April 2007, a coordinated series of snow measurements were made across the Northwest Territories and Nunavut, Canada during a snowmobile traverse from Fairbanks, Alaska to Baker Lake, Nunavut (Derksen et al., 2009). The purpose of the measurements was to document the general nature of the snowpack across this region for the evaluation of satellite and model derived estimates of snow water equivalent (SWE). Systematic snow measurements at the regional scale have not been previously collected across this region. Measurements were made at 45 locations. The west-to-east route included long stretches on frozen lakes, areas of rolling tundra, and areas of rocky, moraine-covered tundra. The most intensive period of sampling occurred during the Daring Lake, Northwest Territories to Baker Lake, Nunavut portion of the traverse (16 to 26 April, 2007). Sample sites were located at least every 1 degree of longitude. At these sites, we measured snow depth, density, snow water equivalent (SWE), stratigraphy, and grain size. The goal was to make measurements at paired sites, one on tundra (land) and one on ice (lake or river ice depending on what was available).

The Boreal Ecosystem Research and Monitoring Sites (BERMS) program is a joint initiative of Canadian government agencies, universities and other research partners. The main objective is to study the role that the Canadian boreal forest plays in the global carbon budget in response to climate change. Flux tower measurements (from the surface to above the canopy) are available for sites representative of old growth boreal forest (aspen, black spruce, jack pine), a chrono-sequence of harvested sites (1975, 1994, 2002), fire disturbed stands (1977, 1989, 1998), and a boreal fen. At each site, snow depth is measured at 30 minute intervals with SR-50 sonic snow depth gauges. Time series range from five to eleven complete snow seasons. In the mature stands, measurements are available both under the canopy and in clearings. Bi-weekly snow course measurements (direct measurements of depth, density and SWE) are also available both at the BERMS sites (Figure 2.6), and similar land cover types in the same region. Bi-weekly snow surveys at open prairie sites south of the boreal forest are also available for three seasons. These prairie measurements take into account different agricultural land use practises (i.e. fallow vs. stubble fields) through multiple sampling transects.

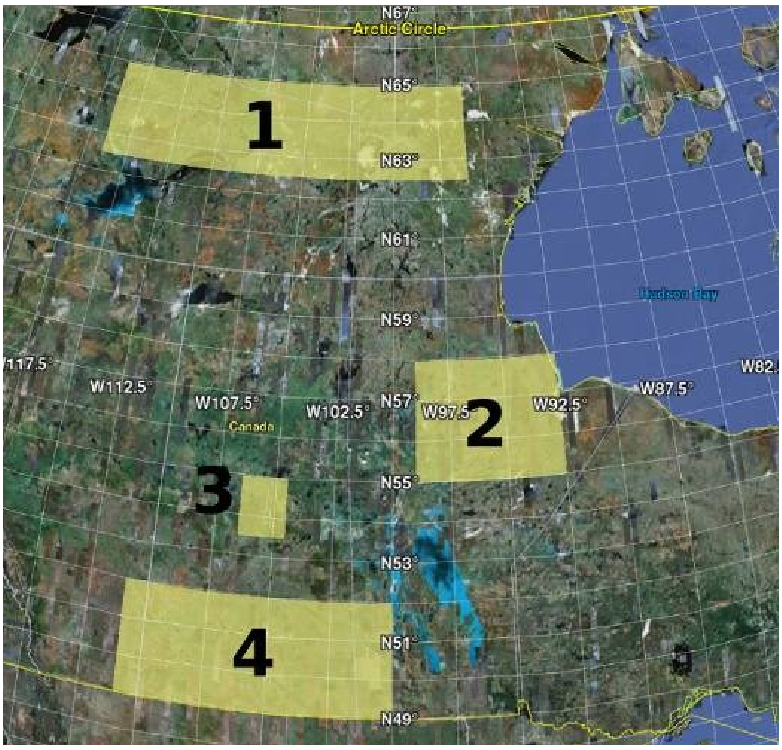

Figure 3.3.1. Regions for land cover specific algorithm evaluation. 1: tundra; 2: northern boreal; 3: southern boreal and BERMS sites; 4: prairie.

4 VALIDATION METHODS

4.1 Validation using snow transect data of Finland and Russia

Evaluation of coarse resolution SWE retrieval is typically carried out using distributed data collected from region or a snow transect representing the snow conditions typical of a footprint of a passive microwave sensor (in the range of ten kilometers). For this reason, the most useful reference data are the snow transect data acquired from Russia and the snow course data from Finland, both described in Chapter 3.

The snow transect and snow course data are considered ground truth for the assessment and the satellite based retrievals are compared with them. Due to a very large datasets, common statistical characteristics, such as root-mean-squared (RMS)-error, bias and correlation coefficient are determined to give indication of the retrieval accuracy. For all evaluations comparing two different methods, only the exact same samples are used in assessments.

4.2 Validation using Canadian data

Evaluations of satellite passive microwave SWE retrievals with single point measurements (i.e. from climate stations) or a small number of sub-grid measurements can be problematic because there is a clear disconnect between the scale of satellite passive microwave measurements, at tens of kilometres, and the scale of snow cover variability (meters to hundreds of meters depending on land cover). Regardless, it is necessary to perform this type of assessment because of the effort required to complete thorough sub-grid sampling. Assuming appropriate site selection, this can be a meaningful exercise (for example, Derksen, 2008). Canadian datasets available for this level of evaluation for GlobSnow are field measurements from Environment Canada field campaigns and snow surveys as described in Section 3.3 (the same datasets used in previous evaluations of GlobSnow Full Product Suites). Except for maritime snow, these measurements cover the primary snow classes for which GlobSnow retrievals are produced (prairie, taiga, tundra, but not alpine). While care was taken to ensure these measurements were spatially representative, they provide only a single snapshot in time. Because some of these campaign measurements were made at a network of sites across the taiga to tundra transition in northern Manitoba (2004 through 2007), and the Northwest Territories (2005 through 2008) these are also suitable datasets for assessing the changes in snow cover properties than can occur across changing land cover. Validation over the complete seasonal cycle is conducted using automated snow depth measurements from the network of Boreal Ecosystem Monitoring and Modelling Sites in central Saskatchewan.

5 VALIDATION RESULTS

5.1 Validation results using INTAS SCCONE data from Russia

The data from the Russian snow transects were used to investigate the performance of the new SWE retrieval method utilizing multi-layer snow emission model and spatially and temporally varying snow density. The retrieval results acquired using the new method are compared with the retrieval performance from the baseline GlobSnow-1 SWE dataset v1.3 for different geographical, climatological and temporal domains.

5.1.1 Comparison of the complete dataset for years 2003 - 2008

The SWE retrieval accuracy was assessed for the available new variable density dataset covering years 2003 to 2008. The retrieval performance, determined using the Russian snow transect data, was compared with the retrieval performance of the baseline GlobSnow v1.3 SWE data for the same exact time period and exact same reference data (only reference data available for both datasets were used). The overall retrieval performance is shown in Figure 5.1.1.

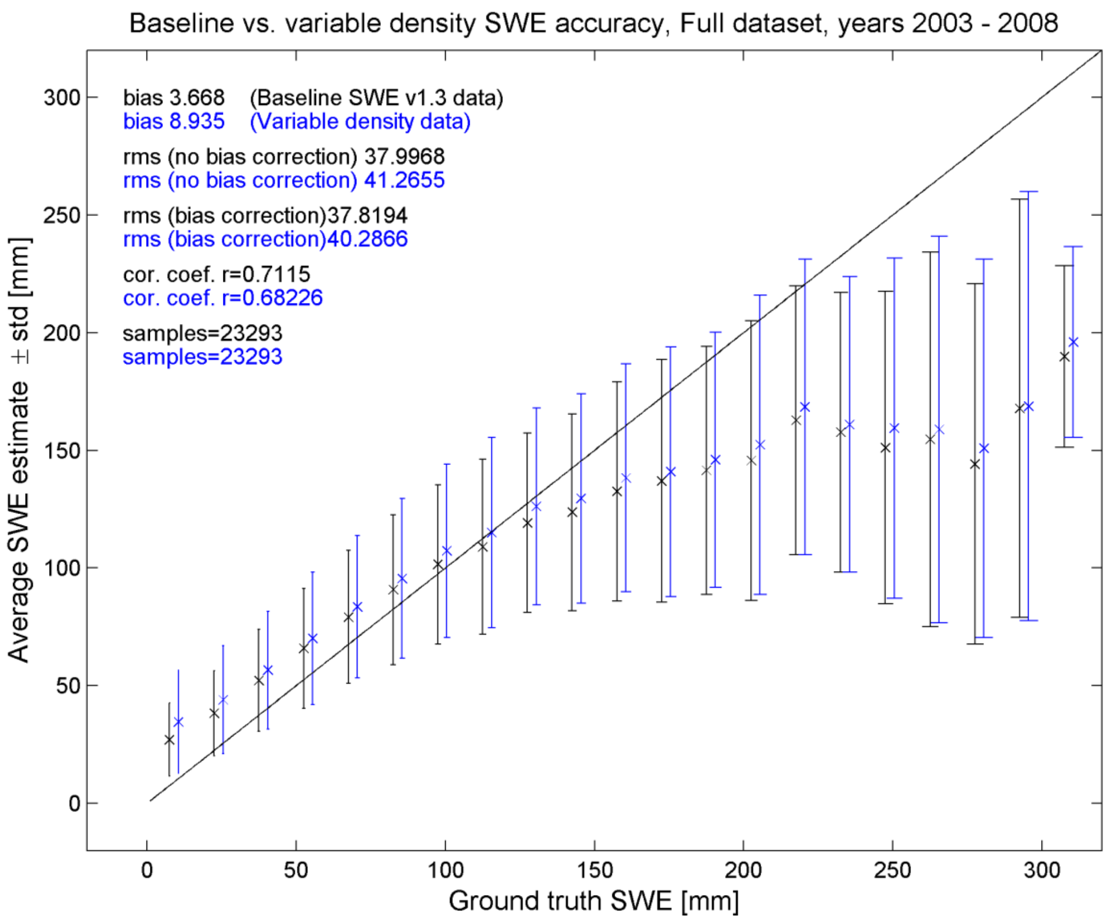

Figure 5.1.1, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets acquired using Russian snow transect data. Black color shows the results for baseline v1.3 method, blue color used for the variable density method.

The evaluation using the full dataset from 2003 to 2008, including data from all seasons (fall, winter and spring) and all climatological regions shows inferior retrieval accuracy for the variable density dataset. The RMS-error for the baseline dataset is 38,0mm while for the variable density dataset the RMS-error is 41,3mm. The bias for the baseline dataset is 3,7mm and for the variable density dataset it is 8,9mm. Both datasets had 23293 samples that were evaluated. It can be observed from Figure 5.1.1 that in general the variable density retrieval seems to produce higher SWE estimates than the previous baseline version. This is seen throughout the retrieval spectrum from low SWE estimates to high ones. The change in retrieval accuracy for independent samples is show in in Figure 5.1.2.

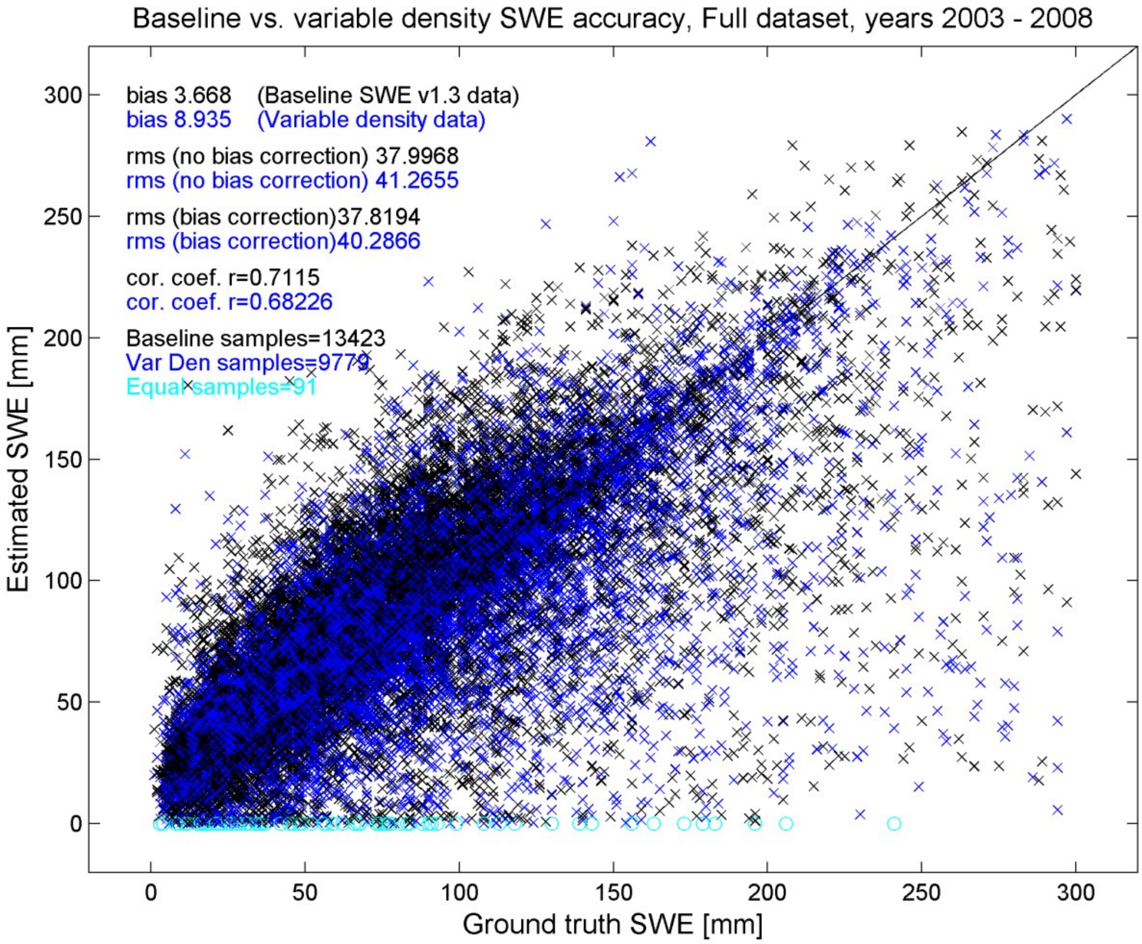

Figure 5.1.2, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets acquired using Russian snow transect data. The black points show the samples that were more accurate with the baseline v1.3 method, blue points show the samples that were more accurate with the variable density method. The baseline method results in more accurate retrieval in 13423 cases and the variable density approach resulted in more accurate retrieval in 9779 cases. 91 cases had equal accuracy for both methods.

Overall it seems that the GlobSnow-1 v1.3 SWE dataset without the variable density consideration produces more accurate SWE estimates when observed over a period of six years using Russian snow transect data. The retrieval performance for different climatological domains is investigated in the following section.

5.1.2 Different climatological domains

Investigation of the SWE retrieval for different climatological domains was carried out by selecting the SWE data from the specific domain and assessing the performance for both retrieval methodologies (baseline and variable density) using only the selected samples.

The evaluations for Russia show that there are significant differences on retrieval performance across the different domains. The Table 5.1.1 lists the retrieval performance for the baseline dataset and the variable density dataset for different climatological domains.

Table 5.1.1 SWE retrieval performance for different climatological domains within Russia. The results for the baseline dataset are shown using normal font, bold fonts denote the results from the variable density data.

	RMS-error [mm]	Bias [mm]	Corr.coeff	Samples
All	38.00 / **41.27**	3.67 / **8.94**	0.712 / **0.682**	23293
Tundra	38.27 / **42.97**	8.01 / **15.40**	0.732 / **0.703**	4337
Taiga	38.68 / **41.87**	5.38 / **9.62**	0.740 / **0.708**	8804
Prairie	28.37 / **33.60**	1.41 / **9.76**	0.763 / **0.732**	2984
Other domains	40.41 / **42.34**	-0.11 / **3.85**	0.635 / **0.620**	7168

The evaluation using the full dataset from 2003 to 2008, including data from all seasons, divided into separate climatological regions shows inferior retrieval accuracy for the variable density dataset across all domains. The RMS-error for the baseline dataset is 1.9mm - 5.6mm superior to that observed for the variable density data. The bias and correlation coefficients for the baseline dataset are also superior to those of the variable density dataset on all domains. The amount of samples indicates that the most prevalent climatological domain is Taiga over Russia. The results for Taiga are shown on Figure 5.1.3. Other domains include, water, maritime, ephemeral, alpine and ice, the domains are according to the classification by (Sturm et al. 1995).

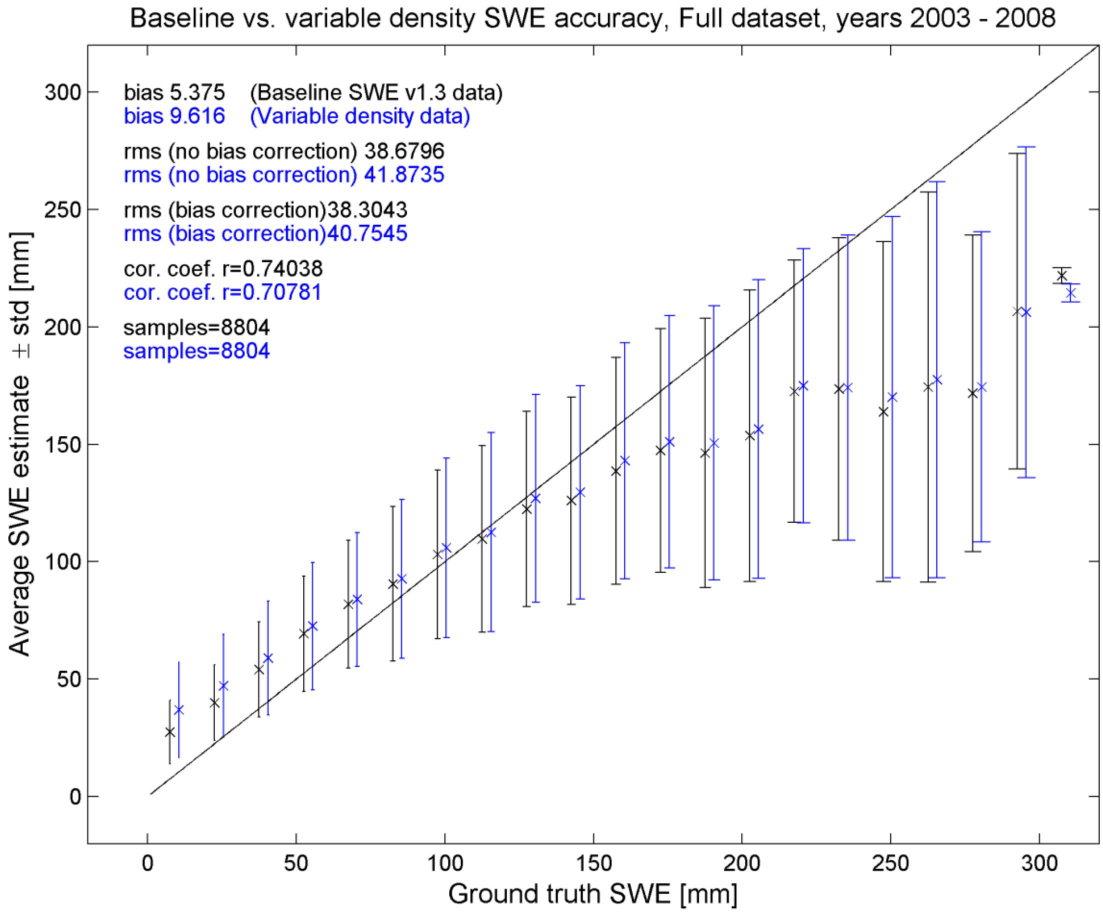

Figure 5.1.3, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for Taiga, acquired using Russian snow transect data. Black color shows the results for baseline v1.3 method, blue color used for the variable density method.

Overall it appears that the GlobSnow-1 v1.3 SWE product without the variable density consideration produces more accurate SWE estimates when observed over a period of six years using Russian snow transect data. The retrieval performance for different geographical regions is investigated in the following section.

5.1.3 Different geographical regions within Russia

Investigation of the SWE retrieval for different geographical regions was carried out by selecting the SWE data from the specific region and assessing the performance for both retrieval methodologies (baseline and variable density) using only the selected samples.

The evaluations for Russia show that there are significant differences on retrieval performance across different regions. The Table 5.1.2 lists the retrieval performance for the baseline dataset and the variable density dataset for the different geographical regions.

Table 5.1.2 SWE retrieval performance for different regions within Russia

	latitudes [°]	longitudes [°]	RMS-error [mm]	Bias [mm]	Corr.coeff	Samples
Region 1	55-75	20-80	37.13 / **40.11**	3.84 / **7.38**	0.710 / **0.688**	9025
Region 2	55-75	80-120	41.93 / **43.64**	5.66 / **8.54**	0.727 / **0.719**	3547
Region 3	55-75	120-180	37.50 / **38.04**	4.63 / **7.11**	0.499 / **0.510**	1969
Region 4	40-55	20-80	29.19 / **34.07**	3.18 / **13.6**	0.697 / **0.703**	3841
Region 5	40-55	80-120	38.23 / **45.76**	5.82 / **16.9**	0.624 / **0.531**	3188
Region 6	40-55	120-180	48.98 / **49.76**	-5.28 / **-4.35**	0.591 / **0.572**	1979

The evaluation using the full dataset from 2003 to 2008, including data from all seasons, all climatological domains, divided into separate geographical regions shows inferior retrieval accuracy for the variable density dataset across all regions. The RMS-error for the baseline dataset is 0.5mm - 7.5mm superior to that observed for the variable density data. The bias and correlation coefficients for the baseline dataset are also superior to those of the variable density dataset on all regions. The amount of samples indicates that the bulk of reference data is found near the European border at longitudes between 20°-80° East. The results for the region 5 (latitudes 40°-55° North and longitudes 80°-120° East) that shows the biggest difference between the two retrieval methods, are shown on Figure 5.1.4.

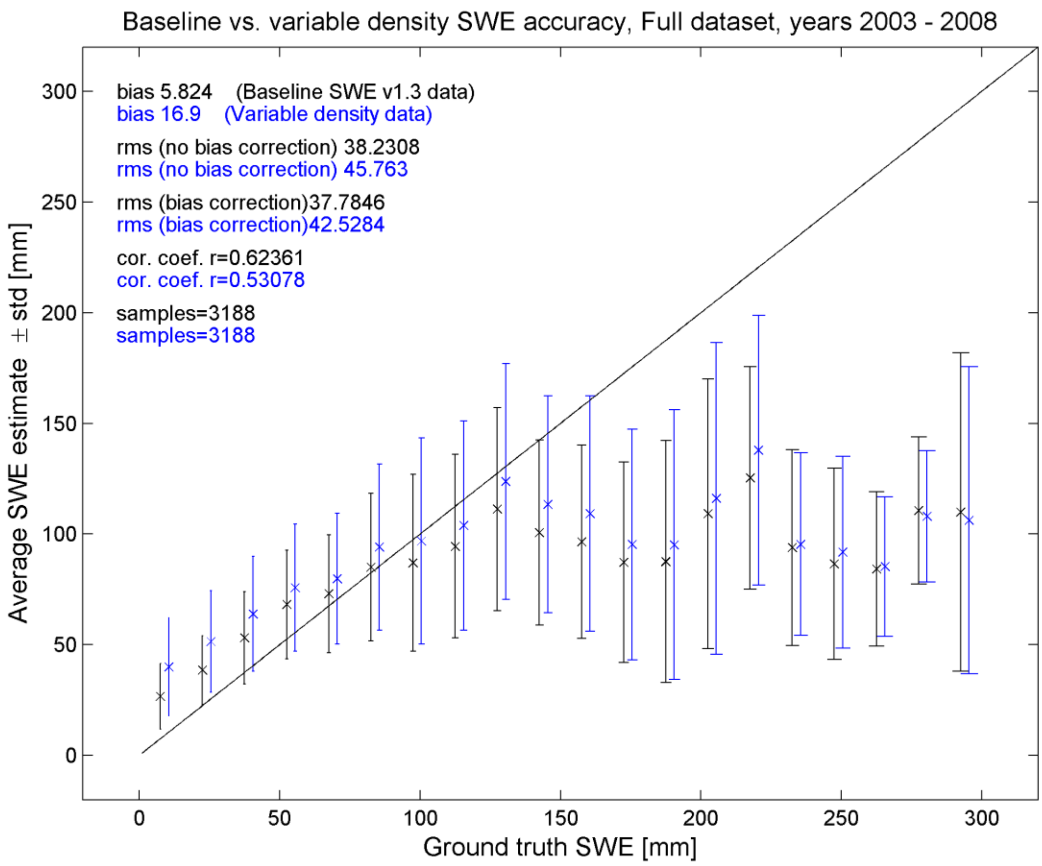

Figure 5.1.4, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for region 5 (latitudes 40°-55° North and longitudes 80°-120° East), acquired using Russian snow transect data. Black color shows the results for baseline v1.3 method, blue color used for the variable density method.

5.1.4 Different temporal domains of SWE data

Investigation of the SWE retrieval for different temporal domains was carried out by selecting the SWE data from the specific time span and assessing the performance for both retrieval methodologies (baseline and variable density) using only the selected samples.

The evaluations for different seasons are listed on Table 5.1.3. The evaluations for different years are listed on Table 5.1.4.

Table 5.1.3 SWE retrieval performance for different seasons

	RMS-error [mm]	Bias [mm]	Corr.coeff	Samples
All seasons	38.00 / **41.27**	3.67 / **8.94**	0.712 / **0.682**	23293
Sept.-December	25.53 / **28.13**	11.82 / **12.33**	0.710 / **0.643**	4438
January-March	35.54 / **39.84**	7.78 / **14.35**	0.73768/ **0.702**	15358
April, May	56.93 / **57.98**	-24.68 / **-19.14**	0.60457/ **0.578**	3496

The results for different seasons show that the retrieval accuracy is highest during the Fall season (between September and December) and the baseline v1.3 SWE dataset is more accurate than the variable density dataset. During winter and early spring the retrieval accuracy is lower than that of the Fall winter and again the variable density retrieval is inferior when compared with the baseline v1.3 SWE data. The late spring show relatively similar retrieval performance in regard to RMS-error, but the bias is clearly lower (better) for the variable density dataset. The key difference between the two methodologies is the increasing snow density of within the variable density method, which has the highest effect during late spring. This result suggest that there is some merit in the variable density consideration in late spring, but the low amount of data and probably problems with some now classes show a predominantly negative result in SWE retrieval accuracy for the variable density method.

The retrieval performance for late spring (April and May) is shown in Figure 5.1.5.

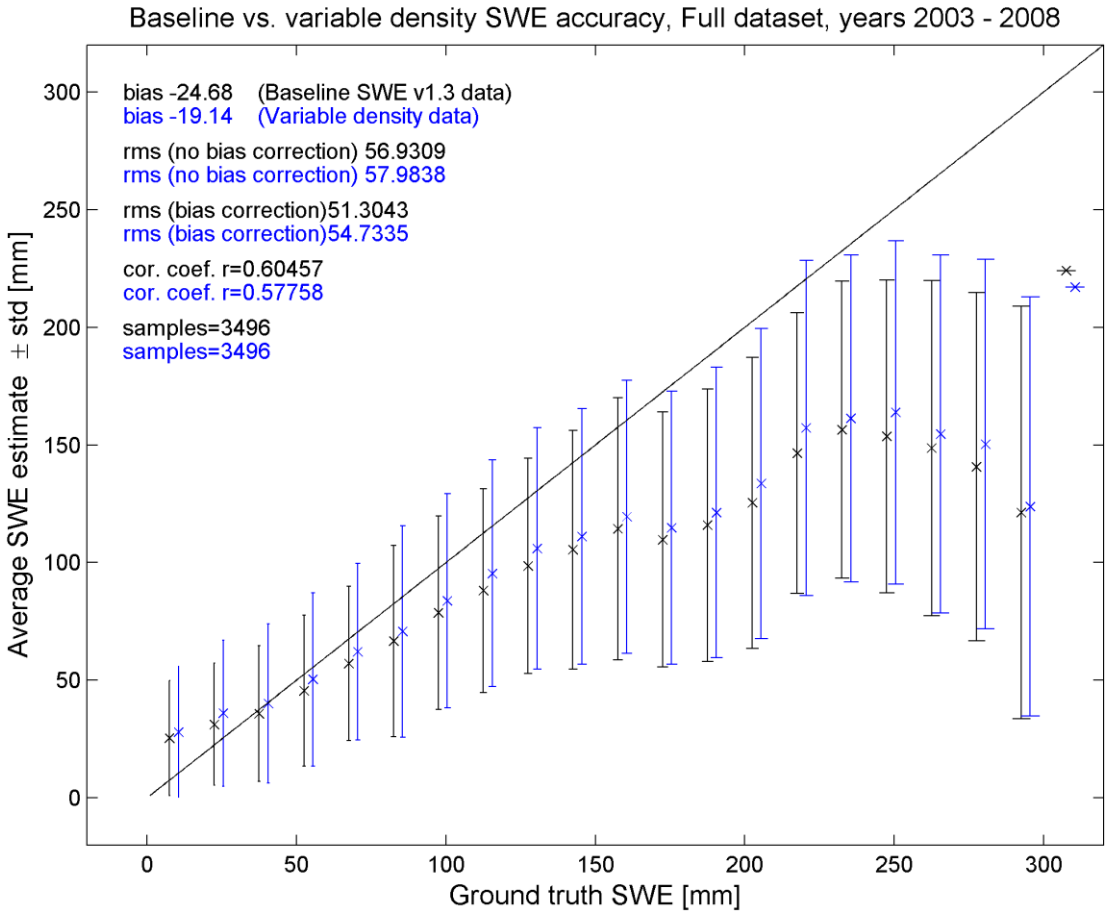

Figure 5.1.5, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for April and May, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 method, blue color used for the variable density method. Improved retrieval for high SWE values (SWE values above 50 mm) is evident in the figure.

Table 5.1.4 SWE retrieval performance for different years

	RMS-error [mm]	Bias [mm]	Corr.coeff	Samples
2003-2008	38.00 / **41.27**	3.67 / **8.94**	0.712 / **0.682**	23293
2003	34.01 / **37.35**	8.93 / **13.14**	0.799 / **0.774**	2349
2004	36.07 /**38.56**	5.53 / **9.493**	0.720 / **0.699**	3151
2005	34.11 / **39.18**	7.94 / **14.59**	0.720 / **0.687**	3614
2006	34.15 / **37.42**	6.52 / **12.65**	0.726 / **0.706**	4393
2007	39.97 / **43.07**	2.12 / **7.41**	0.691 / **0.661**	4846
2008	44.41 / **47.21**	-4.16 / **0.63**	0.682 / **0.648**	4940

The results for different years do not reveal any news differences between the baseline v1.3 SWE dataset and variable density dataset. The inferior retrieval accuracy for the variable density dataset is obvious for all evaluated years with the Russian snow transect data.

5.2 Validation results using Canadian data

The prototype SWE retrievals using variable density were assessed with the same Canadian reference datasets as were used in evaluations of previous GlobSnow FPS versions. While minor improvements in retrieval performance were noted for boreal and prairie environments, more notable improvement was evident at tundra sites (Figure 5.2.1). The RMSE was reduced from ~45 mm with FPS1.3 to 26 mm when the variable density was applied. Bias was reduced from -40 mm to -19 mm, and correlation improved from 0.20 to 0.40. The variable density approach resulted in higher snow density across tundra regions, which is responsible for the improvement in retrievals, although the -19 cm bias indicates the SWE estimates are still too low.

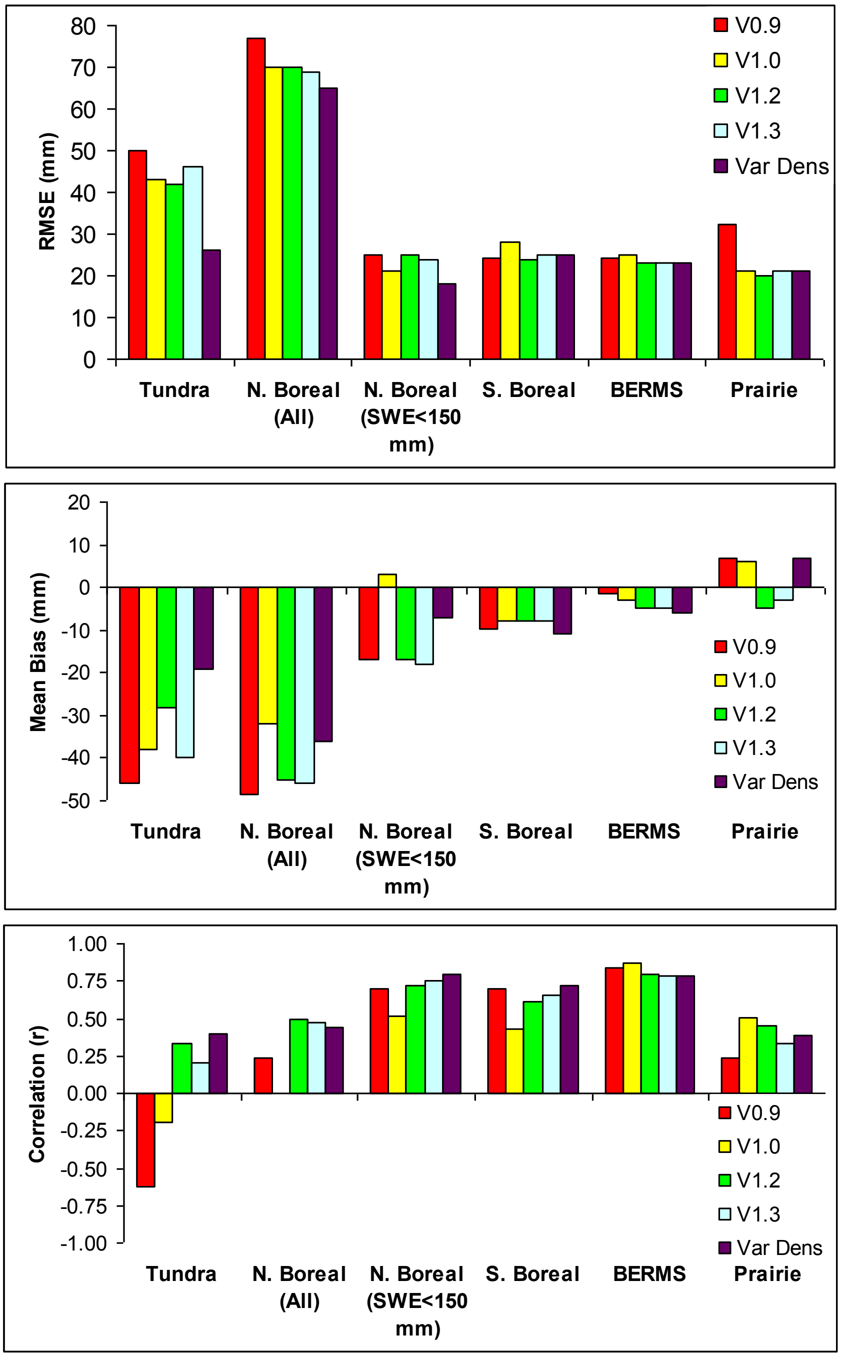

Figure 5.2.1. RMSE (top) mean bias (middle) and correlation computed for the variable density prototype with Canadian reference datasets, separate by land cover type.

A scatterplot of reference SWE versus the prototype variable density GlobSnow retrieval is shown in Figure 5.5.2. As was evident in the assessments of previous FPS, exceptionally deep snow in the northern boreal forest in 2007 is not captured by the retrievals, but agreement up to a threshold of 150 mm is well within the GlobSnow thematic accuracy requirements. The relative impact of the variable density formulation relative to FPS 1.3 is shown in Figure 5.2.3. Early season differences are minimal, but by April there is clear separation owing to the different densification coefficients used in the dynamic density scheme for each land cover type.

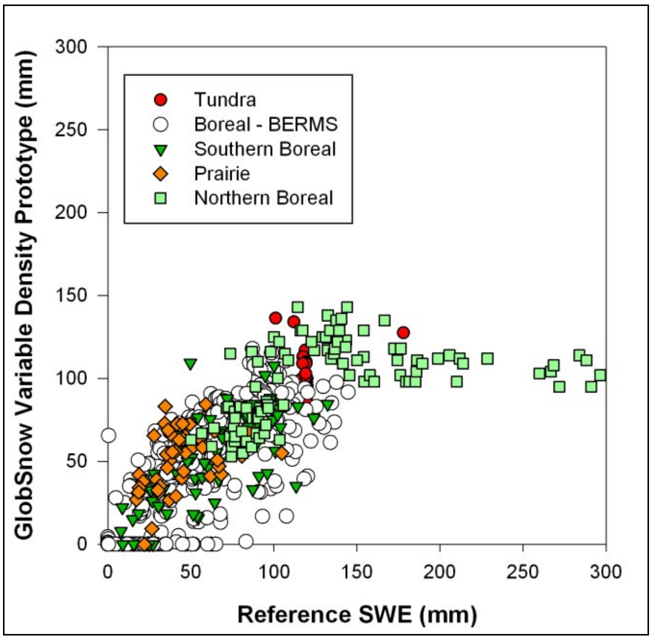

Figure 5.2.2. Scatterplot of reference SWE vs GlobSnow retrieval including variable density.

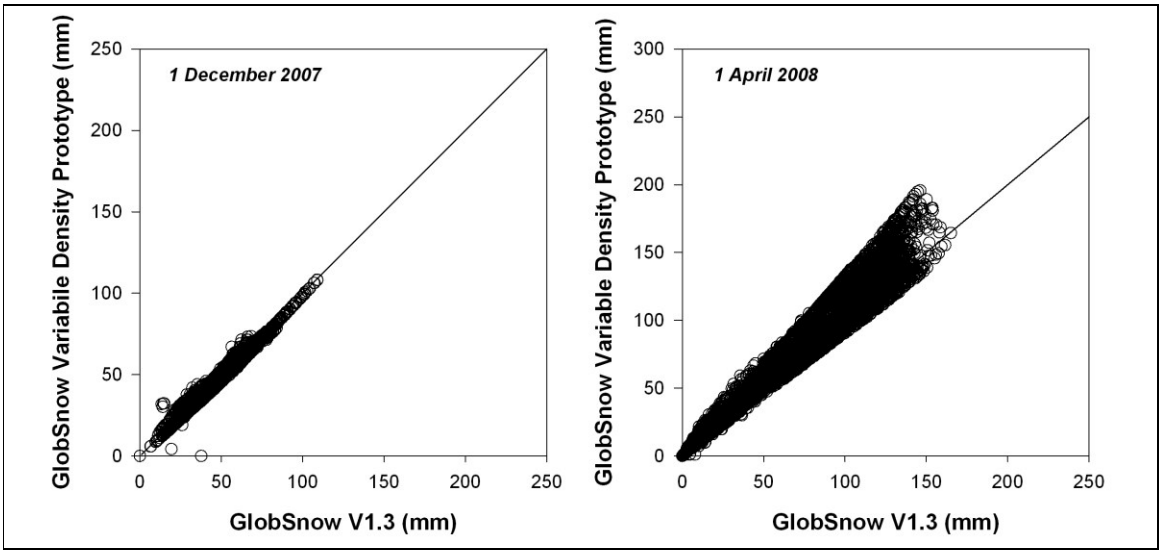

Figure 5.2.3. Co-located FPS1.3 and variable density retrievals for 1 December 2007 (left) and 1 April 2008 (right).

The previously released GlobSnow FPS datasets are characterized by spatially 'smooth' SWE patterns (see Figure 5.2.4 for a comparison with other gridded SWE datasets over eastern Canada). This is likely the result of the kriging of (1) background snow depth from climate station measurements, and (2) snow grain size information estimated at climate station locations using forward snow emission model simulations. The kriging procedure does not consider the impact of land surface characteristics (i.e. forest versus open), that can strongly influence mesoscale variability in snow cover properties. For instance, snow in the boreal forest is largely shaped by snowfall interactions with standing vegetation, with little influence from wind which produces deep snow with relatively low density. Conversely, tundra snow is shallow, dense, and composed of fine grained wind slabs shaped by blowing snow events.

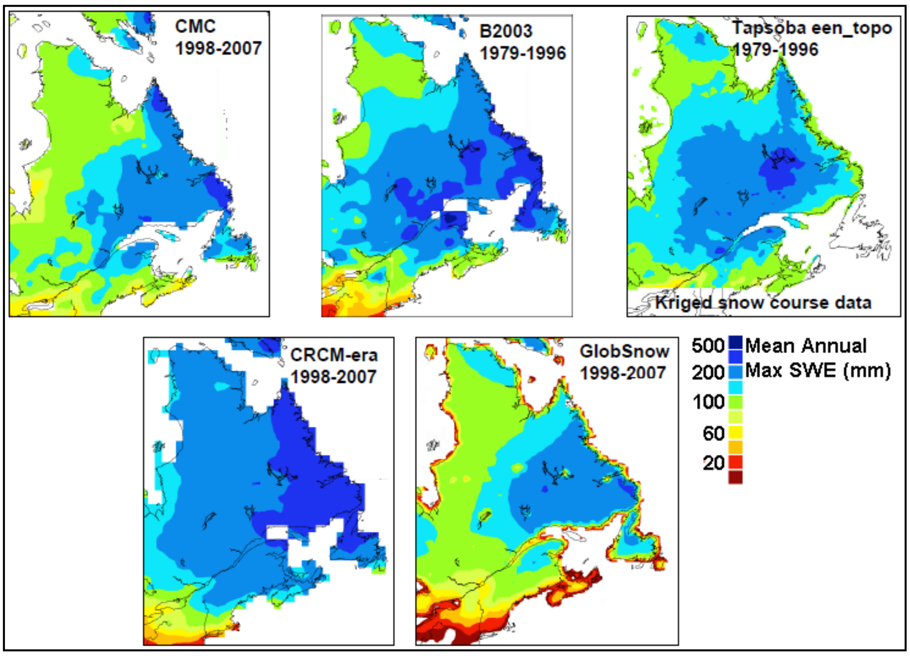

Figure 5.2.4. Comparisons of maximum seasonal SWE from various gridded datasets over eastern Canada.

Experimenting with the introduction of a variable density formulation in the GlobSnow retrieval produced clearly apparent boundaries in SWE between land cover types (i.e. from taiga to tundra). This was mitigated in the retrieval used for the prototype algorithm evaluated here, by considering open and forested fractions within the taiga zone, thereby applying the dynamically derived densities in a spatially weighted manner.

Transects of snow surveys conducted across the boreal to tundra transition in northern Manitoba and the Northwest Territories between 2004 and 2007 (see Figure 5.2.5) were utilized to determine the extent to which snow properties can vary over relatively short distances (i.e. between adjacent EASE-Grid cells). As summarized in Table 5.2.1, bulk snow properties are very similar between adjacent grid cells within the same land cover class, but between adjacent grid cells that change from boreal to tundra the changes can be notable – ranging from -35% for SWE to +46% for density. The mean percentage change in SWE between adjacent boreal and tundra grid cells in the GlobSnow prototype varying density dataset is only -6.6%, much lower than observations (Figure 5.2.6), suggesting the GlobSnow retrievals are too 'smooth' (see Liston and Hiemstra, 2011, for snow model derived depictions of the spatial heterogeneity in SWE in the subarctic and Arctic).

Figure 5.2.5. Location of sites for snow surveys across the boreal – tundra transition.

Table 5.2.1. Percentage change in bulk snow properties at the scale of adjacent PMW grid cells using long transect snow surveys conducted by Environment Canada in northern Manitoba and Northwest Territories, 2003-2007.

	Boreal to Boreal	**Tundra to Tundra**	**Boreal to Tundra**
Mean distance between sites (km)	20.3	17.5	24.6
n	63	22	9
∆ Density (%)	2.6	1.4	46
∆ Depth (%)	-2.6	-18.2	-57
∆ SWE (%)	0.1	14.1	-34.7
GlobSnow prototype ∆ SWE (%)	-3.6	-3	-6.6

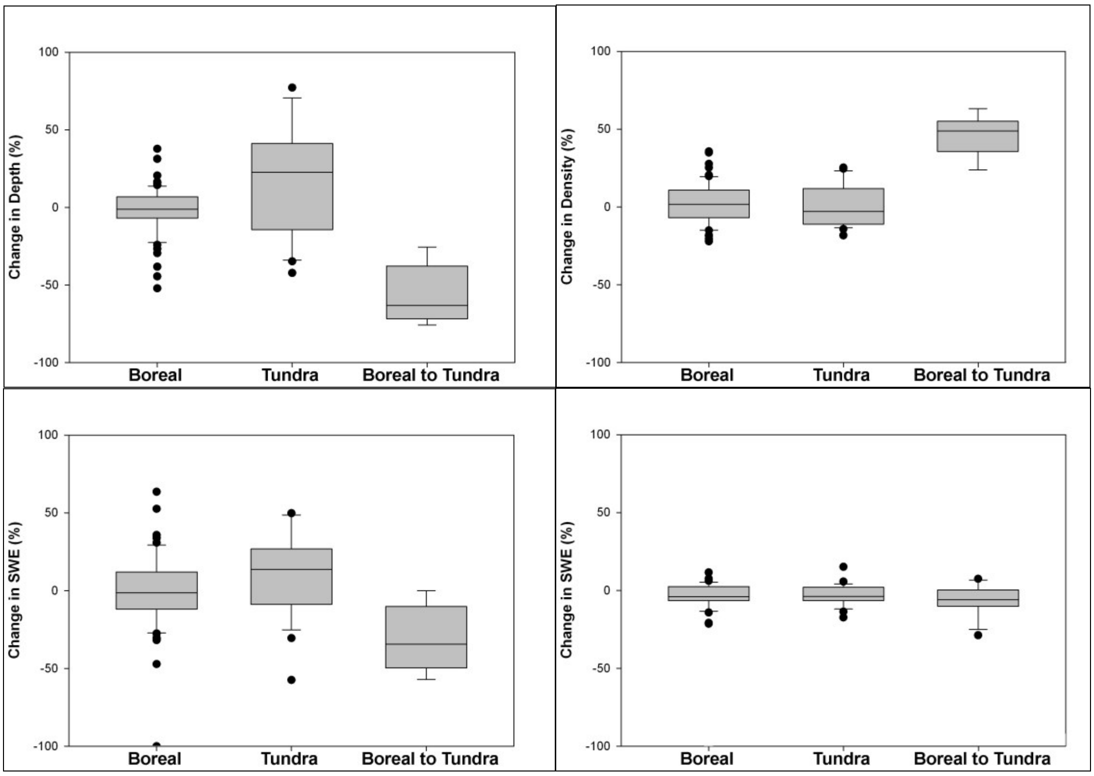

Figure 5.2.6. Boxplots of percentage change in snow properties between adjacent EASE-Grid cells across the boreal to tundra transition. Field measurements of (a) snow depth (b) snow density (c) SWE and (d) GlobSnow SWE retrievals (varying density prototype).

5.3 Validation results using Finnish snow course data

The data from the Finnish snow courses were used to investigate the performance of the new SWE retrieval method utilizing multi-layer snow emission model and spatially and temporally varying snow density. The retrieval results acquired using the new method are compared with the retrieval performance from the baseline GlobSnow-1 SWE dataset v1.3 using the Finnish snow course data.

5.3.1 Comparison of the complete dataset for years 2006 - 2008

The SWE retrieval accuracy was assessed for the available new variable density dataset covering years 2006 to 2008. The retrieval performance, determined using the Finnish snow course data, was compared with the retrieval performance of the baseline GlobSnow v1.3 SWE data for the same exact time period and exact same reference data (only reference data available for both datasets were used). The overall retrieval performance is shown in Figure 5.3.1.

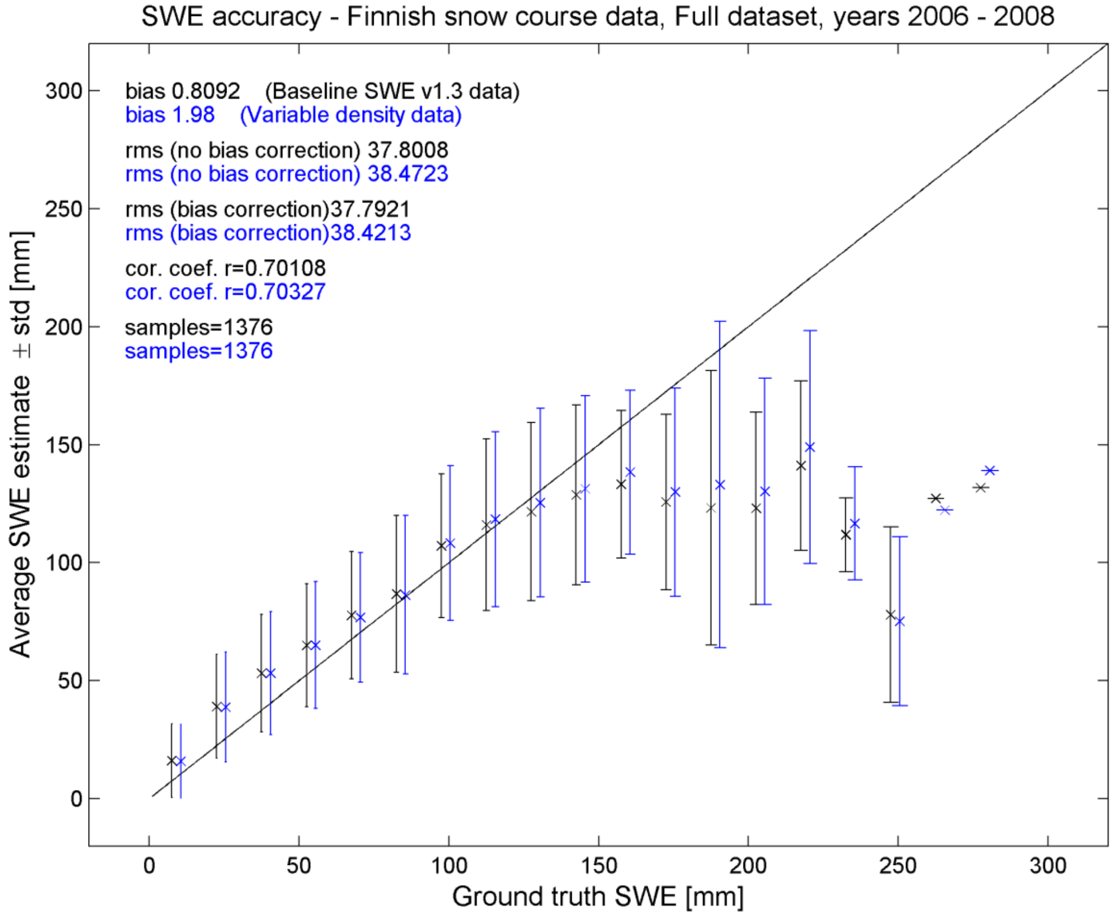

Figure 5.3.1, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets acquired using Finnish snow course data. Black color shows the results for baseline v1.3 method, blue color used for the variable density method.

The evaluation using the coinciding dataset from 2006 to 2008, including data from all seasons (fall, winter and spring) and all climatological regions shows slightly inferior retrieval accuracy for the variable density method. The RMS-error for the baseline dataset is 37.8mm while for the variable density dataset the RMS-error is 38.5mm. The bias for the baseline dataset is 0.81mm and for the variable density dataset it is 1.98mm. Both datasets had 1376 samples that were evaluated. It can be observed from Figure 5.3.1 that for SWE values higher than 100mm the variable density retrieval method seems to produce somewhat higher SWE estimates than the baseline retrieval method. For low SWE estimates this is not the case however, but the retrievals seem to be of same magnitude. Overall it seems that the GlobSnow-1 v1.3 SWE dataset without the variable density consideration produces slightly more accurate SWE estimates when observed over a period of three years using Finnish snow course data.

The change in retrieval accuracy for independent samples is show in in Figure 5.3.2.

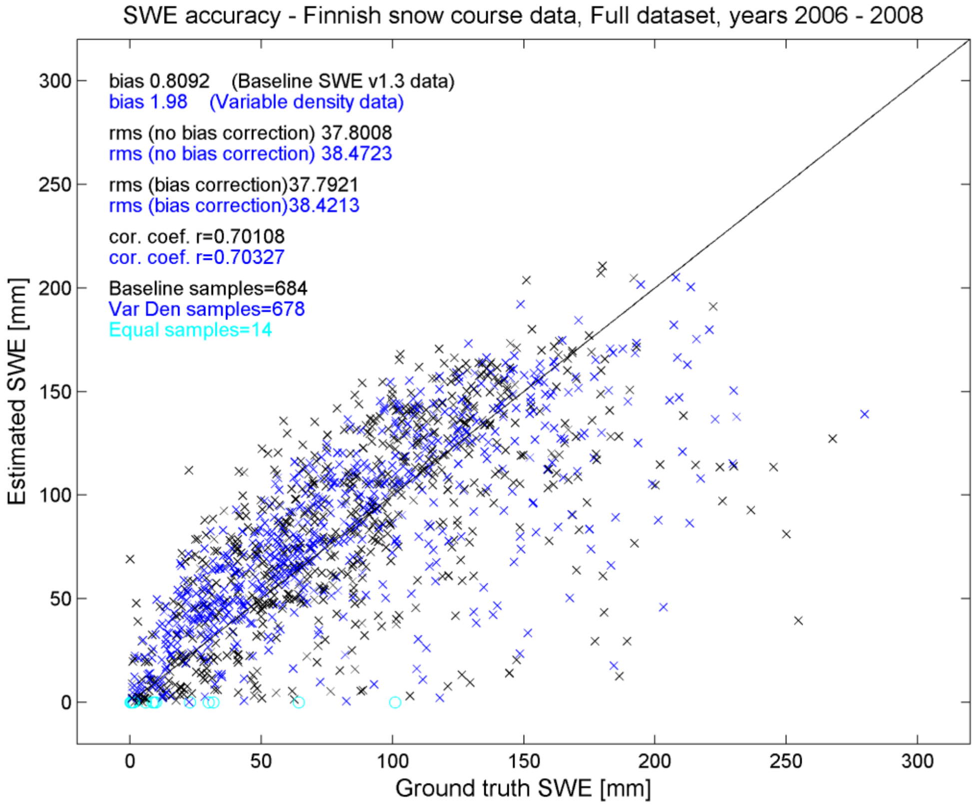

Figure 5.3.2, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets acquired using Finnish snow course data. The black points show the samples that were more accurate with the baseline v1.3 method, blue points show the samples that were more accurate with the variable density method. The baseline method results in more accurate retrieval in 684 cases and the variable density approach resulted in more accurate retrieval in 678 cases. 14 cases had equal accuracy for both methods.

6 SUMMARY AND CONCLUSIONS

The introduction of spatially and temporally varying snow density in the GlobSnow retrieval had a generally consistent impact with respect to Russian snow transect dataset. In general the retrieval performance was inferior with the variable density consideration, when compared with the GlobSnow baseline v1.3 method. The same result was observed for the consideration over the whole dataset, over different climatological, geographical and temporal domains.

The investigations using the Finnish snow course data are in line with the analysis from the Russian snow transect data. The difference in retrieval performance between the baseline GlobSnow v.1.3 retrieval method and the new variable density method was not as high as was observed with the Russian dataset.

The introduction of spatially and temporally varying snow density in the GlobSnow retrieval had a varying impact with respect to Canadian reference datasets, depending on the land cover.

Tundra: the increased density values that resulted from with the variable density scheme produced significant improvement in the GlobSnow retrievals. The large negative bias in previous GlobSnow FPS datasets (-40 mm) was improved to -19 mm, a result of the previously fixed density of 0.24 g cm^3 being unrealistically low for tundra snow.

Boreal forest: the change to a variable density had little impact over the boreal forest sites in Canada because the densification model from Sturm et al (2009) essentially fixes snow density for boreal snow at 0.217 g cm^3. This lower density is realistic early in the snow season, but revisiting the densification of boreal snow will be necessary for future implementations.

Prairie: Incremental improvement was noted for the Prairie sites, due largely to increases in the SWE retrievals resulting from higher late season density (which, however, produced an overall positive bias). Lower correlations between reference measurements and the retrievals for Prairie sites compared to other land cover regions is consistent with previous GlobSnow FPS evaluations, suggesting treatment of density is not the primary source of uncertainty across this region.

A comparison of ground measurements and SWE retrievals across the boreal to tundra transitions suggests the relatively abrupt measured changes in density, depth (and hence, SWE) are not reflected in the GlobSnow dataset. While this conclusion is based on a small in situ dataset, it is consistent with the relatively smooth SWE distributions characterized by GlobSnow compared to other gridded products. While changes to the treatment of varying density will address this issue, it is likely more strongly linked to the lack of land cover consideration in the kriging of background snow depth and grain size fields within the retrieval processing chain.

The final conclusion and recommendation of the SWE validation team is to continue improving the SWE retrieval scheme before initiating the reprocessing of the long term (30+ years) SWE time series.

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A APPENDIX – COMPLETE RESULTS FROM RUSSIAN DATA

This appendix collects all the results from the Russian snow transect assessments. The results collected in Tables 5.1.1 – 5.1.4 are visualized here.

I. Results for different climatological domains

Tundra

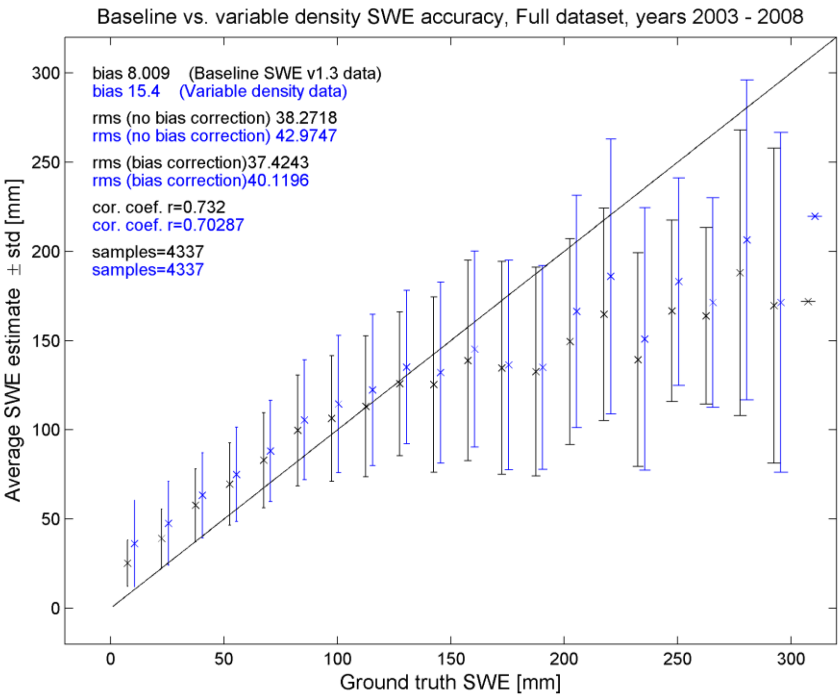

Figure A.1.1, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for tundra, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Taiga

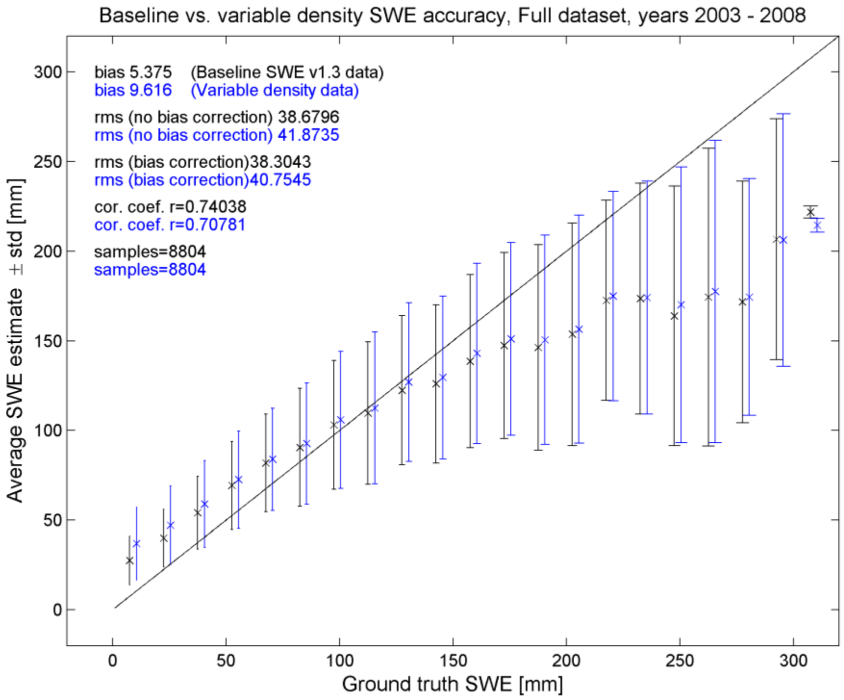

Figure A.1.2, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for taiga, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Prairie

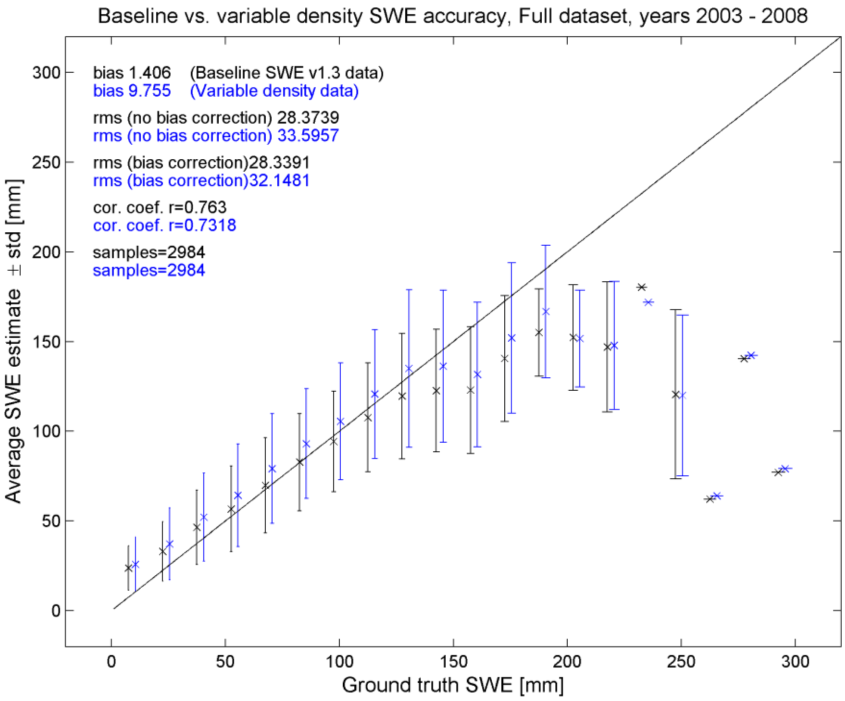

Figure A.1.3, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for prairie, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Other domains

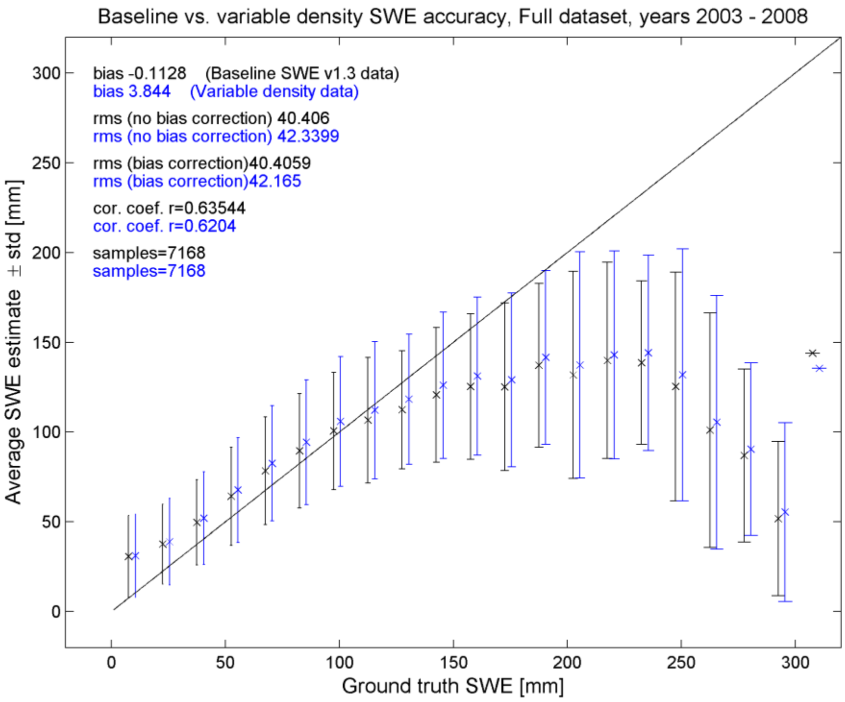

Figure A.1.4, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for other domains, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

II. Results for different geographical regions

Region 1

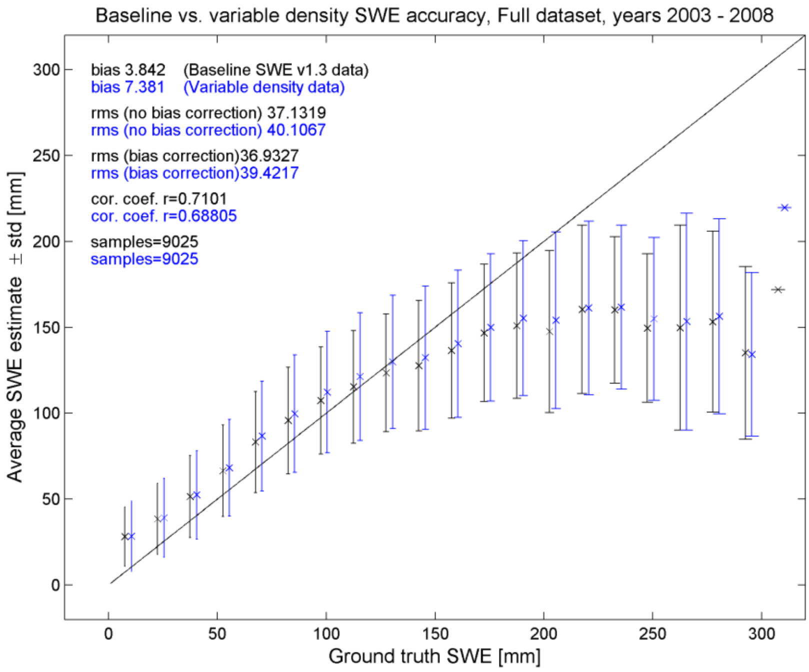

Figure A.2.1, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for region 1, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Region 2

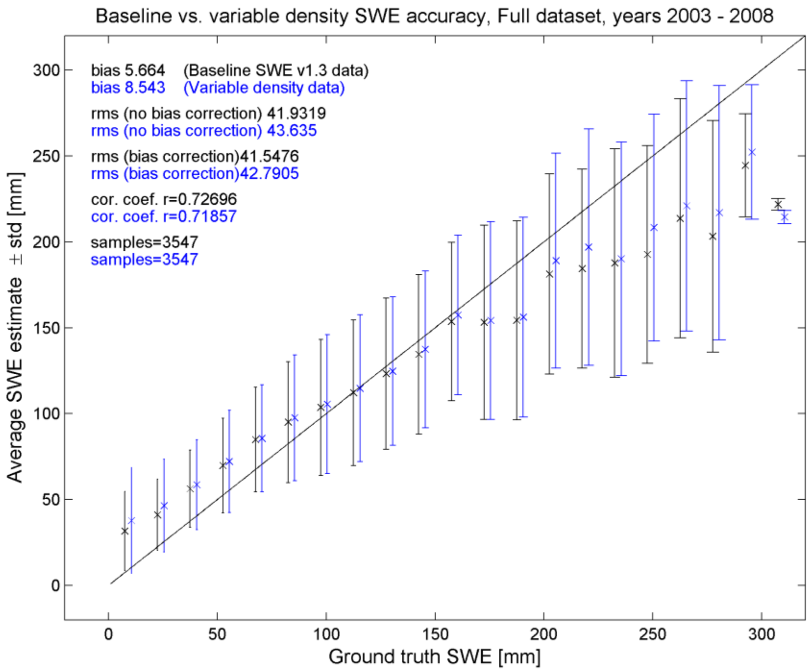

Figure A.2.2, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for region 2, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Region 3

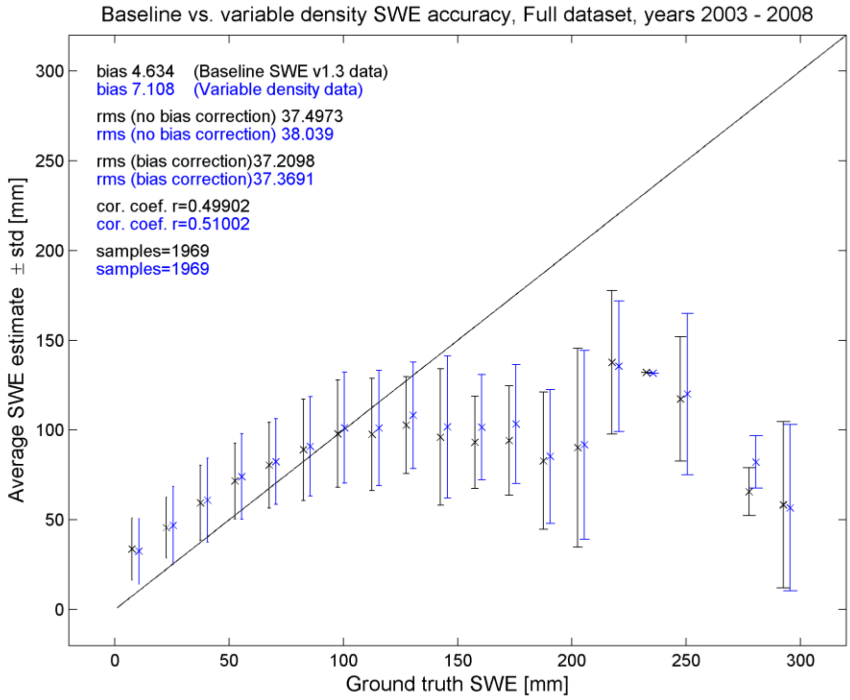

Figure A.2.3, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for region 3, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Region 4

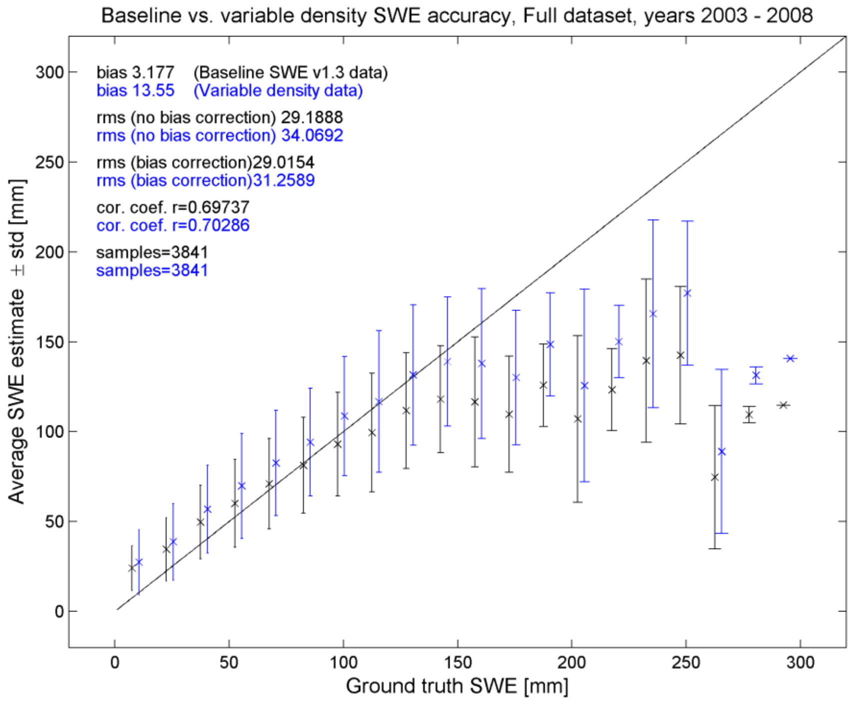

Figure A.2.4, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for region 4, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Region 5

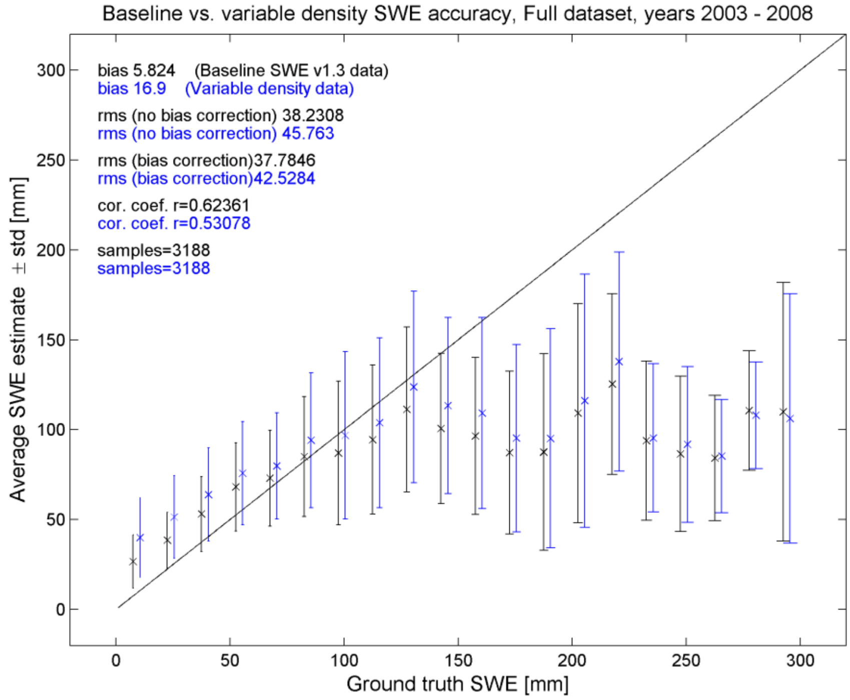

Figure A.2.5, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for region 5, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Region 6

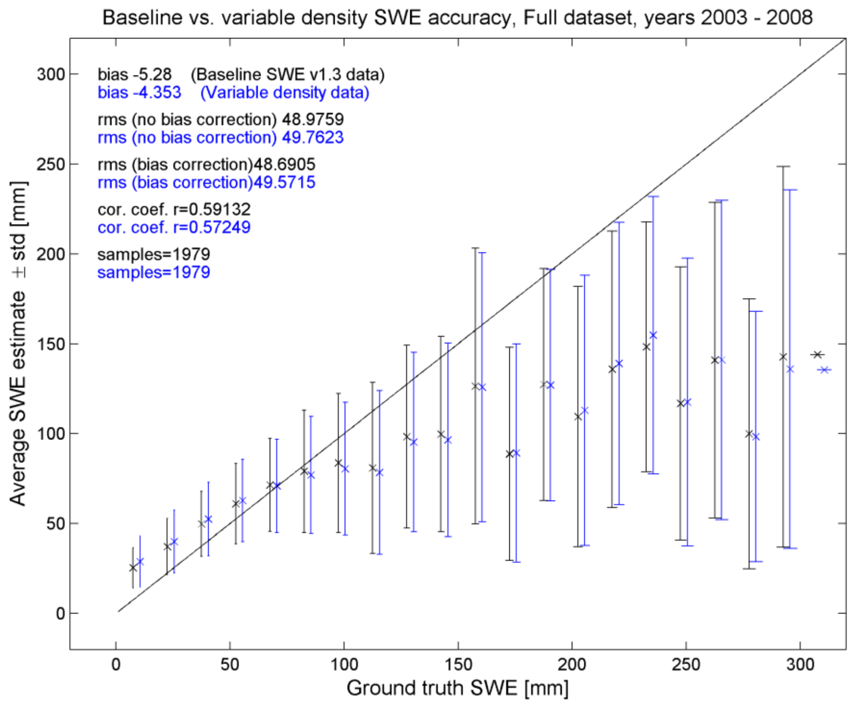

Figure A.2.6, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for region 6, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

III. Results for different seasons

Autumn (September – December)

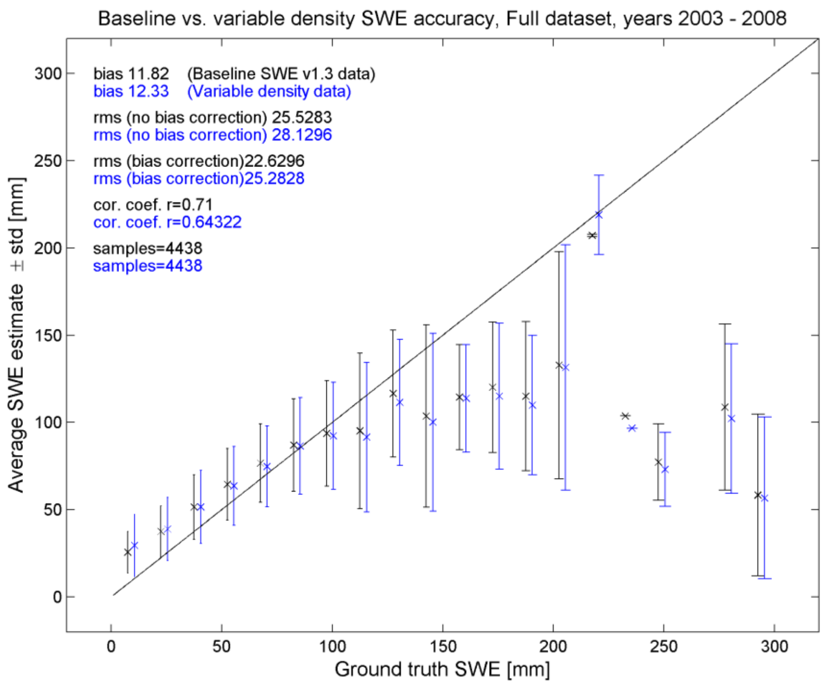

Figure A.3.1, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets during autumn, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Winter (January-March)

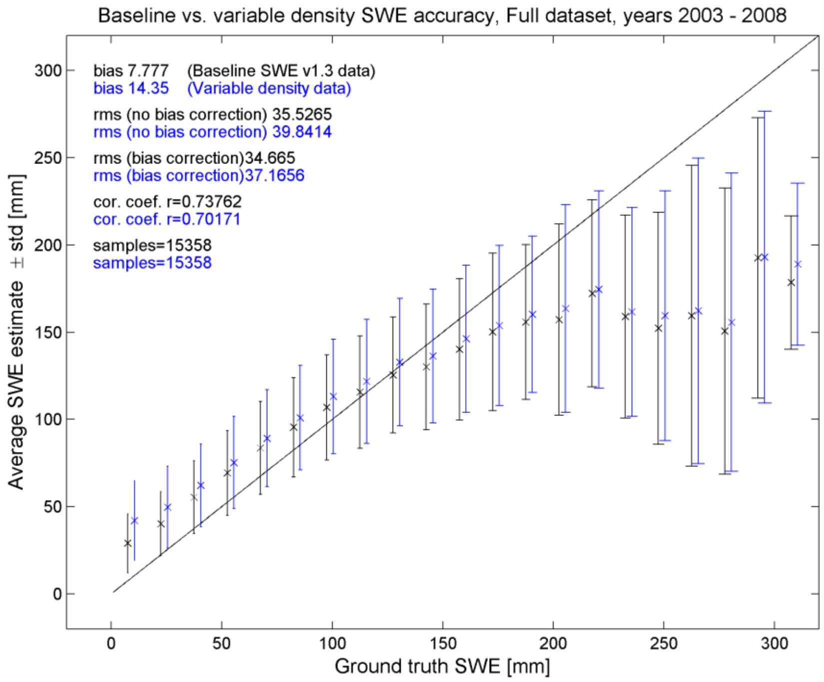

Figure A.3.2, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets during autumn, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

Spring (April, May)

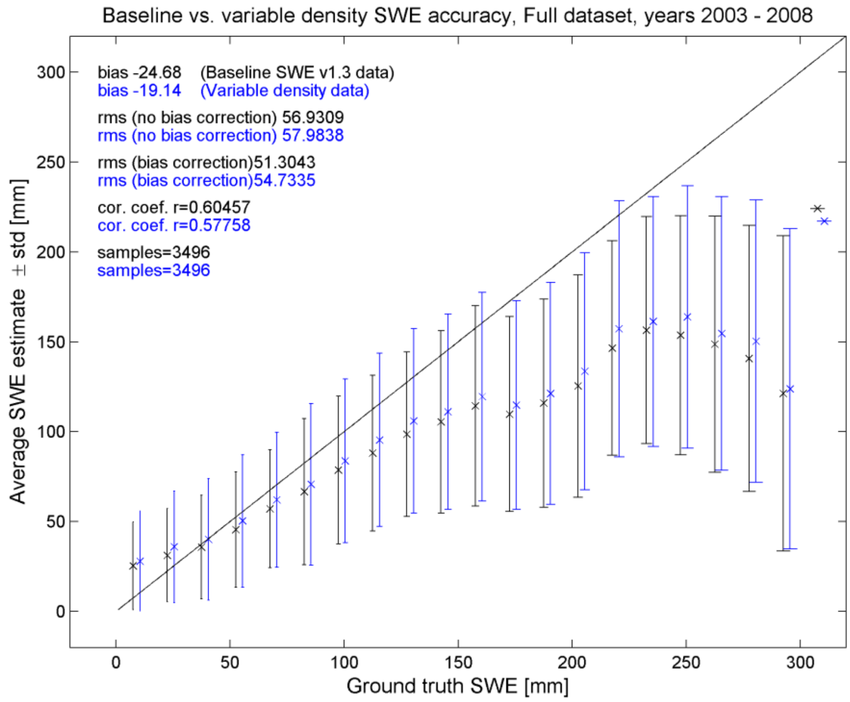

Figure A.3.3, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets during autumn, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

IV. Results for different years

2003

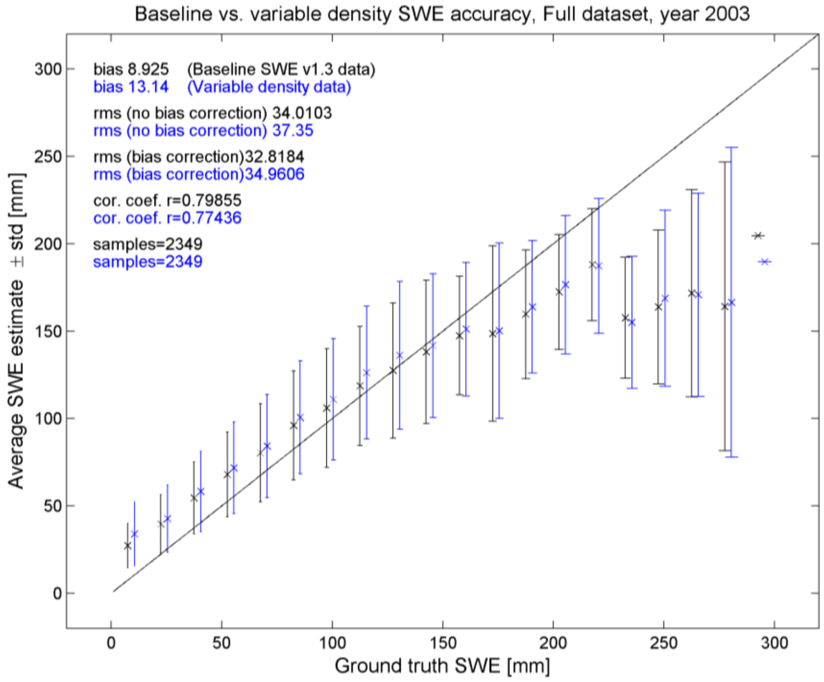

Figure A.4.1, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for year 2003, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

2004

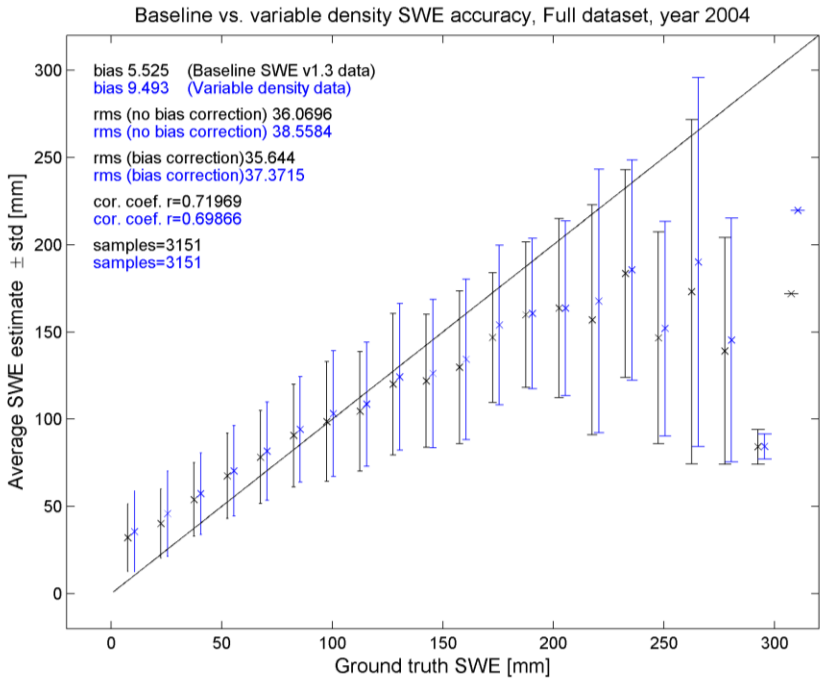

Figure A.4.2, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for year 2004, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

2005

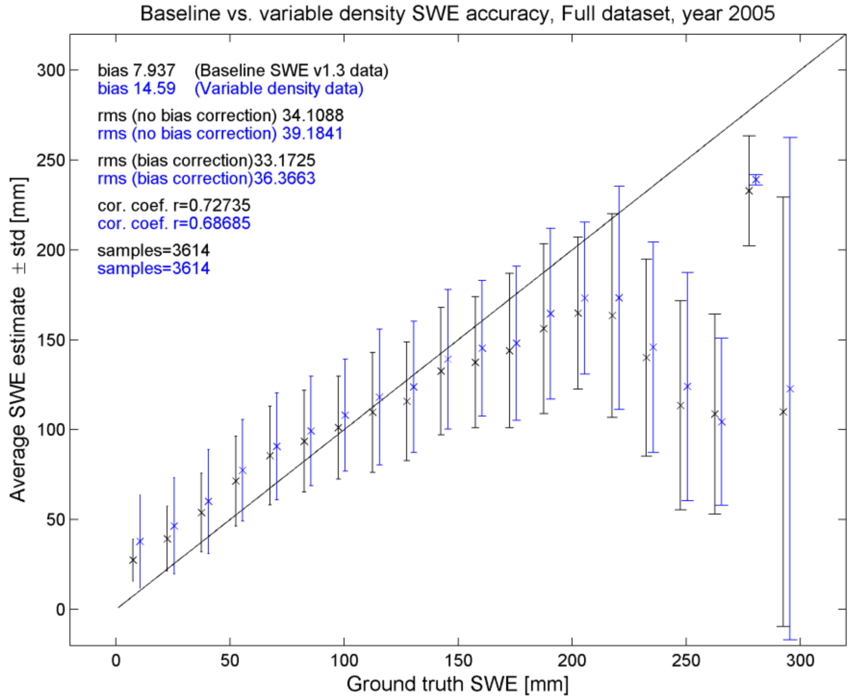

Figure A.4.3, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for year 2005, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

2006

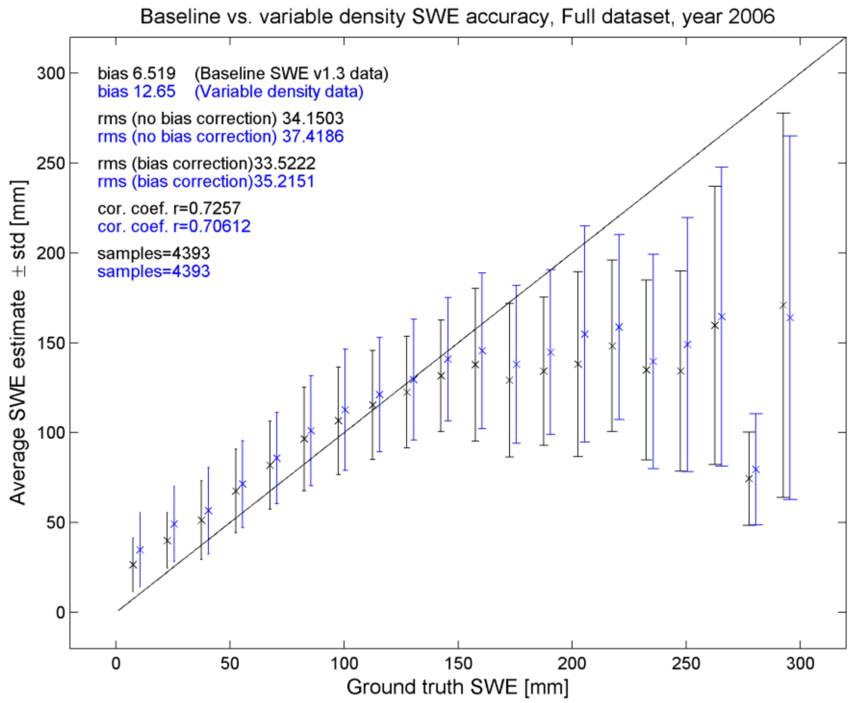

Figure A.4.4, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for year 2006, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

2007

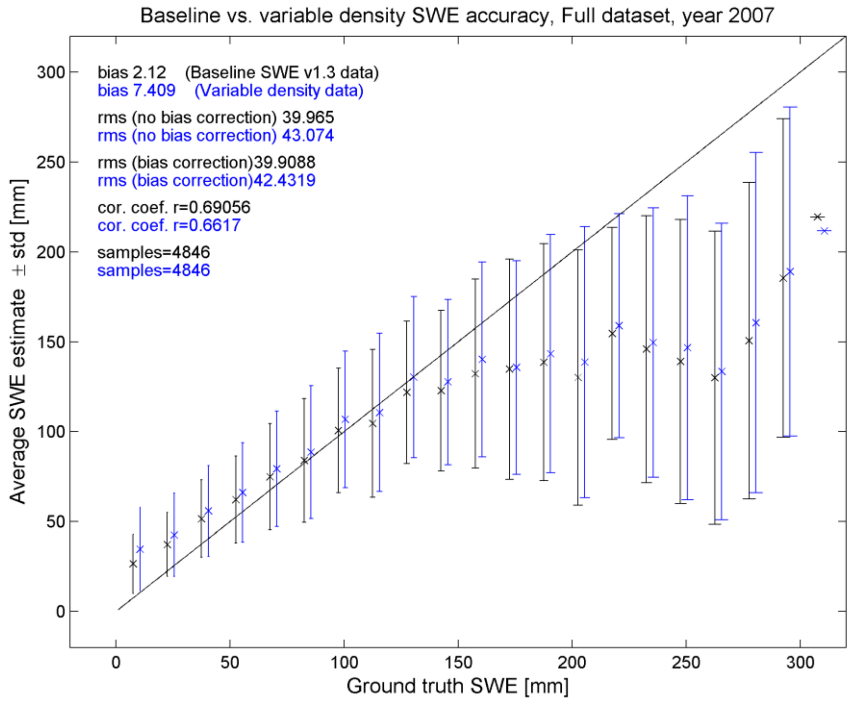

Figure A.4.5, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for year 2007, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.

2008

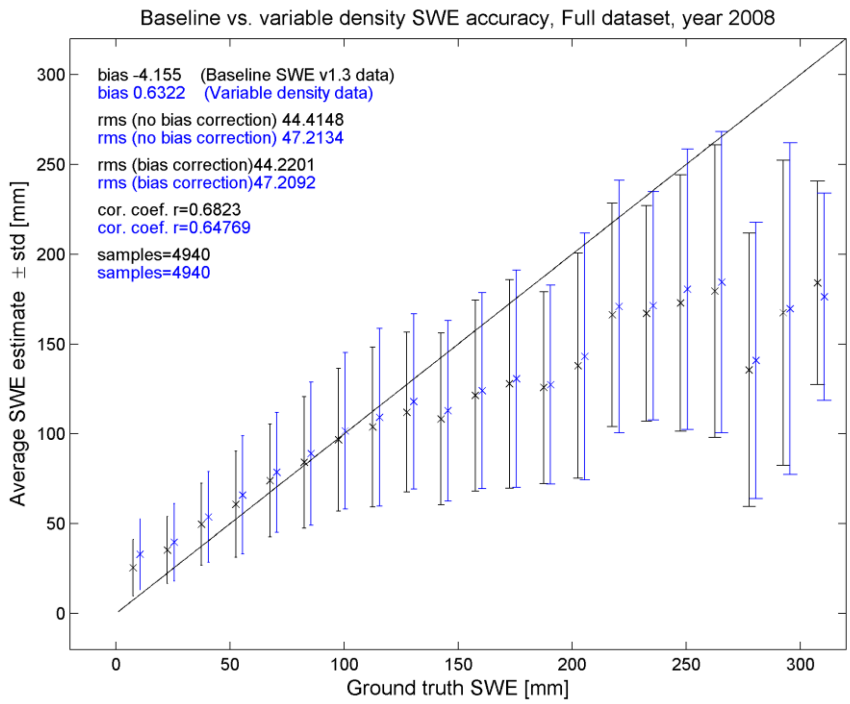

Figure A.4.6, SWE retrieval comparison between the baseline GlobSnow-1 v1.3 SWE and the variable density datasets for year 2008, acquired using Russian snow transect data. Black color shows the results of baseline v1.3 data, blue color used for the variable density data.