Global Snow Monitoring for Climate Research

Full Snow Extent Validation and Intercomparison Report

EUROPEAN SPACE AGENCY STUDY CONTRACT REPORT
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DOCUMENT CHANGE LOG

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0.1 / 01	24 February 2014	lead: G. Bippus, all		Template
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0.3	17.04.2014	G. Bippus		Description of validation reference data
0.4	25.04.2014	G. Bippus		Description of snow extent algorithms, Appendix sourced out in individual document
0.5	08.05.2014	G. Bippus		Description of snow extent algorithms and validation methods
0.6	22.08.2014	G. Bippus		Compilation of revised contributions from SYKE and UBE for SE v2.1 validation, revisions from ENVEO
0.7	27.08.2014	G. Bippus and R. Ripper		Validation results from HR/MR EO data, restructuring of document
0.8	29.08.2014	G. Bippus, E. Malnes		Validation results from HR/MR EO data, Trend analysis
0.9	31.08.2014	G. Bippus		Validation results from EO data
0.91	1.9.2014	G. Bippus		Draft version
0.92	3.9.2014	G. Bippus		Minor revisions and corrections, formatting
0.93	3.9.2014	G. Bippus		Full document formatting
0.94	4.9.2014	G. Bippus		Final Draft
0.95	5.9.2014	K. Luojus		Revision of chapter 6

0.96	7.9.2014	S. Metsämäki		General revision, particularly chapters 5.1 and 6
0.97	8.9.2014	G. Bippus		Correction of Fig. 5.1, compilation of revisions
0.98	9.9.2014	G. Bippus		Compilation of final corrections by contributing partners
1.0	10.9.2014	G. Bippus		Final Formatting of full document

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1 INTRODUCTION

1.1 Purpose of the Document

The purpose of this document is to provide a detailed description of the validation and intercomparison activities and results for the full GlobSnow-2 Snow Extent (SE) version 2.1 products (fractional and binary).

The quality assessment of the most recent GlobSnow-2 SE v2.1 products (http://www.globsnow.info/se/archive_v2.1/) is based on intercomparison with various reference data sets (REF) available for different spatial extents and resolution:

- Global snow extent products (NSIDC MOD10_L2)
- European snow extent products (CryoLand)
- Regional/local snow products (Landsat 5 TM / 7 ETM+, Kompsat-2, AVHRR SPARC)
- In-situ data for single spots (Finland, Austria, Switzerland)
- Gridded snow depth data from snow models (Austria, Carpathian region)

H-SAF SE products will not be used for intercomparison / evaluation activities. This decision has been made at the Progress Meeting 2, on 27 September 2013 in Helsinki, Finland.

Figure 1.1 gives an overview of the validation procedure with different reference data sets.

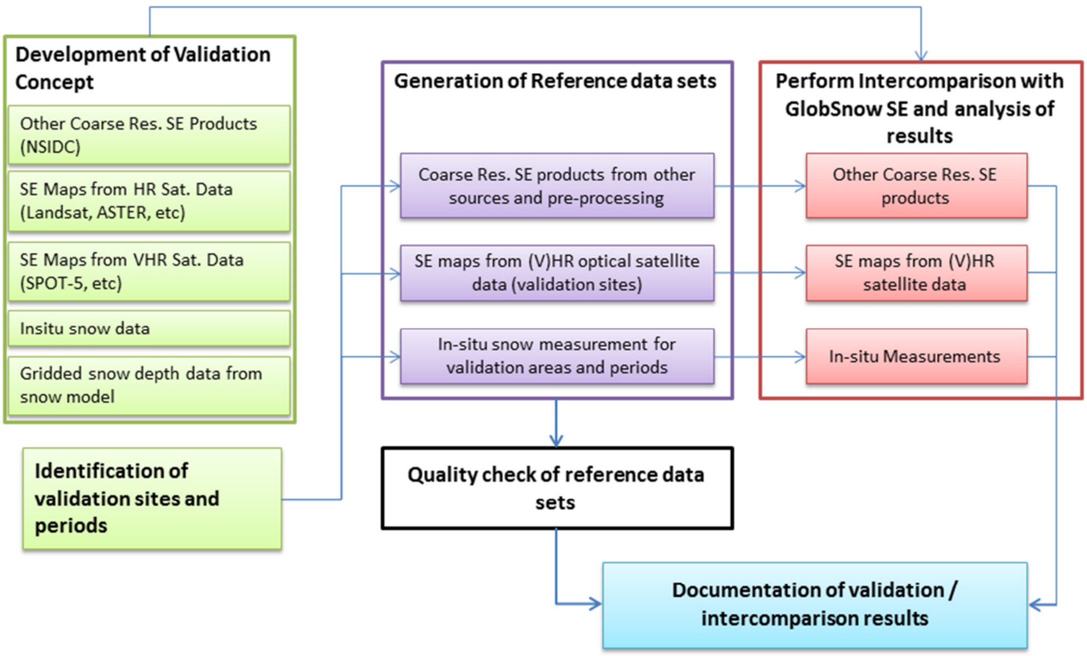

Figure 1.1: General concept of GlobSnow-2 snow extent evaluation with low, (very) high resolution and in-situ data.

A first full intercomparison with all described datasets has been performed with the GlobSnow-2 SE version 2.0 product set. When these evaluation activities were already completed, a shift in the geolocation of the SE v2.0 products was discovered. The causing error in the coding was solved, the full SE product data set was reprocessed with the corrected orthorectification, and most of the evaluation and intercomparison activities were repeated by the contributing partners with the new SE v2.1 product data set.

Only the intercomparison and evaluations with in-situ measurements in Switzerland could not be repeated for the new SE v2.1 product data set due to lack of remaining resources. Anyway, evaluation results of the GlobSnow-2 SE version 2.0 products in Switzerland are expected to be qualitatively representative for a generic product assessment in this region, and are thus also provided in this report.

1.2 Structure of the Document

This document provides detailed information on the validation and intercomparison activities of the full GlobSnow-2 SE v2.1 product data set. In Chapter 2 the selected reference data set, including Earth Observation (EO) based snow products, and snow information from in-situ and modelled data, as well as used ancillary data, are described.
For those algorithms already described in detail in the Preliminary SE Validation Report (Del-11) only changes applied since this document was released are described.
In Chapter 3 the preparation steps applied on the various products selected for validation and intercomparison are documented, including detailed descriptions of algorithms selected for the generation from EO data, of the generation of snow maps from in-situ measurements, and of applied resampling methods to make the products from reference data directly comparable with the GlobSnow-2 SE v2.1 product data set.
Chapter 4 gives a detailed overview on the methods used for the full evaluation and intercomparison of the GlobSnow-2 SE v2.1 products with the selected reference data. In Chapter 0 the results of the validation and intercomparison exercises for the full GlobSnow-2 SE v2.1 product set are reported, including also a consistency check and a trend analysis.
A summary and final conclusion is provided in Chapter 6.
In the Appendix, which is outsourced in an additional document, are the detailed results and any further relevant information reported.

1.3 Acronyms

AATSR	Advanced Along-Track Scanning Radiometer (instrument of Envisat)
ATSR	Along-Track Scanning Radiometer (instrument of Envisat)
AVHRR	Advanced Very High Resolution Radiometer
CASPR	Cloud and Surface Property Retrieval
DDS	Diagnostic Data Set
DEM	Digital Elevation Model
EEA	European Environment Agency
ENVEO	Environmental Earth Observation IT GmbH
ENVISAT	Environmental Satellite of ESA
ERS	European Remote Sensing Satellite of ESA
ESA	European Space Agency
FAR	False Alarm Ratio
FCDR	Fundamental Climate Data Record
FMI	Finnish Meteorological Institute
FSC	Fractional Snow Cover
FPS	Full Product Set
GCOS	Global Climate Observing System
HR	Hit Rate
KSS	Kuiper Skill Score
MODIS	Moderate Resolution Imaging Spectro-radiometer (Instrument of Terra)

NBCN-S	National Basic Climatological Network for Snow
NDSI	Normalized Difference Snow Index
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Association
NR	Norwegian Computing Center
POD	Probability of Detection
QC	Quality Control
RMSD	Root Mean Square Deviation
RMS	Root Mean Square
RMSE	Root Mean Square Error
SCA	Snow Covered Area
SCDA	SYKE's Cloud Detection Algorithm
SD	Snow Depth
SE	Snow Extent
SPARC	Separation of Pixels using Aggregated Rating over Canada
SYKE	Finnish Environment Institute
TOA	Top of Atmosphere
UniBe	University of Bern
WMO	World Meteorological Organization
ZAMG	Zentralanstalt für Meteorologie und Geodynamik

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.
[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.
[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.
[TN2] Technical note 2 – Cloud Detection Algorithm SCDA, GlobSnow team, 2011.
[TN] Technical note - Snow Extent Validation Concept, GlobSnow team, 2014.
[DEL-9] GlobSnow-2, ATBD for SE Algorithm, GlobSnow team, 2013.
[DEL-11] GlobSnow-2, Preliminary SE Validation Report, GlobSnow team, 2013.

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2 SELECTED REFERENCE DATA

For the intercomparison of the daily GlobSnow-2 version 2.1 SE product on global, continental, regional and local scales different snow extent products from in-situ measurements, other EO data or derived by different algorithms are used. An overview on the various data sets, as well as the sensor and areas covered by the particular reference snow products is provided in Table 2.1. Further details on the selected reference data sets are given in the following sections.

Table 2.1: Sensor and product definitions for datasets used for validation.

Data set	Sensor	Area
NSIDC MOD10_L2	MOD10_L2	Global / northern hemisphere
CryoLand FSC	MODIS	Pan-Europe
UBE AVHRR SPARC	AVHRR_SPARC	European Alps
Landsat 5-7	LS5/LS7	Selected mountain and non-mountain locations in different parts of Eurasia and North America
Kompsat-2	MSC	Selected mountain locations in different parts of Eurasia and North America
Weather station data	e-code (FSC)	Finland
Snow depths along transects or on weather stations	In-situ	Finland, Austria, Switzerland
Gridded snow data	Modelled	Austria, Carpathian region

2.1 Hemispheric, continental and regional snow extent products from medium resolution satellite data

2.1.1 MOD10_L2 – Fractional Snow Cover for northern hemisphere

Gabriele Bippus (ENVEO)

The MODIS/Terra Fractional Snow Cover field, Version 5, from NASA (Hall et al., 2006) with 500 m pixel size was selected for intercomparison with the GlobSnow-2 SE v2.1 product data set on a hemispheric scale. The daily NASA snow product exploits the NDSI (Hall et al. 1998, cf. Section 3.3.1.1) and further criteria tests, and uses the approach of Salomonson & Appel (2004, 2006, cf. Section 3.3.1.3) for retrieving fractional snow cover from MODIS data. The MODIS cloud product (MOD35_L2) is used as cloud mask, and the 1 km land/water mask of the MODIS geolocation layer (MOD03) is used to mask ocean and inland water. The fractional snow cover information is provided in percentage for each cloud free land or in-land water body pixel. The tool Swath2Grid is used to convert the MOD10_L2 data from HDF5 format to the GeoTiff format selected for the intercomparison activities.

For the intercomparison with the GlobSnow-2 SE v2.1 product the years 2003, 2004 and 2010 were selected.

2.1.2 CryoLand – Fractional Snow Cover for Pan-European Area

Gabriele Bippus (ENVEO)

The fractional snow cover product of the EU FP7 project CryoLand provided for the pan-European area with 500 m pixel size was selected for intercomparison with the GlobSnow-2 SE v2.1 product on a continental scale. The daily CryoLand FSC product, extending from 72°N/11°W to 35°N/50°E, is based on MODIS/ Terra data (version 5) applying a NDSI based pre-classification followed by an adapted (by Enveo) SCAmod approach (Metsämäki et al., 2005, 2012) for fractional snow cover mapping. An improved transmissivity map (version 14) for the CryoLand FSC product generation was prepared by SYKE with 500 m pixel size for the pan-European area. For mapping cloud covered areas the MODIS cloud product (MOD35) is used. For discriminating different land cover types the Corine Land Cover Version 16 of 2006 (CLC2006), published by the European Environment Agency (EEA) in 2012, and the ESA GlobCover 2009 (V2.3) outside of European countries are used. The digital elevation model EU-DEM generated within the GMES service for geospatial Reference Data Access (RDA) for Europe, and published by EEA in 2013 (http://land.copernicus.eu/in-situ/eu-dem) is used for the CryoLand pan-European FSC product generation. Outside the EU-DEM coverage the SRTM v4.1 DEM south of 60°N, and the ASTER GDEM 2 north of 60°N are used.

For the intercomparison with the GlobSnow-2 SE v2.1 product data set the years 2003, 2004 and 2010 were selected.

2.1.3 AVHRR SPARC – Binary Snow Cover for the European Alps

Fabia Hüsler (UBE)

The AVHRR SPARC dataset consists of daily 1-km gridded binary snow cover maps for the European Alps generated from a full-resolution AVHRR data archive (Hüsler et al. 2011).

The SPARC AVHRR product is provided in a geographical (latitude/longitude) coordinate system based on the reference ellipsoid and datum WGS84 and with a grid resolution of 0.01°x0.01°. The product covers the European Alps from 40°N to 50°N and 0°W to 17°E. For the intercomparison with the GlobSnow-2 SE v2.1 product data set the years 1999, 2003, 2004, 2006 and 2010 were selected.

2.2 High resolution satellite data

The snow map generation from high resolution satellite data mainly relied on the freely available Landsat 5 TM and 7 ETM+ sensors. Additionally, a few Kompsat-2 scenes usable for snow mapping were available at NR by an accepted third party mission proposal. The Kompsat-2 scenes cover 7 locations in different environments and climate zones.

High resolution satellite scenes to be used for the validation of the reprocessed GlobSnow-2 SE v2.1 product data set were searched and selected within the period 2003 – 2012. An overview on the spatial distribution of the selected high resolution satellite data used as reference data set for validation of the GlobSnow-2 SE v2.1 product data set is shown in Figure 2.1.

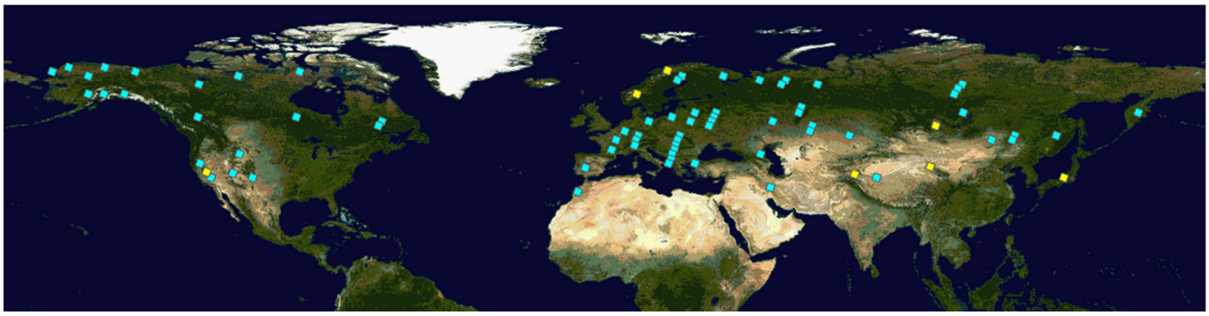


Figure 2.1: Locations of the selected Landsat (cyan) and Kompsat-2 (yellow) scenes used for GlobSnow-2 SE v2.1 evaluation activities.

2.2.1 Landsat Data

Elisabeth Ripper, Gabriele Bippus (ENVEO) and Sari Metsämäki (SYKE)

Multiple Landsat 5 TM and 7 ETM+ scenes were selected as main reference data set for evaluating the GlobSnow-2 SE v2.1 product with snow products derived from high resolution optical satellite data.

Each pair of AATSR and Landsat imagery used for intercomparison was acquired on the same date with nearly clear sky conditions. In total, a set of 70 Landsat 5 TM and 7 ETM+ scenes located in different environments and climate zones was selected for the evaluation of the GlobSnow-2 SE v2.1 product data set. Table 2.2 lists the scene IDs of the used Landsat imagery. More details on the used scenes are provided in Appendix A.

Table 2.2: List of Landsat 5 TM and 7 ETM+ scenes acquired between 2003 and 2010 selected for the intercomparison with GlobSnow-2 SE v2.1 product set. An overview on the spatial distribution of these scenes is shown in Figure 2.1. Details to each scene are given in Appendix B.

Landsat Scene ID	Landsat Scene ID	Landsat Scene ID	Landsat Scene ID
LE70410352003002EDC00	LE70370302003006EDC00	LE72020332003010EDC00	LE70330352003042EDC00
LE72020382003042EDC00	LE71130262003043EDC00	LE71930232003043EDC00	LE71980272003046EDC00
LE71980292003046EDC00	LE71890222003047SGS00	LE71940262003050EDC00	LE71940272003050EDC00
LE71940282003050EDC00	LE71970252003055EDC00	LE71860262003058SGS00	LE71860272003058SGS00
LE71860282003058SGS00	LE71860292003058SGS00	LE71860302003058SGS00	LE71860312003058SGS00
LE71860322003058SGS00	LE71250272003063EDC00	LE70410352003066EDC00	LE71850212003067SGS00
LE70690172003070EDC00	LE71810322003071SGS00	LE71530262003083SGS00	LE71850232003083ASN00
LE71650372003087EDC00	LE71810212003087ASN00	LE71810222003087ASN00	LE71810232003087ASN00
LE71810242003087ASN00	LE71770142003091ASN00	LE71210262003099EDC00	LE71210272003099EDC00
LE71850132003099ASN00	LE71650152003103ASN00	LE71650202003103ASN00	LE71650212003103ASN00
LE71450352003107ASN00	LE71610242003107ASN00	LE71610252003107ASN00	LE71930132003107ASN00
LE71930142003107ASN00	LE70520152003111EDC00	LE70650172003122EDC00	LE70810112003122EDC00
LE70720172003123EDC00	LE70480222003131EDC01	LE71370152003131ASN00	LE71370162003131ASN00
LE71370172003131ASN00	LE71690302003131EDC00	LE70120232003135EDC01	LE70120242003135EDC00
LE71330212003135ASN00	LE71720142003136ASN00	LE71720152003136ASN00	LE70990212003137EDC00
LE70440322003151EDC00	LT50460132006133PAC00	LT50670122006136PAC00	LT50750132006144GLC00
LT50290222008100PAC01	LT50830122009144GLC00	LT50740112009145GLC01	LT50370342009334PAC01
LT51690232010094KHC00	LT50350122010179PAC00		

2.2.2 Kompsat-2 data

Øivind Due Trier and Rune Solberg (NR)

Kompsat-2 (Korea Multi-Purpose Satellite-2), also referred to as Arirang-2 by South Korea, has been developed by KARI (Korea Aerospace Research Institute) to continue the observation program of the Kompsat-1 mission. Kompsat-2 is an ESA Third Party Mission (TPM), and approved scientific users have the possibility to order Kompsat-2 data from the archive.

The Kompsat-2 satellite was launched 28 July 2006. It goes in a Sun-synchronous orbit with a 14-days repeat cycle. The Multi-Spectral Camera (MSC) is a pushbroom-scanned sensor which incorporates a single nadir-looking telescope. The MSC collects panchromatic (PAN) and multi-spectral (MS) monoscopic images. The MS spectral bands cover the ranges 450-520 nm, 520-600 nm, 630-690 nm and 760-900 nm. The spectral range for PAN is 500-900 nm. Stereoscopic images are made by ground processing of the images from multiple orbits. The MSC pointing is accomplished by rolling the spacecraft, as needed, so that the line of sight of the MSC may pass over the desired location or swath. At the nominal mission altitude with the spacecraft nadir pointing, the MSC collects data with a ground sample distance (GSD) of 1 meter for PAN and 4 meters for MS data and with a swath width of approximately 15 km. The MSC is designed to operate with a duty cycle of up to 20% per orbit.

We got accepted a Kompsat-2 ESA Third Party Mission proposal for archived data for validation of snow maps. Images from the Northern Hemisphere in mountain areas were, by using the archived data search and browser web portal, compared with products available in the GlobSnow SE archive. A set of (close to) cloud-free matches were chosen as to achieve a reasonable distribution in various mountain regions under different local/regional climate, topography and geology (Table 2.3). A full description of the selected Kompsat-2 scenes is provided in Appendix B.

Table 2.3: Scene list of analysed Kompsat-2 images. Scene ID includes sensor abbreviation (MSC), followed by Date and time (YYMMDDhhmmss), orbit, path and row (each 4 digits), product type (B = Bundle = Multispectral + Panchromatic), tilting angle (P = positive, N = negative, and 2 digits) and processing level (1G = geometrically corrected image data.

Kompsat-2 scene ID (scenes used for validation)	Kompsat-2 scene ID (discarded scenes)
MSC_100606002040_20578_11621270BN08_1G	MSC_110411083231_25098_02301463BP24_1G
MSC_100620042351_20785_06671277BN16_1G	MSC_091102025224_17424_09021389BN02_1G
MSC_110408081645_25054_02301461BP07_1G	MSC_091102025224_17424_09021390BN02_1G
MSC_090323082048_14155_03591520BP26_1G	MSC_091102025224_17424_09021391BN02_1G
MSC_090323082048_14155_03591519BP26_1G	MSC_091102025224_17424_09021392BN02_1G
MSC_081029033358_12034_08521294BP00_1G	MSC_091102025224_17424_09021393BN02_1G
MSC_081029033358_12034_08521295BP00_1G	MSC_090305175733_13898_19861283BP01_1G
MSC_090305175733_13898_19861282BP01_1G	

2.3 Snow information from in-situ measurements

2.3.1 Weather station data in Finland (ground observation on snow coverage)

Kristin Böttcher (SYKE)

For the evaluation of GlobSnow SE products v2.1, weather station e-code observations were extracted for years 1999, 2000, 2003 and 2006 covering the period from February to October. The total number of comparison pairs in the final dataset was 8688, with 2296 observations of more than 50% snow cover (e-codes 6, 7, 8 or 9) and 6392 observations of less than 50% snow cover (e-codes 3, 4 and 5), see the first row in Table 2.4. During the non-snow season (mid-June to mid-September), the number of comparison pairs was 3745, including only five e-code observations with an e-code of 4 or 5.

Table 2.4: Number of reference snow observations for different FSC thresholds.

	Threshold value FSC	e-code	Number of observations	Threshold value FSC	e-code	Number of observations
SE50	≥0.5	6-9	2296	<0.5	0-5	6392
SE15	≥0.15	4-9	3087	<0.15	0-3	5601
SE0	>0	4-9	3087	=0	0-3	5601

2.3.2 Snow course measurements (Finnish ground data on FSC)

Sari Metsämäki (SYKE)

The snow course network for Finland, managed by SYKE, is a collection of monthly visited 2-4 km long transects in different parts of Finland. Observations on snow covered area, snow depth and snow density are made at 40-80 locations along the transects. The network covers ~150 snow courses. For validation, average FSC from all the observations from one snow course visiting is calculated and compared against the average FSC from the corresponding day's product pixels overlaying the course. Data of the years 2003 – 2011 are used for the validation of the GlobSnow-2 SE v2.1 product data set.

2.3.3 Snow depth measurements (ground data)

Rainer Unger (ZAMG)

2.3.3.1 Austria

For the intercomparison of GlobSnow-2 SE products with in-situ measurements in Austria, a total of 43 ZAMG weather stations have been carefully selected. The quality assessment of the snow depth measurements has been carried out during a currently running ZAMG-project called "SNOWPAT - Snow in Austria during the instrumental period – spatiotemporal patterns and their causes - relevance for future snow scenarios".

The stations represent the main climatological regimes in Austria as well as varying altitudes and topography with "Baden" (245 m a.s.l.) being the lowest station and "Hahnenkamm" (1794 m a.s.l.) the most elevated one. The snow depth time series is reaching back to 1895.

Of the 43 selected stations, 35 have no data gaps. Eight had data gaps that were homogenized using correlation thresholds between neighboring stations. Homogenization work was carried out within the “SNOWPAT”-project. As a result all selected stations are quality controlled and have valid data without gaps during the GS2 validation period. Years to be validated were chosen analog to snow model validation over the same region: 2003, 2004, 2006 and 2010.

A map showing the spatial distribution of the validation sites is presented in Figure 2.2. In addition, Table 2.5 provides an overview of the station attributes including the Station ID, observation period and geographical position.

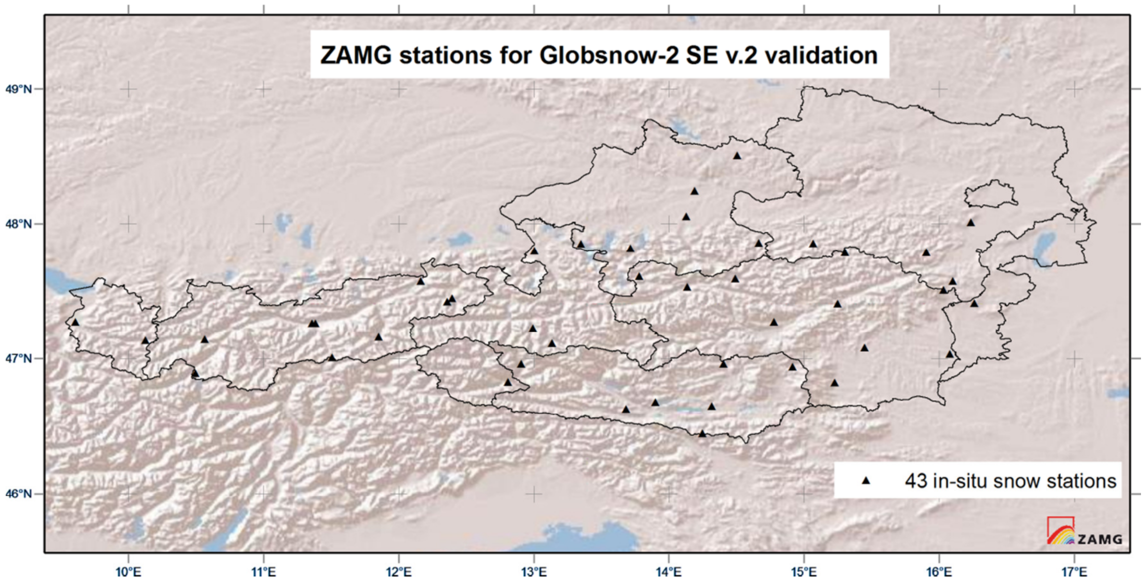


Figure 2.2: Location of ZAMG Weather stations used in the validation study of the GlobSnow-2 AATSR data set product (SE product v2.0)

Table 2.5: ZAMG Weather Stations used for the validation study over Austria.

Stat.ID	Station name	Lat.	Lon.	Elevation, m. (asl.)	Observation Start	Observation End	Data Gaps	Temp. Res.
1600	FREISTADT	48.51	14.51	549	19360101	20110331	no	daily
5000	HOERSCHING	48.24	14.19	298	19420515	20110930	no	daily
5010	KREMSMUENSTER	48.06	14.13	382	19170101	20110331	no	daily
5871	BADEN	48.01	16.24	245	19540401	20110531	no	daily
6300	SALZBURG_ FLUGHAFEN	47.80	13.00	430	19390301	20110331	no	daily
6515	MONDSEE	47.85	13.35	481	19560101	20101231	no	daily
6610	FEUERKOGEL	47.82	13.72	1618	19300101	20120531	no	daily
7000	WEYER	47.86	14.67	428	19680601	20120731	no	daily
7110	LUNZ_AM_SEE	47.85	15.07	612	19950401	20120731	no	daily
7202	MARIAZELL	47.79	15.30	862	19501201	20120930	no	daily
7502	PUCHBERG	47.79	15.91	583	19490601	20120731	no	daily
9010	KUFSTEIN	47.58	12.16	490	19360101	20111231	no	daily

Stat.ID	Station name	Lat.	Lon.	Elevation, m. (asl.)	Observation Start	Observation End	Data Gaps	Temp. Res.
9641	BAD_AUSSEE	47.61	13.78	667	19570501	20120930	no	daily
9800	AIGEN/ENNSTAL	47.53	14.14	641	19390301	20120930	no	daily
9901	ADMONT-MOOR-WIRTSCHAFT	47.59	14.49	637	19550801	20120930	no	daily
10502	MOENICH-KIRCHEN	47.51	16.03	991	19540801	20120731	no	daily
10600	ASPANG	47.58	16.10	454	19480501	20120731	no	daily
11110	FELDKIRCH	47.27	9.61	438	19360101	20111231	no	daily
11800	INNSBRUCK-FLUGPLATZ	47.26	11.36	578	19520101	20111231	no	daily
11801	INNSBRUCK-UNIV.	47.26	11.38	578	19161101	20111231	no	daily
12200	KITZBUEHEL	47.45	12.39	744	19360101	20111231	no	daily
12210	HAHNENKAMM	47.42	12.36	1794	19380101	20111231	no	daily
13110	SECKAU	47.27	14.78	863	19710101	20120930	no	daily
13300	BRUCK/MUR	47.41	15.25	482	19360101	20120930	no	daily
13700	BERNSTEIN	47.41	16.26	631	19491101	20120731	no	daily
14310	LANGEN/ARLBERG	47.14	10.12	1270	19521001	20111231	no	daily
14400	LANDECK	47.14	10.56	796	19460201	20111231	no	daily
14800	BRENNER	47.01	11.51	1372	19480101	20111231	no	daily
15000	MAYRHOFEN	47.16	11.85	643	19360113	20111231	no	daily
15403	RAURIS	47.22	12.99	934	18950101	20110331	no	daily
15500	BAD_GASTEIN	47.11	13.13	1092	19480101	20110331	no	daily
16402	GRAZ-UNIVERSITAET	47.08	15.45	366	18960101	20120930	no	daily
16600	FUERSTENFELD	47.03	16.08	271	19360101	20120930	no	daily
17100	NAUDERS	46.89	10.50	1330	19580601	20111231	no	daily
17900	LIENZ	46.83	12.81	661	19340101	20111231	no	daily
18000	DOELLACH-SAGRITZ	46.96	12.90	1078	19301201	20111231	no	daily
18600	FRIESACH	46.96	14.41	640	19580501	20111231	no	daily
18800	PREITENEGG	46.94	14.92	1034	19500701	20111231	no	daily
18900	DEUTSCHLANDS-BERG	46.82	15.23	353	19391001	20120930	no	daily
20000	BAD_BLEIBERG	46.63	13.68	909	19380101	20111231	no	daily
20100	KANZELHOEHE	46.68	13.90	1520	19380101	20111231	no	daily
20210	KLAGENFURT	46.65	14.32	450	19500401	20111231	no	daily
21100	LOIBL-TUNNEL	46.44	14.25	1097	19590101	20111231	no	daily

2.3.3.2 Switzerland

Nando Foppa and Fabio Fontana (MeteoSwiss)

Mountains are sensitive regions, being among the most vulnerable to climate variability and change. Hence, systematic observation snow cover is, in these regions, extremely important and requires high-quality in-situ snow observations on a long-term basis. The estimation of snow parameters such as snow extent, snow depth, and snow water equivalent plays a vital role in the Swiss Alps (e.g. Uhlmann et al. 2009). Therefore, ground-based monitoring of snow cover has a long tradition in Switzerland and a number of studies on snow cover have been published over the last years, focusing on its temporal variability and long-term trends (e.g. Marty 2008; Scherrer et al. 2013).

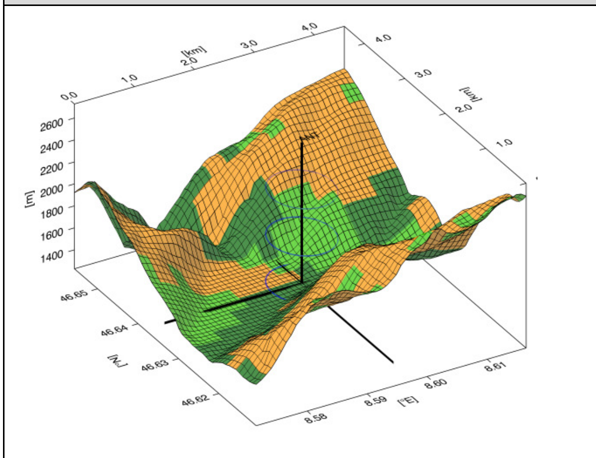
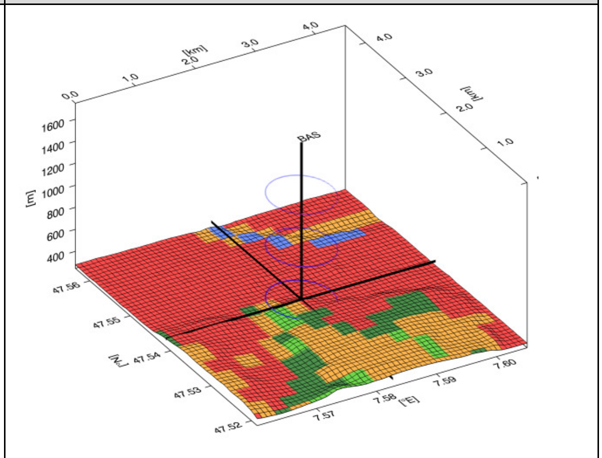
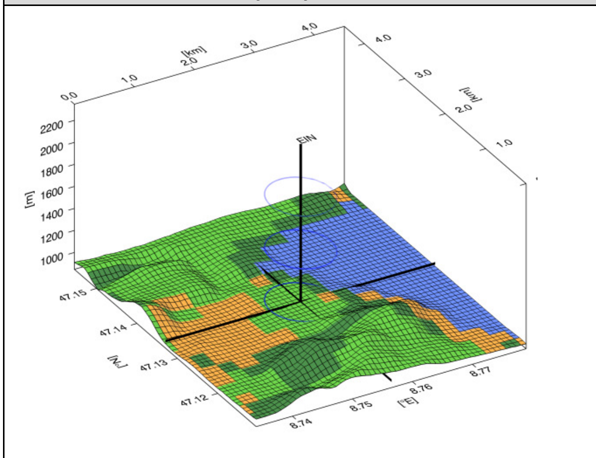
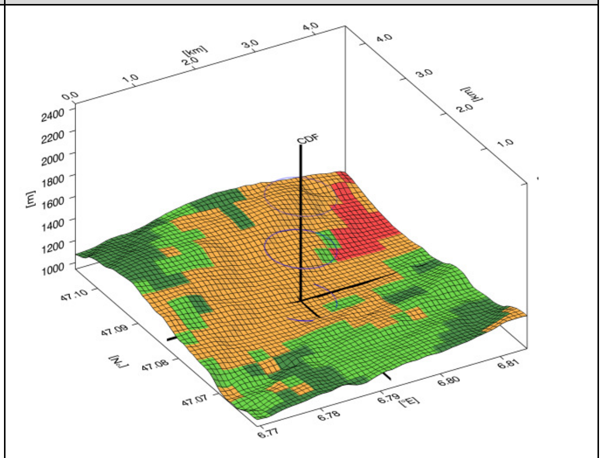
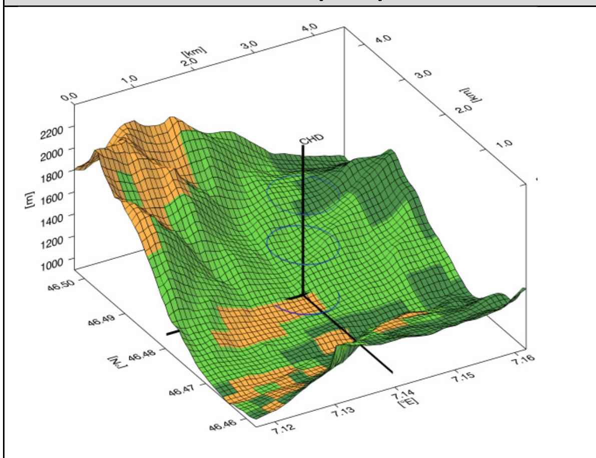
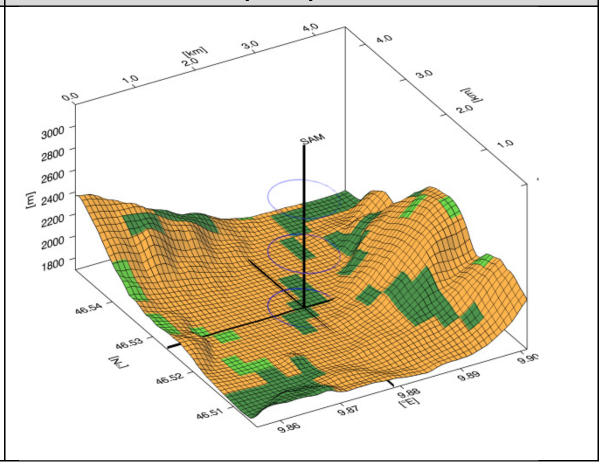
In Switzerland, snow variables such as total snow depth and new snow depth are measured by the Federal Office of Meteorology and Climatology MeteoSwiss at various altitudes. The amount of new snow and total snow depth at conventional stations is measured twice daily (morning and evening) by an observer on a representative plot in horizontal terrain. This network of conventional observations covers the entire region of Switzerland. The advantage of manual observations are the long time series of up to 50+ years providing valuable information for climatological studies. Over the past few years, efforts have been made to identify, digitize and explore snow measurements from historical data sources dating back to the second half of the 19th century. A recently published report by MeteoSwiss (Wüthrich et al., 2010) defined a potential basic climatological network for snow, based on the analysis of 160 historical snow measurement series. Within the National Climate Observing System (GCOS Switzerland) (Seiz and Foppa, 2011) a subset of this so-called National Basic Climatological Network for Snow (NBCN-S) has been selected as the 17 potential Swiss GCOS snow stations, representing main climatological regimes in Switzerland and varying altitudes.

Long-term in-situ measurements serve for validation purposes of satellite-based snow products. With high-quality in-situ data, accuracy assessment can be delivered and product uncertainties identified. This is required to increase the confidence of users and decision makers in satellite–based snow products. Therefore, efforts were required in the selection process of in-situ snow station sites over Switzerland focusing on the validation of satellite-based snow products. Within the GlobSnow-2 activities the potential Swiss GCOS snow stations were analysed in detail to define the reference sites explicitly for the assessment of the SE product 2.0. The following processing steps were undertaken:

- collect and document systematically the metadata of each Swiss GCOS snow site
- assure a temporal stability of the in-situ observation plot without vertical and/or horizontal displacement
- guarantee a complete data time series without undefined large periods of data gaps (starting Jan. 1 1980 – Dec. 31 2012)
- calculate the elevation gradient for each geographic orientation within a radius of 0.5km surrounding the station site using SRTM data (DEM 90 m) (Rabus et al., 2003)
- describe the landcover within a 2.5 by 2.5 km square around the station site based on ESA's GlobCover landcover map (300 m) (Bontemps et al., 2010)

Based on latter, so-called 3D plots of each station site were created to visualize the site characteristics and to evaluate its suitability for satellite versus in-situ intercomparisons (Table 2.6). In addition, this helps to understand differences between the SE product and in-situ observations.

Table 2.6: So-called 3D environmental plots for selected Swiss GCOS Snow stations. Visualization is based on SRTM (90 m) and ESA GlobCover data (300 m). Landcover classes were re-classified to cultivated (brown), forested (dark green), grass (light green), urban (red), and bare (grey) ground as well as water bodies (blue).

Station: Andermatt (AND)	**Station: Basel (BAS)**
	
Station: Einsiedeln (EIN)	**Station: La Chaux-de-Fonds (LCF)**
	
Station: Château-d' Oex (CHD)	**Station: Samedan (SAM)**
	

Finally, ten out of the potential Swiss GCOS snow stations were selected for validation purposes (see Figure 2.3 and Table 2.7). The selected reference sites are part of dedicated and sustainable long-term measurement networks in Switzerland, operated within a sustainable framework. The in-situ observation data are quality controlled and verified through several standard quality-processing steps (Bezzola 2004).

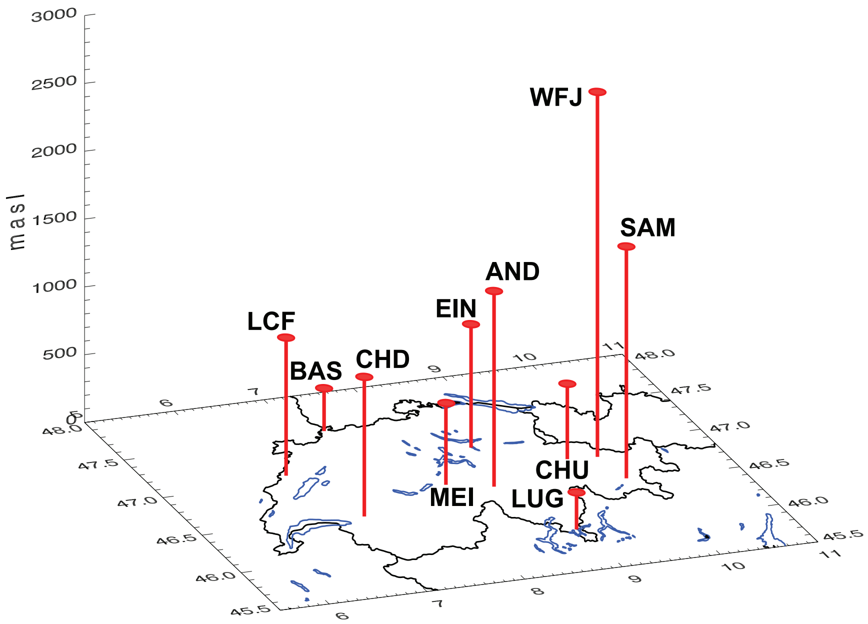


Figure 2.3: Location and altitude of the Swiss GCOS Snow stations used in the validation study of the GlobSnow-2 SE v2.0 full product data set.

Table 2.7: Swiss GCOS snow stations used for the validation study over Switzerland.

Station name	Geogr. Coordinates	Altitude, m (a.s.l.)	Climatological region (CH)	Temporal resoliution	Start date	End date	Data gaps
Andermatt (AND)	46.633441434 N 8.594394398 E	1442	Central Alpine north slope	Daily	1941	-	No
Basel (BAS)	47.541049838 N 7.583549291 E	316	Eastern Jura	Daily	1931	-	No
Einsiedeln (EIN)	47.132950928 N 8.756540704 E	910	Central Alpine north slope	Daily	1931	-	No
La Chaux-de-Fonds (LCF)	47.082836846 N 6.791785013 E	1018	Western Jura	Daily	1931	-	No
Lugano (LUG)	46.006930252 N 8.936521920 E	370	Alpine south side	Daily	1931	-	No
Samedan (SAM)	46.526393965 N 9.878962941 E	1709	Engadine	Daily	1931	-	No
Weissfluhjoch (WFJ)*	46.82962907 N 9.809247004 E	2672	North and central Grisons	Daily	1936	-	No
Meiringen (MEI)	46.732138626 N 8.169233473 E	595	Western alpine north slope	Daily	1958	-	No
Chur (CHU)	46.847226146 N 9.515239257 E	556	North and central Grisons	Daily	1958	-	No
Château-d'Oex (CHD)	46.476724111 N 7.141754831 E	1029	Western alpine north slope	Daily	1941	-	No

**Weissfluhjoch is proposed as an Initial Global Cryosphere Watch (GCW) CryoNet site.*

2.4 Model data (snow extent)

Rainer Unger (ZAMG)

Validation of AATSR and data for the Austrian domain was carried out using modelled snow depth data. Daily snow depth values (in cm) were generated by the so-called “Schöner snow model” that is driven by daily temperature and precipitation values. With input data of 71 Austrian meteorological service measuring points (see Figure 2.4) and a digital elevation model a grid based dataset of snow depth values covering the years of 1970 until 2006 has been created. In general the model underestimates the height of snow cover. With increasing altitude of the sites the difference between computed and observed snow data grows. That means that Sonnblick, the highest station (3105 m) shows the largest differences between the actual and theoretical values whereas the low-altitude Klagenfurt station (450 m) shows very high agreement (see Figure 2.5). The computation of the snow model contributed to the Austrian StartClim – Research Programme for climate change related studies in Austria. For further reading refer to Schöner et al. (2009), Auer et al. (2008) and http://www.austroclim.at/.

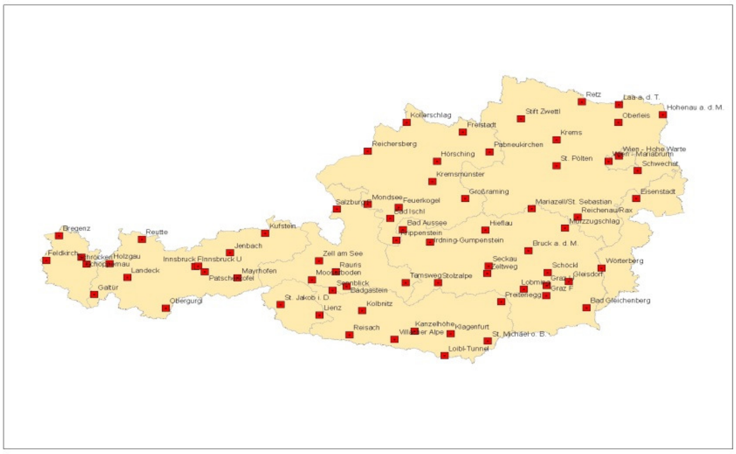


Figure 2.4: ZAMG – meteorological stations used for the snow model (Schöner et al., 2003)

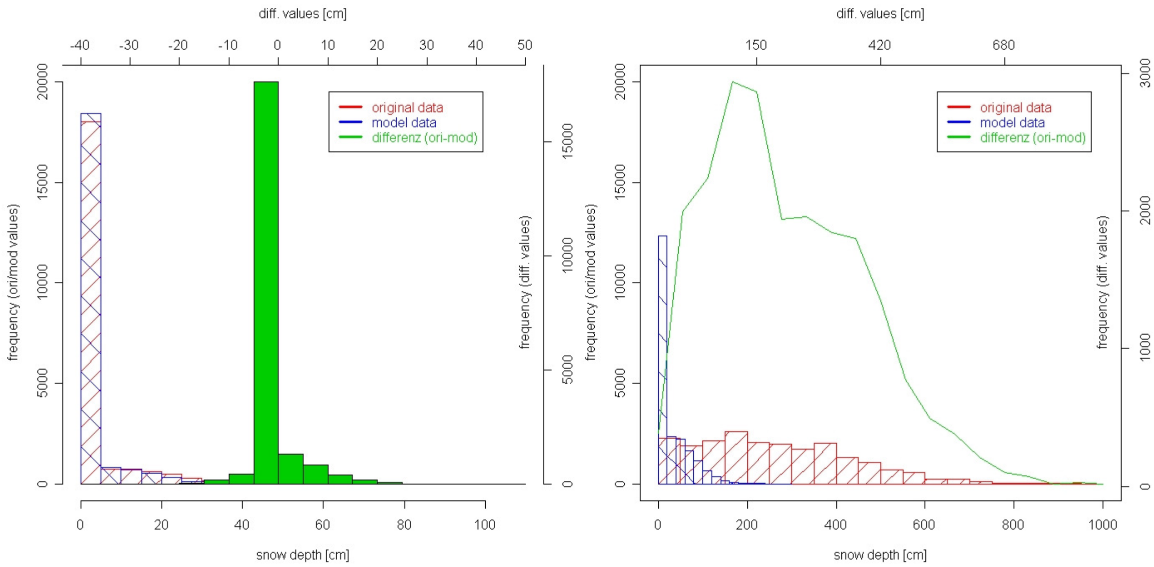


Figure 2.5: Frequency distribution of the element snow depth showing original, model data and differences (left: Klagenfurt station (450 m); right: Sonnblick station (3105 m) (Auer et al. 2008)

2.5 Auxiliary data

Gabriele Bippus and Elisabeth Ripper (ENVEO)

The following auxiliary maps are used for the generation of snow products from satellite data and for the discrimination of particular surface types used for the evaluation and intercomparison with the GlobSnow-2 SE v2.1 product data set:

- Transmissivity map (used as input for SCAmod)
- Digital Elevation Model (DEM): GETASSE30, SRTM v4.1, ASTER GDEM2, EU-DEM
- Surface classification map: GlobCover 2009 v2.3, Corine Land Cover 2006, Forest and Water masks published by Hansen et al. (2013)

The following masks retrieved from the auxiliary maps or generated by third parties are used:

- Forest mask (coarse and high resolution)
- Mountain mask (coarse resolution)
- Water mask (coarse and high resolution)

The **forest map for coarse resolution data** is derived from the transmissivity map with 1 km pixel size.

A global **high resolution forest map** for the year 2000 is derived from multiple Landsat scenes with 30m pixel size by Hansen et al. (2013).

The **coarse resolution mountain mask** with 1 km pixel size is based on the slope mask derived from the globally available GETASSE30 DEM.

As **high resolution water mask** the SRTM water body mask with 30 m pixel size is used for the area between 60°N and 60°S. North of 60°N the **high resolution water mask** published by Hansen et al., 2013, including no data values, mapped land surface and permanent water bodies with 30 m pixel size derived from multiple Landsat scenes, is used. For the Landsat scene of Utah the MOD44 product is used to identify water bodies, as both high resolution water masks have gaps at this location.

The **coarse resolution water masks** with 500 m and 1 km pixel size, respectively, are derived from GLOBCOVER 2009 and the transmissivity map.

The **high resolution digital elevation model** EU-DEM (http://www.eea.europa.eu/data-and-maps/data/eu-dem) with 30 m pixel size is used as auxiliary map for snow map generation from HR EO data over Europe. Outside the coverage of the EU-DEM the DEM of SRTM v4.1 (up to 60°N, 90 m pixel size) and the ASTER GDEM 2 (north of 60°N, 30 m pixel size) are used.

3 PREPARATION OF SNOW MAPS AND IN-SITU MEASUREMENTS

3.1 Daily GlobSnow-2 SE product

Gabriele Bippus (ENVEO)

This section focus on changes in the snow extent algorithms since the preliminary validation report (D11) used for the daily GlobSnow-2 Snow Extent (SE) v2.1 product generation. The daily GlobSnow-2 SE v2.1 products (DFSC), generated from the recently (2013) reprocessed AATSR data for the years 2003 – 2012, are available from http://www.globsnow.info/se/archive_v2.1/. This data set is used for most of the intercomparison and evaluation activities. With the third reprocessing of the full (A)ATSR data set by ESA also the known geolocation problem, resulting in a systematic shift of ± 2 pixels, has been solved (O'Hara et al., 2013). The reprocessed AATSR data set has an improved absolute geolocation.

The GlobSnow-2 SE product generation from ATSR-2 data for the period 1999 – 2002 is based on the 3rd reprocessing version of ATSR-2, but is only available in the GlobSnow-2 SE v2.0 product data set, as the updated GlobSnow processor used for the GlobSnow-2 SE v2.1 product generation from AATSR data showed less accurate geolocation for ATSR-2 data. Versions 2.0 and v2.1 however are identical regarding the FSC-retrieval methodology and can be jointly used. The years 2001 and 2002 were excluded from any validation activities due to severe problems in the geolocation of ATSR-2 data in this period.

As mentioned in the introduction only the intercomparison and validation activities with the in-situ measurements of Switzerland were not repeated for the new daily GlobSnow-2 SE v2.1 product data set, but have been performed for the GlobSnow-2 SE v2.0 product (DFSC), available from http://www.globsnow.info/se/archive_v2.0/.

The weekly and monthly aggregates of the GlobSnow-2 SE v2.1 products are not used for any validation or intercomparison exercise.

3.1.1 Concept of SCAmod

Sari Metsämäki (SYKE)

The algorithm for Fractional Snow Cover (FSC) retrieval is the semi-empirical reflectance model-based method SCAmod developed at SYKE. SCAmod originates from the radiative transfer theory and describes the scene-level reflectance as a mixture of three major constituents – opaque forest canopy, snow and snow-free ground, which are interconnected through apparent forest transmissivity and snow fraction. The feasible values for these constituents as well as for the transmissivity are based on Earth-observation data and at-ground spectral measurements (Metsämäki et al. 2005&2012, GlobSnow-2 SE ATBD, DEL-09). They are wavelength-specific and can be determined with the applied sensor.

3.1.2 Retrieval of Transmissivity Map

Sari Metsämäki (SYKE)

The transmissivity map is essential to the SCAmod algorithm, describing the transparency (and therefore, the density) of forest canopy, which is then accounted for in the FSC-estimation. Transmissivity is a fusion of MODIS-derived (based on SCAmod reflectance model) and

GlobCover classification (Metsämäki et al. 2012; GlobSnow-2 SE ATBD, DEL-09). The transmissivity is determined for each GlobSnow 0.01°×0.01° pixel, in range [0-1]. The possible errors/uncertainties in transmissivity map have a direct influence to the FSC-retrievals. This may be the case e.g if GlobCover classification presents notable misclassifications (this is particularly relevant if there is confusion between forests and non-forest pixels). The transmissivity map employed in the production of SE v2.1 is the latest version generated within GlobSnow-2. A particular emphasis with the determination work was on the proper consideration of dense forest areas, which are necessarily not well (in terms of transmissivity) distinguishable in GlobCover data. The current transmissivity is therefore partly based on global albedo data (GlobAlbedo, Bicheron et al. 2008) as well, see GlobSnow-2 SE ATBD, DEL-09 for details.

3.1.3 AATSR SCAmod (fractional snow cover)

Sari Metsämäki (SYKE)

The semi-empirical reflectance model-based method *SCAmod* originates from the radiative transfer theory and describes the scene reflectance as a mixture of three major reflectance constituents – opaque forest canopy (ρ_{forest}), snow (ρ_{snow}) and snow-free ground (ρ_{ground}), which are interconnected through the *apparent forest transmissivity* and the snow fraction. In GlobSnow, SCAmod employs top-of-atmosphere reflectance acquisitions of ATSR-2/AATSR Band 1 (545–565nm) as $\rho_{\lambda,obs}$. The feasible values for the three reflectance constituents are based on MODIS band 4 (550nm) reflectance observations and field. Also Band 4 (1.58-1.64 µm) is used together with Band 1 to provide Normalized Difference Snow Index (NDSI) for detecting snow-free areas. To improve the detection of snow-free areas a threshold applied on the thermal band 6 (10.40-11.30 µm) is additionally introduced. The previous SE version 1.2 uses generally applicable static values for three reflectance constituents (ρ_{snow}= 0.65, ρ_{ground}=0.10 and ρ_{forest} =0.08). As a significant improvement, the production of current SE v2.1 data uses a spatially varying field for ρ_{ground} (Salminen et al., 2013, GlobSnow-2 SE ATBD, DEL-09).

SCAmod may result to FSC>1 (100%) if the observed reflectance is higher than the maximum allowed by the model. The solution for FSC>1 is to cut it into 100%. SCAmod may also result to FSC<0 if the observed reflectance is lower than the minimum assumed by the model. In this case, FSC is set to zero.

Since SCAmod reflectance model relies on the observed reflectance alone, a separate test for identification of snow-free conditions is applied in order to avoid false snow detection if reflectance is increased due to other reasons than snow. NDSI is used to identify snow-free cases. Hence, if NDSI < -0.02, FSC is set to zero. This low value was chosen to avoid false snow omissions in forests where NDSI can be very low, depending on the density (e.g. Niemi et al. 2012; Xin et al. 2012). Additionally, the brightness temperature of band 6 (11µm) is checked for each pixel. If BT11 > 288 K then FSC is also set to zero.

3.1.4 Generation of Binary Snow Map from Daily GS-2 SE Product

Nando Foppa (MeteoSwiss), Sari Metsämäki and Kristin Böttcher (SYKE), Rainer Unger (ZAMG)

Binary snow cover information is needed for intercomparison with ground based measurements and with other binary snow information form satellite data. Binary snow maps were derived from the GlobSnow-2 Daily Fractional Snow Cover data sets (DFSC) from AATSR SCAmod for all processed years with available validation data. The DFSC product provides highest temporal resolution for the comparison with daily in-situ measurements without introducing any temporal averaging.

Two thresholds were implemented primarily to determine a pixel to be snow covered or snow free:

SE50: if DFSC >= 50%

SE15: if DFSC >= 15%

At Finnish weather stations also snow coverage is observed and documented by e-codes. Thus, an additional threshold was applied for classifying binary snow maps from the GlobSnow-2 SE product to be compared with e-codes of Finnish weather stations:

SE0 :if DFSC >= 0%

3.2 AVHRR Snow Extent (binary)

Fabia Hüsler (UBE)

The snow detection relies on a threshold approach that capitalizes on the spectral properties of snow in the visible and the near infrared spectrum and is applicable to any kind of AVHRR sensor generation. Originally developed for rather flat areas in Canada (Khlopenkov and Trishchenko 2007), the algorithm has been adapted and optimized for use in complex terrain. The modifications of the original algorithm basically include changes in (and differentiation of) the thresholds, taking into account land cover types and topographic features such as terrain shadow. A detailed description of the algorithm itself and an extensive validation of the product can be found in Hüsler et al. (2012).

Data pre-processing includes radiometric calibration using Patmos-X calibration coefficients for visible channels, automated geolocation and orthorectification and a cloud masking (CASPR; Key 2002). Furthermore, daily maximum composites are generated from all available overflights in order to reduce the influence of clouds and to benefit from multiple acquisitions per day. Employed sensors are:

NOAA-16: AVHRR/3 Instrument, Channel 3A configuration available until 31/04/2003,
Channel 3B configuration after (476 scenes, 2003-2004)

NOAA-17: AVHRR/3 Instrument, Channel 3A configuration (940 scenes, 2003-2006)

NOAA-18: AVHRR/3 Instrument, Channel 3B configuration (517 scenes, 2006-2010)

Furthermore, data from NOAA-14 were included for the years 1999 and 2000 and from NOAA-19 with a 3B-configuration for the year 2010.

3.3 Snow maps from high resolution satellite data

This section includes descriptions of algorithms applied on high resolution satellite data used as reference data set for intercomparison and evaluation of the full GlobSnow-2 SE v2.1 product data set.

3.3.1 Applied algorithms

Gabriele Bippus and Elisabeth Ripper (ENVEO), Sari Metsämäki (SYKE)

For the generation of the reference data set from high and very high resolution satellite data different approaches for deriving binary or fractional snow cover maps are applied and intercompared with the GlobSnow-2 SE v2.1 products.

Additionally to the approaches described in the following subsections two conditions were accomplished beforehand on Landsat scenes.

Thermal threshold:

A threshold is applied on the thermal band of Landsat in order to reduce misclassifications due to bright surface classes, as for instance bright rocks:

if B(11 µm) > 288 K then NO SNOW

Shadow and dark surface threshold:

For excluding cast shadowed areas additional thresholds are applied on the visible band at 0.55 µm, the mid infrared band at 1.6 µm, and on the Normalized Difference Vegetation Index (NDVI) calculated with the near infrared band at 0.85 µm and the visible band at 0.66 µm.

$$NDVI = \frac{R_{TOA}(0.85\ \mu m) - R_{TOA}(0.66\ \mu m)}{R_{TOA}(0.85\ \mu m) + R_{TOA}(0.66\ \mu m)} \quad \text{Equ. 3.1}$$

Pixels are classified as No Data if the following condition is met:

if B(1.6 µm) < 0.02 AND B(0.55 µm) < 0.2 AND NDVI < 0.1 then NO DATA

3.3.1.1 Binary SE by adapted method after Dozier and Painter, 2004

Gabriele Bippus and Elisabeth Ripper (ENVEO)

The approach of Dozier and Painter (2004) for snow classification from hyperspectral images, as Landsat TM, MODIS or SPOT, is based on thresholds applied on the Normalized Difference Snow Index (NDSI, Hall et al., 1995), and on a near-infrared band (NIR, 0.85 µm):

$$NDSI = \frac{VIS - SWIR}{VIS + SWIR} = \frac{b_{0.55\ \mu m} - b_{1.6\ \mu m}}{b_{0.55\ \mu m} + b_{1.6\ \mu m}} \quad \text{Equ. 3.2}$$

The following condition is used to classify binary snow:

$$IF \quad NDSI > threshold_{NDSI} \quad AND \quad b_{0.85\ \mu m} > threshold_{NIR} \quad THEN\ SNOW$$

The following thresholds are used to classify

- $threshold_{NIR} = 0.11$
- $threshold_{NDSI} = 0.40$

These thresholds were applied on un-forested and Based on experiences of the evaluation activities in

3.3.1.2 Fractional SE by Multispectral Unmixing with End-member selection

Gabriele Bippus and Elisabeth Ripper (ENVEO)

In the framework of the ASAP-6 Project ASAG – The multispectral unmixing algorithm developed by ENVEO is combined with an adaptive end-member selection. The algorithm applies two clean end-members: fully snow covered and completely snow free pixels. These are directly classified in the selected image using a binary pre-classification. The pre-classification is an **adaptation of the method of Dozier and Painter** $SWIRVIS+SWIR=b0.55\ \mu m- b1.6\ \mu m b0.55\ \mu m+ b1.6\ \mu m$ *Equ. 3.2*) and a NIR band a threshold applied on the blue band (0.48 µm).

IF (NDSI >= 0.70 and R_{TOA}(0.85µm) >= 0.11 and R_{TOA}(0.48µm) >= 0.30)

THEN 100 % SNOW

ELSE IF (NDSI < -0.10 and R_{TOA}(0.85µm) < 0.11 and R_{TOA}(0.48µm) <= 0.10)

THEN SNOWFREE

ELSE mixed pixel (classification by ENVEO's MS Unmixing approach)

The resulting binary snow classification combined with a high-resolution forest mask to identify non-forested areas is used for mapping Fractional Snow Cover from HR optical satellite data over non-forested areas only. Regions with "100% snow" and "mixed snow" over forested areas are binary classified as "snow in forest".

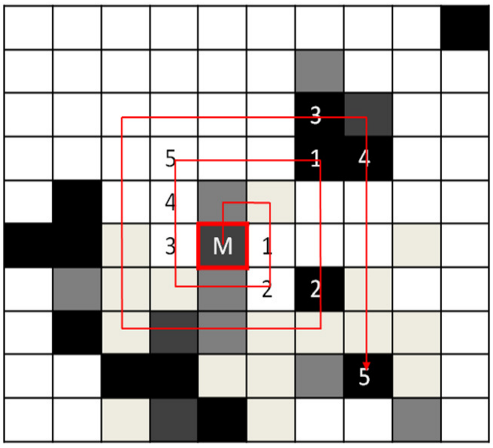


Figure 3.1: End-member selection for mixed pixels.

The algorithm for fractional snow cover applies multi-spectral linear unmixing with local end-member selection for the mixed pixels. For the end-member selection in the algorithm the closest 5 snow free and 5 snow-covered pixels are selected by a helical search, which is illustrated in Figure 3.1.

For each combination of snow covered and snow free pixels (25) spectral unmixing is executed applying the following method: the combination showing the smallest difference between calculated and measured reflectance (ε_λ) is written to the output.

$$R_\lambda = \sum_{i=1}^{M} F_i R_{\lambda,i} + \varepsilon_\lambda \qquad \textit{Equ. 3.3}$$

R_λ = Reflectance of the pixel of wavelength λ
$R_{\lambda,i}$ = Reflectance of end-member i and
F_i = Fraction of end-member i

ε_λ = Residual error at wavelength λ

The processing line enables to achieve good

For areas with mainly fractional snow cover or

3.3.1.3 Fractional SE by adapted method after Salomonson and Appel (2006)

Gabriele Bippus and Elisabeth Ripper (ENVEO) and

The method of Salomonson & Appel (2006) is also based on the Normalized Difference Snow $SWIRVIS+SWIR=b0.55\ \mu m-\ b1.6\ \mu m b0.55\ \mu m+\ b1.6\ \mu m$ *Equ. 3.2*). The approach uses a linear model to weight the binary snow classification derived by the NDSI:

$$FSC = -0.01 + 1.45 * NDSI \qquad \text{Equ. 3.4}$$

For calibrating the weighting values a set of

3.3.1.4 Binary SE by adapted method after Klein et al. 1998

Gabriele Bippus and Elisabeth Ripper (ENVEO) and

$SWIRVIS+SWIR=b0.55\ \mu m-\ b1.6\ \mu m b0.55\ \mu m+\ b1.6\ \mu m$ *Equ. 3.2*) and on $RTOA0.85\ \mu m-\ RTOA0.66\ \mu m RTOA0.85\ \mu m+\ RTOA0.66\ \mu m$ Equ. 3.1).

The following classification rules are applied to generate a binary snow map:

IF TM2 (0.525-0.605um) > 0.10 (10%) AND TM4 (0.75-0.90um) > 0.11 (11%)
AND some of the following is true:
NDSI > 0.4
*OR NDVI >= 0.25 && NDSI >= 0.0652 * EXP(1.8069 * NDVI)*
OR NDVI >= 0.1 && NDVI < 0.25 && NDSI >= (NDVI-0.2883)/-0.4828)
THEN 'snow'
OTHERWISE pixel is 'snow free'.

3.3.2 Processing lines

3.3.2.1 Landsat data

The snow map generation from Landsat data is based on a fully automated processing line. The spectral bands of Landsat 5 TM and Landsat 7 ETM+ (cf. Table 3.1) enable the generation of snow maps by each of the algorithms described in Section 3.3.1. The conceptual processing line for the snow map generation from Landsat data is shown in Figure 3.2.

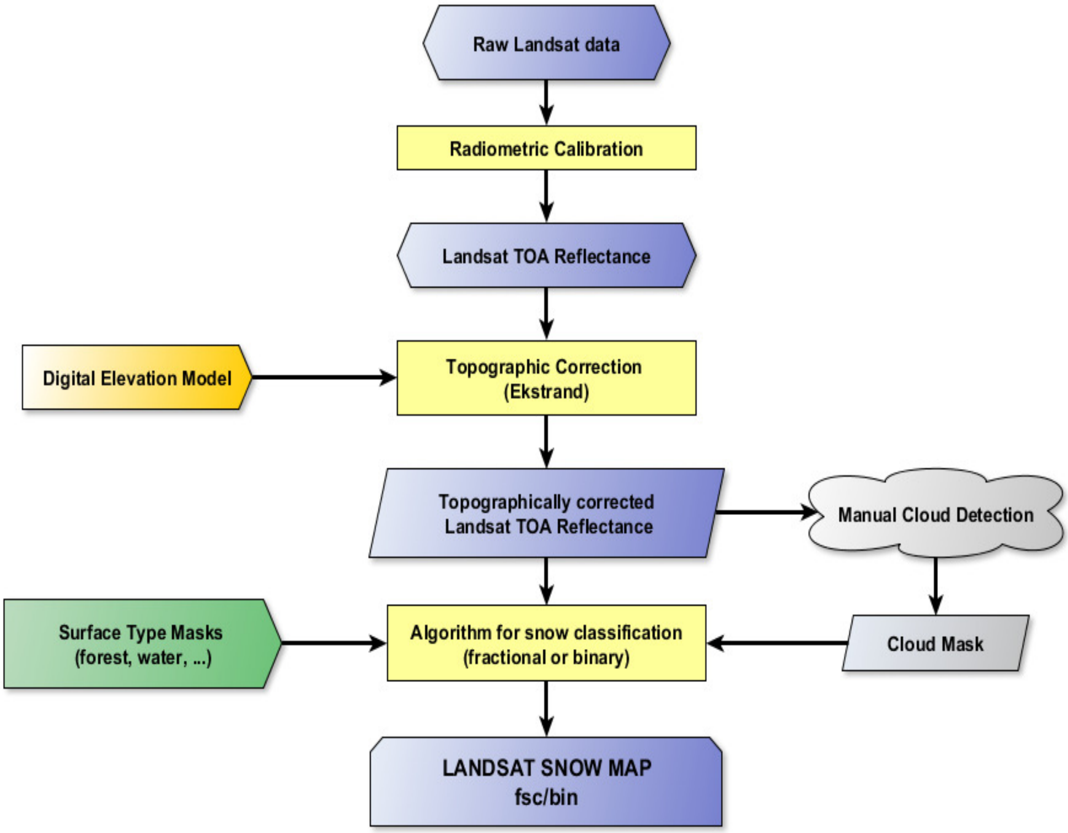


Figure 3.2: Processing line for snow map generation from Landsat data.

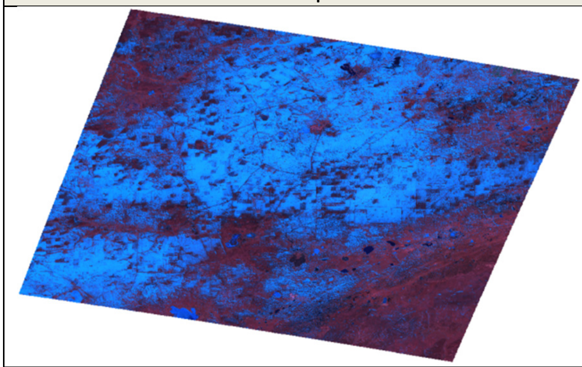
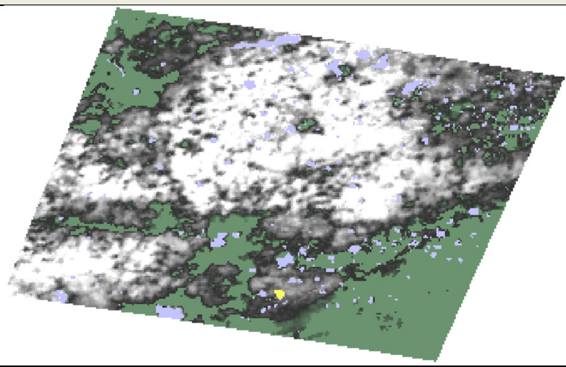
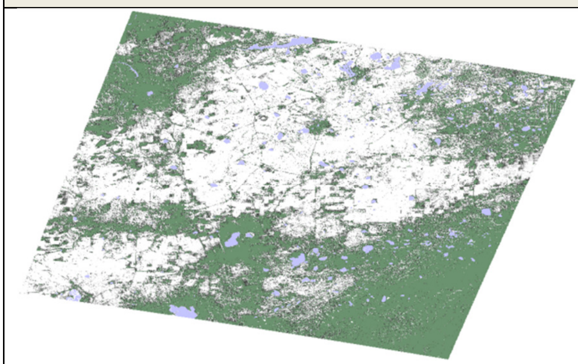
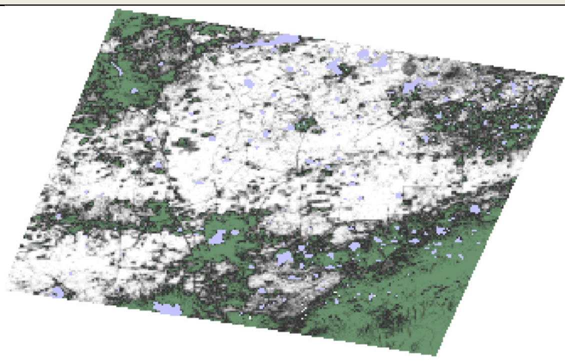
Table 3.1: Band numbers, wavelengths and resolution of Landsat 5 TM and 7 ETM+ sensors.

Sensor	Band No.	Wavelength (micrometers)	Resolution (meters)
Landsat 5 Thematic Mapper (TM)	Band 1	0.45-0.52	30
	Band 2	0.52-0.60	30
	Band 3	0.63-0.69	30
	Band 4	0.76-0.90	30
	Band 5	1.55-1.75	30
	Band 6	10.40-12.50	120* (30)
	Band 7	2.08-2.35	30
Landsat 7 Enhanced Thematic Mapper Plus (ETM+)	Band 1	0.45-0.52	30
	Band 2	0.52-0.60	30
	Band 3	0.63-0.69	30
	Band 4	0.77-0.90	30
	Band 5	1.55-1.75	30
	Band 6	10.40-12.50	60** (30)
	Band 7	2.09-2.35	30
	Band 8	.52-.90	15

* TM Band 6 was acquired at 120-meter resolution, but products processed before February 25, 2010 are resampled to 60-meter pixels. Products processed after February 25, 2010 are resampled to 30-meter pixels.

** ETM+ Band 6 is acquired at 60-meter resolution. Products processed after February 25, 2010 are resampled to 30-meter pixels

Most reference snow maps from Landsat data are prepared with each of these algorithms, resulting in two fractional and two binary snow classification maps per scene. For some scenes the multi-spectral unmixing method of ENVEO could not be successfully applied, either if the main surface class of a scene is forest, or if the clear end-members identified on an image are not well distributed over the full scene. In the latter case the multi-spectral unmixing results in circular fractional snow cover patterns around the fully snow covered pixels. Examples of the Landsat snow maps generated by different approaches, and resampled to the associated fractional snow cover map with the pixel size of the GlobSnow-2 SE v2.1 products used for the intercomparison are shown in Figure 3.3. An RGB composite of the selected Landsat scene, and the subset of the GlobSnow-2 SE v2.1 product of this date matching the extent of the Landsat scene are shown in the first row.

RGB Composite	GlobSnow SE v2.1
	
30 m	1 km
Salomonson	
	
Enveo	

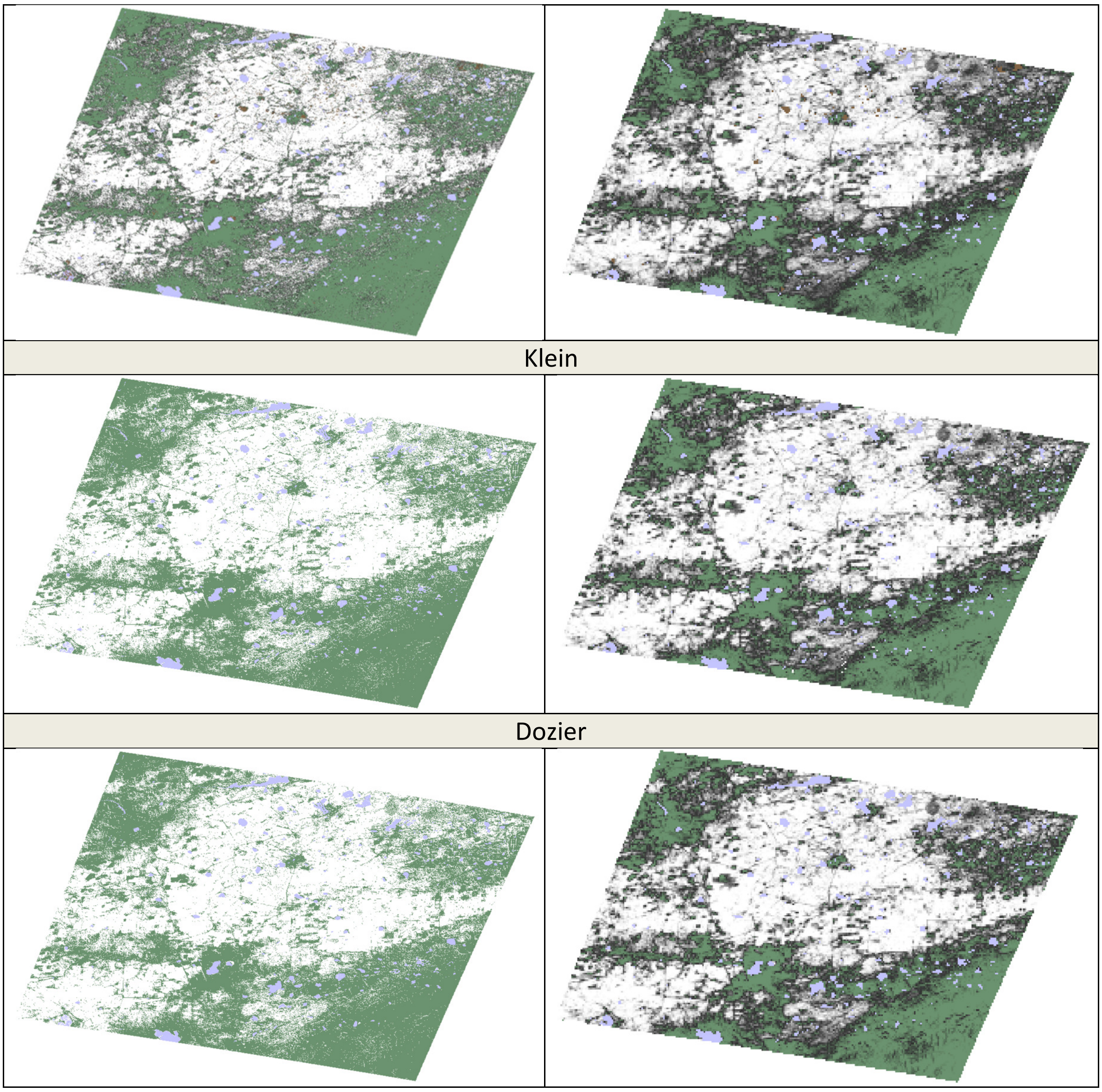


Figure 3.3: Examples of binary and fractional snow maps generated from Landsat 7 ETM+ scene of 17 April 2003 over Kazakhstan (161/024) by the algorithms described in Section 3.3.1, and each resampled to the pixel size of the GlobSnow-2 SE v2.1 product data set (cf. Section 3.3.3).

3.3.2.2 Snow mapping from Kompsat-2 data

Øivind Due Trier and Rune Solberg, (NR)

Making ground truth for fractional snow cover (FSC) is inherently difficult (actually close to impossible in practice) without using remote sensing. However, using remote sensing to validate remote-sensing products urges for particular care. The main challenges making accurate snow maps include:

- **Forest**: If the spatial resolution is not high enough, trees and snow are averaged within a "pixel" (instantaneous field of view, IFOV)
- **Cast shadows**: Extended objects at all scales may create cast shadows as long as the sun in not right above the object. Very apparent in the mountains, but also significant within forests

- **Topography**: As described by Lambert's cosine law the diffuse reflection from a surface depends on the surface's orientation relative to the source of illumination (Sun). Again, effects are very prominent in mountains

The most challenging cases include all three components. For our task here of making accurate snow reference maps for mountains, we have as far as practically possible tried to mitigate the challenges by using very-high spatial resolution. Ideally, imagery of decimetre-scale resolution should have been used (aerial imagery), but this is not available in general when a hemispherical distribution is needed. The Kompsat-2 data represents a "feasible solution" with 4 (MS) and 1 m (PAN) spatial resolution. Individual trees can be seen/detected in the PAN imagery, and the MS imagery helps with land-cover discrimination (such as presence of vegetation). Cast shadows can be clearly identified, and data within and outside the shadows can be analysed separately.

Our goal when analysing the data has been to obtain a quality level as could be expected as from visual image interpretation. However, manually drawing snow maps from 14 scenes of 15 km × 15 km has not been feasible within the budget frame of this work. Therefore, we have approached the problem by using "computer-assisted image interpretation" – we have used image analysis tools to segment the image. We then interpreted the result, corrected the analysis generating a new version, then did a new interpretation, etc. – until the process converged (no more corrections found necessary). In some cases we did not reach convergence and had to discard the result. The approach was further strengthened by using two specialists, one for snow map generation and one for "second opinion" feedback. For convergence, consensus was required. It is the belief of the authors that the snow map results are quite close to the ground truth.

A detailed description of the snow map generation from Kompsat-2 data is provided in Appendix D.

3.3.3 Resampling of HR snow maps

Elisabeth Ripper and Gabriele Bippus (ENVEO)

All high resolution snow maps, the binary and the fractional, are resampled to the grid size of the GlobSnow-2 SE v2.1 products (cf. Section 4.1.1), calculating the associated fractional snow cover for the coarse resolution based on the high resolution snow information. For resampling Landsat snow maps, 40 x 40 pixels with 0.00025 deg pixel size are needed to cover one pixel of the GlobSnow-2 SE v2.1 product (0.01 deg pixel size).

In order to retrieve valid resampled Landsat pixels without losing too much information several resampling criteria were identified. The following resampling criteria are checked in the listed order:

Clouds (1st criterion):

If 1 or more pixels are classified as cloud cover in the Landsat scene the full resampled pixel is classified as "cloud".

Else the next criteria are checked. If none of the following criteria is met the 1600 Landsat pixels are resampled to one fractional snow cover pixel with 0.01 deg pixel size.

Water (2nd criterion):

If more than 480 Landsat pixels (30 %) used for resampling to one GlobSnow-2 pixel are classified as water the resampled pixel is classified as "water".

Else the next criteria are checked. If none of the following criteria is met and less or equal than 480 Landsat pixels used for resampling to one GlobSnow-2 pixel are classified as water, all non-water Landsat pixels are used to identify the fractional snow cover for the associated GlobSnow pixel.

Forest (3rd criterion):

If more than 400 Landsat pixels (25 %) used for resampling to one GlobSnow-2 pixel are classified as forest the resampled pixel is classified as “forest”.

Else the next criterion is checked. If the following criterion is not met and less or equal than 400 Landsat pixels used for resampling to one GlobSnow-2 pixel are classified as forest, all non-forest Landsat pixels are used to identify the fractional snow cover for the associated GlobSnow pixel.

For the snow maps from Landsat data generated by applying the multi-spectral unmixing approach developed by ENVEO for high alpine terrain, and applying a binary classification for forested pixels, two further criteria are checked:

Snow in forest (3a criterion):

If more or equal than 400 Landsat pixels (25 %) used for resampling to one GlobSnow-2 pixel are classified as snow in forest the resampled pixel is classified as “snow in forest”.

Else the next criteria are checked. If the following criteria are not met and less or equal than 400 Landsat pixels used for resampling to one GlobSnow-2 pixel are classified as snow in forest, all Landsat pixels not classified as snow in forest are used to identify the fractional snow cover for the associated GlobSnow pixel.

Forest and Snow in forest (3b criterion):

If each of the classes forest and snow in forest are less or equal than 400 Landsat pixels (25 %) used for resampling to one GlobSnow-2 pixel, but the sum of these two classes is more than 400 Landsat pixels, the resampled pixel is classified as “forest”.

Else, the next criterion is checked. If the next criterion is also not met, all Landsat pixels neither classified as forest nor as snow in forest are used to identify the fractional snow cover for the associated GlobSnow pixel.

No Data (4th criterion):

If more than 480 Landsat pixels (30 %) used for resampling to one GlobSnow-2 pixel are classified as “no data” the resampled pixel is classified as “no data”.

Else the remaining pixels classified as valid data are used to identify the fractional snow cover for the associated GlobSnow pixel.

3.4 Snow maps from in-situ and modelled data

3.4.1 Binary Snow Information from in-situ measurements

A threshold has to be set for the ground based snow depth measurements to define the station site to be snow covered or snow free. In general, a snow day is defined as a day with a snow depth larger than a certain threshold (WMO, 2009). Different thresholds are published in the literature, ranging from varying thresholds for each altitude zone (Marty, 2008) to e.g. 15 cm for the alpine topography (Hüsler et al., 2012). For the validation over Switzerland two thresholds are implemented: >= 1cm (standard of MeteoSwiss) and >= 15 cm (Hüsler et al. 2012).

On a daily basis the pixel-wise fractional snow cover information of the GlobSnow-2 SE product will be re-classified and compared with the snow or no-snow information of in-situ measurements (cf. Section 3.1.4). Primarily, two thresholds (SE15: >= 15%; SE50: >= 50%) are implemented, following the procedure in the preliminary validation study. In the case of observation of snow cover (according to e-codes) at Finnish weather stations, thresholds SE0, SE15 and S50 are directly comparable to observations.

At Finnish Weather stations, observations include also a particular e-code, describing the snow coverage (0-3 = snow-free ground, 4-5 = fractional snow cover < 50%, 6 = Fractional snow cover > 50%, 7-9 = 100% snow cover). These data will be used in generating the binary information as shown in Table 3.2.

Table 3.2: Fractional Snow Cover and associated e-code used for generating binary snow classification.

FSC	e-code
≥ 0.5	6-9
≥ 15	4-9
>0	4-9
<0.5	0-5
<0.15	0-3
=0	0-3

3.4.2 Fractional Snow Information from in-situ measurements

At Finnish Snow courses (transects), observations of local snow fractions are made (40-80 observations along 2-4 km transect). These observations were used directly for fractional-fractional comparison, applying the metrics described in Section 4.3. One sample (case) in the comparison is an average FSC from SE product pixels covering the transect, typically 3-6 pixels. Due to the very limited number of snow course observations coinciding with clear-sky SE-product, the statistical parameters are provided as a single set for the period 2003-2011.

3.4.3 Snow extent from modelled data

For the validation of the AATSR dataset (SE product v2.1) based on model snow data over Austria and the Carpathian region, binary information of snow cover had to be derived from all data (cf. Section 3.1.4). A second threshold had to be set for the modelled snow depth data to define a pixel as snow covered or snow free.

Reference snow model data of the Carpathian region had to be resampled (from 0.1° to 0.01°) and co-registered to meet Globsnow-2 resolution and extent. According to the validation guidelines an averaging algorithm was therefore applied (cf. Section 4.1.1). For Austria only co-registering needed to be done since both datasets were already in the same resolution.

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4 VALIDATION METHODS

4.1 General considerations

4.1.1 Projection, Pixel Size and Snow Classification

All snow products used as reference data sets were prepared in geographic coordinates (Lat/Lon) on WGS84 ellipsoid (EPSG code: 4326). If a reference data set was only available in different projection the snow map was generated in the original projection of the reference data set. The final snow map was then reprojected to geographic coordinates (Lat/Lon) on WGS84 ellipsoid.

For Landsat data, which are originally available in UTM/WGS84 with 30 m pixel size, the resulting projection information was Lat/Lon, WGS84, with 0.00025 deg pixel size, using bilinear interpolation for the reprojection.

The spatial resolution for all snow products used for the statistical analysis was 0.01° x 0.01° pixel spacing according to the GlobSnow-2 SE v2.1 resolution. Thus, all products with a higher spatial resolution were resampled to GlobSnow-2 resolution applying pixel averaging algorithm:

$$FSC_{res} = \frac{\sum_{hr=1}^{N} FSC_{hr}}{N} \qquad \textit{Equ. 4.1}$$

where FSCres is the resampled averaged fractional
To accomplish the product intercomparison the

- The following areas were excluded from the intercomparison:
  - areas not acquired either by AATSR or by the reference data set
  - areas which are cloud covered in one of the products
  - open water areas (ocean, lakes, etc.), derived from water mask used for GlobSnow-2 SE v2.1 product generation.
- For the remaining area all snow covered and snow free pixels (overlapping pixels, $\boldsymbol{N_{ui}}$) were used for the intercomparison of the GlobSnow-2 SE version 2.1 products with the reference products. Thus the following cases can occur for the intercomparison:
  - both products have overlapping pixels with fractional snow cover (FSC 1-100 %),
  - pixels where the GlobSnow-2 SE v2.1 product shows fractional snow cover (FSC 1-100%) and the reference product (e.g. resampled Landsat-7, etc.) is snow free,
  - pixels where the reference product shows fractional snow cover (FSC 1-100%) and the GlobSnow-2 SE v2.1 product is snow free,
  - both products have overlapping snow free pixels.
- The snow cover ranges 0 – 100 % and 1 – 100 % are both used for intercomparisons.

Table 4.1: Pixel sizes and classifications for GlobSnow-2 SE v.2.1 evaluation.

D	Pixel sizes of evaluation products	Sn
	Global / Northern Hemisphere	
Gl	0.01 deg	fra

D	Pixel sizes of evaluation products	Sn
Gl	0.01 deg	fra
NS	0.005 deg, 0.01 deg $FSCres = hr{=}1NFSChrN$ *Equ. 4.1* $FSCres = hr{=}1NFSChrN$ *Equ. 4.1*)	fra
Europe		
Cr	0.005 deg, 0.01 deg $FSCres = hr{=}1NFSChrN$ *Equ. 4.1*)	fra
Regional		
U	0.01 deg	bin
La	30 m, 0.01 deg $FSCres = hr{=}1NFSChrN$ *Equ. 4.1*)	fra
Ko	4 m / 1 m, 0.01 deg $FSCres = hr{=}1NFSChrN$ *Equ. 4.1*)	Binary, resampled to fractional

4.1.2 Pixel Reference

Rounded coordinates refer to the upper left pixel corner for all provided snow products, i.e. if the upper left corner of a pixel is for instance 84.00 N / 168.00 W, the centre of the same pixel is 83.995 N/ 167.995 W.

4.1.3 Coding

All validation data have to be coded using GlobSnow-2 standards as provided in Table 4.2.

Table 4.2: GlobSnow-2 coding.

Code	Description
	Snow information for DFSC product
100	100: FSC = 0 %
101	101: FSC = 1 %
...	...
200	200: FSC = 100 %
	General thematic class codes
0	No data
20	Cloud
30	Glacier

40	Water body
	Exception codes applied in all products
51	Outside mapping area
53	Not mapped in product time frame
54	Too low solar angle for snow retrieval (<17°)
55	Missing or invalid satellite data
57	Snow retrieval algorithm breakdown
58	No snow retrieval algorithm applicable
	Additional codes for evaluation
60	Forest (binary forest mask)
61	Mountain (binary mountain mask)
62	Snow in forest (LS-FSC product)

4.1.4 Differentiation of surface classes

The intercomparison and evaluation of snow products was done for all surfaces covered by the GlobSnow-2 SE v2.1 and the particular reference products. Additionally the intercomparison of GlobSnow-2 SE v2.1 and reference snow products was separated for the following different surface classes:

- Forest
- Non forested areas
- Mountains
- Plains

For snow products from high resolution satellite data algorithms for retrieving binary and fractional snow cover are used. For **forested and non-forested areas** different approaches were tested for classifying binary and fractional snow extent, respectively, from high resolution satellite data: the methods of Klein et al. (1998), Dozier and Painter (2004), and an adapted version of Dozier and Painter (2004) developed by ENVEO for binary snow classification, and the method of Salomonson and Appel (2004, 2006) for fractional snow classification. For only **non-forested areas** additionally the multi-spectral unmixing approach developed by ENVEO is used for fractional snow cover mapping.

Table 4.3: Surface classes used for statistical evaluation.

Surface Classes	Class Name
Total Area	
total image	total
all forested areas	forest
all un-forested areas	noforest
Plain area	
plain terrain	plain_total
only forested plain terrain	plain_forest
only un-forested plain terrain	plain_noforest
Mountainous area	

mountainous terrain	mountain_total
only forested mountainous terrain	mountain_forest
only un-forested mountainous terrain	mountain_noforest

As topography can significantly affect the snow classification, the evaluation and intercomparison is performed separately for mountainous areas. The general mountain mask includes all areas with slopes >2 deg.

Additionally to the particular surface classes combinations of the classes are possible. Table 4.3 summarizes all the classes and class combinations. The forest and slope masks as described above are used as auxiliary data to identify these classes.

4.2 Binary metrics

The following measures based on contingency table statistics are used for the accuracy assessment of satellite-based binary snow products, generated as described in Section 3.1.4:

- the accuracy as hit rate (ACC),
- the probability of detection for snow (POD) and no snow events (PODns),
- the false alarm ratio for snow (FAR) and no snow (FARns),
- the probability of false detection (POFD), and
- the Kuiper's skill score (KSS).

Table 4.4: Variables for binary metrics.

Scenario	SCAmod AATSR snow	SCAmod AATSR no snow
Reference data: snow	a	b
Reference data: no-snow	c	d

where

$$PODsnow = a / (a + b) \quad \text{Equ. 4.2}$$

$$PODno\text{-}snow = d / (c + d) \quad \text{Equ. 4.3}$$

$$FARsnow = c / (a + c) \quad \text{Equ. 4.4}$$

$$FARno\text{-}snow = b / (b + d) \quad \text{Equ. 4.5}$$

$$HR = (a + d) / (a + b + c + d) \quad \text{Equ. 4.6}$$

$$KSS = (a * d – c * b) / ((a + b) * (c + d)) \quad \text{Equ. 4.7}$$

4.3 Fractional metrics

In this section the statistical parameters for validating the different fractional snow cover products from satellite data are defined.

The following statistical parameters were calculated to evaluate the agreement of snow extent products:

- The snow covered area of each individual product is derived by the number of equivalent fully snow covered pixels (***N_{equ}***), which is given according to

$$N_{equ} = \sum_{j=0}^{y} \sum_{i=0}^{x} \frac{FSC(i,j)}{100} \qquad \textit{Equ. 4.8}$$

  where the fractional snow coverage is in per cent (values between 0 to 100 %).

- The correlation coefficient calculation between the GlobSnow-2 FSC (GS) and the reference product (REF) includes only the suitable pixels for the inter-comparison (Nui) and is given by

$$CorrCoef = \frac{\sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{GS}(i,j) - \overline{FSC_{GS}}\right)\left(FSC_{REF}(i,j) - \overline{FSC_{REF}}\right)}{\sqrt{\sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{GS}(i,j) - \overline{FSC_{GS}}\right)^2 \sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{REF}(i,j) - \overline{FSC_{REF}}\right)^2}} \qquad \textit{Equ. 4.9}$$

  where $\overline{FSC}$ is the average fractional snow cover value.

- For determining the Bias between the GlobSnow-2 and the reference product, the pixels specified by Nui are used as calculation basis:

$$BIAS = \frac{1}{N_{ui}} \sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{GS}(i,j) - FSC_{REF}(i,j)\right) \qquad \textit{Equ. 4.10}$$

- The root-mean-square deviation, RMSD, between the GlobSnow-2 and the reference products is calculated using all pixels suitable for inter-comparison (Nui) according to

$$RMSD = \sqrt{\frac{1}{N_{ui}} \sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{GS}(i,j) - FSC_{REF}(i,j)\right)^2} \qquad \textit{Equ. 4.11}$$

- In addition to the RMSD, the unbiased RMSD is applied using the same input dataset (Nui) and is described by

$$unbiased\ RMSD = \sqrt{\frac{1}{N_{ui}} \sum_{j=0}^{y} \sum_{i=0}^{x} \left(\left(FSC_{GS}(i,j) - \overline{FSC_{GS}}\right) - \left(FSC_{REF}(i,j) - \overline{FSC_{REF}}\right)\right)^2}$$

Equ. 4.12

- Standard deviation

$$StdDev = \sigma = \sqrt{\frac{1}{N_{ui}} \sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{GS}(i,j) - \overline{FSC_{REF}} \right)^2} \qquad \textit{Equ. 4.13}$$

4.4 Inter-satellite comparison

Inter-satellite comparison between ERS-2/ATSR-2 and Envisat/AATSR can be made e.g. by determining the correlation between the corresponding products for the time period where observations by both sensors are provided. Melting period 2003 serves as such a season. For the comparisons, ATSR-2 observations from all analysed dates are combined into dataset #1, and all AATSR observations from the corresponding dates into dataset #2; then correlation coefficient between these datasets is determined.

In contrast to the method of inter-satellite comparison presented in DEL-11 the AVHRR SPARC BIN data set was taken as a reference here. Hence, the evaluation was carried out using difference images and binary metrics (see 4.2) for the Alpine Region for different surface classes, namely forest, non-forested areas, mountains and plains for the Alpine Region.

4.4.1 Intercomparison with global / European SE products

The intercomparison of the daily GlobSnow-2 SE v2.1 products with other daily snow products available with global or European coverage was carried out for 3 annual periods. The years **2003**, **2004** and **2010** were therefore selected.

4.4.2 Statistical Parameters

For the product intercomparison of the daily GS-2 SE product with SE products over large areas derived from other sensors and/or using other algorithms the statistical parameters described in Section 4.3 are used.

4.4.3 Snow Difference Maps

Snow extent difference maps can help to identify possible patterns of the snow distribution on the northern hemisphere derived from different sensors and with different algorithms.

For global and European reference snow products daily difference maps with the GS-2 SE v2.1 products, were generated for the years 2003, 2004 and 2010:

$$FSC_{DIFF} = FSC_{GS} - FSC_{REF} \qquad \textit{Equ. 4.14}$$

Based on the daily difference maps mean monthly difference maps using the absolute differences per pixel are generated.

4.4.4 Intercomparison with local SE products

Local SE products were generated from high resolution (HR) optical satellite data, as available from Landsat or Kompsat-2 satellites. Short descriptions on multiple options for snow map generation from high resolution satellite data are provided in Section 3.3. Local SE-products (mainly Landsat TM/ETM+ scenes) were selected so that they match temporally and spatially the GlobSnow-2 SE v2.1 products. The scenes represent differed landscapes in North America and Eurasia and also feature different stages of snow coverage, from low snow fractions to high snow fractions/full snow cover.

Binary snow maps from HR data are derived by using the methods of Dozier and Painter (2004) and Klein et al. (1998). Binary snow classification from HR data is applied on all surface classes.

Fractional snow maps from HR data are derived by 2 different approaches:

- the multi-spectral unmixing method developed by ENVEO, described in GlobSnow-2 Deliverable D11, Section 2.8.
- the approach of Salomonson and Appel (2006).

For the multi-spectral unmixing method a binary snow classification is needed for the adaptive end-member selection. Fractional snow cover from HR data by this method is only retrieved for non-forested areas, in mountainous and plain terrain. For identifying forested and non-forested areas a global forest mask with 30 m pixel size derived from Landsat data (Hansen et al. 2013) is used.

Fractional snow cover by the method of Salomonson and Appel (2006) is retrieved for all surface classes.

4.4.5 Evaluation of Fractional Snow Extent

For the evaluation of the daily GS-2 SE v2.1 products with local Fractional Snow Cover products from high resolution satellite data the statistical parameters described in Section 4.3 are used.

Fractional snow retrievals are assessed for

- non-forested areas, applying all three above mentioned methods for HR-data,
- all land pixels, applying Dozier and Painter (2004), Klein et al. (1998) and Salomonson and Appel (2006).

The non-forested areas are determined using the same HR-forest data as used in ENVEO's multi-spectral unmixing method. Water bodies are excluded using the HR water mask from the SRTM DEM.

4.4.6 Evaluation of Binary Snow Classification

For the intercomparison of the binary snow maps derived from the daily GS-2 version 2.1 SE products following the procedure described in Section 3.1.4 with the AVHRR SPARC snow maps the statistical parameters described in Section 4.2 are used.

4.5 Evaluation of Daily GlobSnow-2 SE product with In-Situ Data

The evaluation procedure of the snow extent products based on in-situ data will follow the same approach used for the preliminary validation process. In-situ data include ground-based snow observations (snow depth measurements and observations of snow coverage at a specific station site or at a snow course along a transect through various landscapes).

Snow depth data are available for **Austria**, **Finland**, and **Switzerland**. Data on fractional snow cover are available for Finland.

4.5.1 Description of in-situ snow stations

The in-situ snow stations were selected carefully. All the station sites were analysed including metadata information (e.g. station history) and documented in detail. A list of all station sites from the relevant GlobSnow-2 partners, including geographical position, date range, data gaps, temporal resolution, etc., is provided in 2.3 and Appendix C. A comprehensive analysis and description of the validation sites is of great importance for the interpretation of the validation results. The in-situ observation data were quality controlled and verified through quality processing steps before using for validation purposes.

4.5.2 Statistical parameters and Output

For Switzerland and Austria, the statistical parameters specified in Section 4.2 are calculated on a daily basis for each station separately and for each four threshold combinations (in-situ vs. satellite) separately.

For Finland, statistics are provided separately for each year but for all stations and dates as a whole. This is due to a large number of stations and observations used in the analyses.

For all three geographic regions, the results will be documented for each year and summarized as multi-year averaged values in corresponding tables.

4.6 Intercomparison of Daily GlobSnow-2 SE product with Gridded Snow depth data from Snow Models

The intercomparison of daily GlobSnow-2 SE v2.1 products with gridded snow depth data from snow models has been performed for two test sites:

- Austria
- Carpathian Mountains

The intercomparison follows the same procedure as the intercomparison of the daily GS-2 SE version 2.1 products with in – situ data using binary snow information (cf. Section 4.5).

The binary snow information was generated following the evaluation procedure with in-situ data (cf. Section 3.4.1). Thus for the conversion of snow depth two thresholds are implemented: >= 1cm and >= 15 cm. On a daily basis the pixel-wise fractional snow cover information of Globsnow-2 SE v2.1 products were re-classified and compared with the snow or no-snow information (cf. Section 3.1.4). Therefore two thresholds (SE15: >= 15%; SE50: >= 50%) are implemented, following the procedure of the in-situ validation (cf. Section 3.4.1).

On a daily basis the classified snow covered pixel was compared with the snow or no-snow information from the modelled snow depth data. Contingency matrices for day were designed to calculate different statistical indices and scores as described in Section 4.2. The entire set of statistical parameters is calculated for each threshold combination separately (SE15_SD01, SE15_SD15, SE50_SD01, SE50_SD15).

The validation was carried out for the years 2003, 2004 and 2006 for Austria plus 2010 for the Carpathians.

Additionally, a land cover mask (forest, plain, mountains) was applied to the data in order to find differences on various land cover types. Contingency matrices for each day with coinciding data elements were then designed to calculate the statistical indices and scores. Eventually the daily indices and scores were averaged for the different years individually and for the entire period.

The results for each year and summarized for each geographical region (Austria, Carpathians) as multi-year averaged values are provided in Section 5.8.

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5 RESULTS OF GLOBSNOW-2 SE V2.1 VALIDATION

5.1 Validation against Landsat snow maps

Gabriele Bippus and Elisabeth Ripper (ENVEO)

The GlobSnow-2 SE v2.1 product data set was evaluated with a set of 70 Landsat 5 TM and 7 ETM+ scenes selected over different environments, with different topography and in different climate zones. All selected Landsat scenes were coincidently acquired with AATSR images used for the generation of the GlobSnow-2 SE v2.1 products.

In this section the main evaluation results with all selected Landsat scenes are reported, including the mean results of the statistical analyses (cf. Section 4.3) for snow maps from all Landsat scenes generated with different algorithms, considering also the particular surface types selected to be discriminated (Section 4.1.1). The algorithms of Dozier and Klein were applied on all 70 Landsat scenes, the Salomonson algorithm was used for 69 scenes, and ENVEO's approach was applied on 34 Landsat scenes in high alpine terrain with less forest cover to generate snow maps for the evaluation of the GlobSnow-2 SE v2.1 product data set.

The full evaluation of the GlobSnow-2 SE v2.1 product data set with the selected Landsat images shows partly large differences, dependent on the algorithm used for the generation of the snow maps from Landsat data. The mean correlation coefficients for all intercomparisons using the selected algorithms for generating snow maps from Landsat imagery resulted in correlation coefficients of 0.69 for Salomonson and Klein, 0.68 for Dozier, and 0.81 for ENVEO's approach, each for the total area. While the approaches of Salomonson, Klein and Dozier were applied on almost all or all scenes, ENVEO's approach was applied on only about the half of the scenes.

The resulting mean correlation coefficient for the used pairs of GlobSnow-2 SE v2.1 and Landsat snow products are very similar for the snow maps generated by Dozier's, Klein's or Salomonson's algorithm, in the order of 0.69. Only the evaluation with snow maps generated with ENVEO's approach, applied only on high alpine terrain with less forest cover, shows a significantly higher mean correlation coefficient. This is expectable, as one of the main challenges in mapping snow is the correct detection of snow in forested areas. Scenes with mainly forested areas are not used for the snow mapping with ENVEO's algorithm, as it was not developed for this purpose. The mean unbiased RMSD values range between 11.5 % FSC for snow maps generated by ENVEO's algorithm, and 15 % FSC for these generated with Dozier's approach. The mean unbiased RMSD values for snow maps generated with Klein's and Salomonson's algorithm are similar, each in the order of 14 %, but the mean absolute Bias for snow maps by Klein's algorithm is significantly smaller compared to the mean values for snow maps by all other approaches. The mean standard deviations for all intercomparison pairs are each in the order of 24 %, independently of the algorithm used for the snow map generation from Landsat data. In Table 5.1 all mean statistical parameters for all Landsat scenes and the applied algorithms are shown, each for the total scenes.

If the statistical analyses are executed for particular surface classes some of the resulting measures change significantly, dependent also on the applied algorithm. The main challenge in mapping snow from optical satellite data is the detection of fractional snow cover in forested areas. If the forested area is additionally in mountainous terrain, the correct snow mapping is even more complex. Snow mapping for plain and non-forested areas should provide the best results, as the environmental effects are minor. In order to reduce topographically induced effects in complex terrain, a topographic correction is applied on the top-of-atmosphere-reflectances before any snow mapping algorithm is applied.

Table 5.1: Mean statistical parameters for all evaluations of the GlobSnow-2 SE v2.1 products with snow maps from selected Landsat scenes generated by different algorithms.

Algorithm	No. of analysed Scenes	Mean Corr. Coefficient	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean Std. Deviation	Class
Dozier	70	0,68	-3,36	15,78	15,00	25,13	Total
Enveo	34	0,81	-2,86	12,43	11,49	24,67	Total
Klein	70	0,69	0,57	14,04	13,56	24,02	Total
Salomonson	69	0,69	-3,51	15,01	14,08	23,96	Total

Evaluating the GlobSnow-2 SE v2.1 products with snow maps from Landsat imagery generated with different algorithms clearly indicates the problematic mapping regions, and also shows differences caused by different algorithms. The evaluation results show the worst matching of the GlobSnow-2 SE v2.1 products with Landsat snow maps over mountainous forested terrain, and the best fit for plain non-forested areas. It must be noted however, that the apparent poor matching particularly for forests may be due to the problems in Landsat reference map, not in the GlobSnow SE v2.1 product. Typically the methods applied on the Landsat scenes cannot properly capture the snow in forests but lead to FSC underestimation (e.g. Rittger et al. 2013) which shows up falsely as a poor statistical measure. Also in non-forest regions, their performance may vary significantly, as described by Metsämäki et al. (2014). The mean statistical analyses of the GlobSnow-2 SE v2.1 products versus the snow maps from Landsat generated by the algorithms of Dozier, Klein and Salomonson show in most classes similar correlation coefficients, but compared to Dozier and Salomonson, the mean unbiased RMSD and the mean Bias are often smallest for snow maps by Klein's algorithm. The snow maps generated with ENVEO's approach from selected Landsat scenes show the best agreement with the GlobSnow-2 SE v2.1 products in all classes.

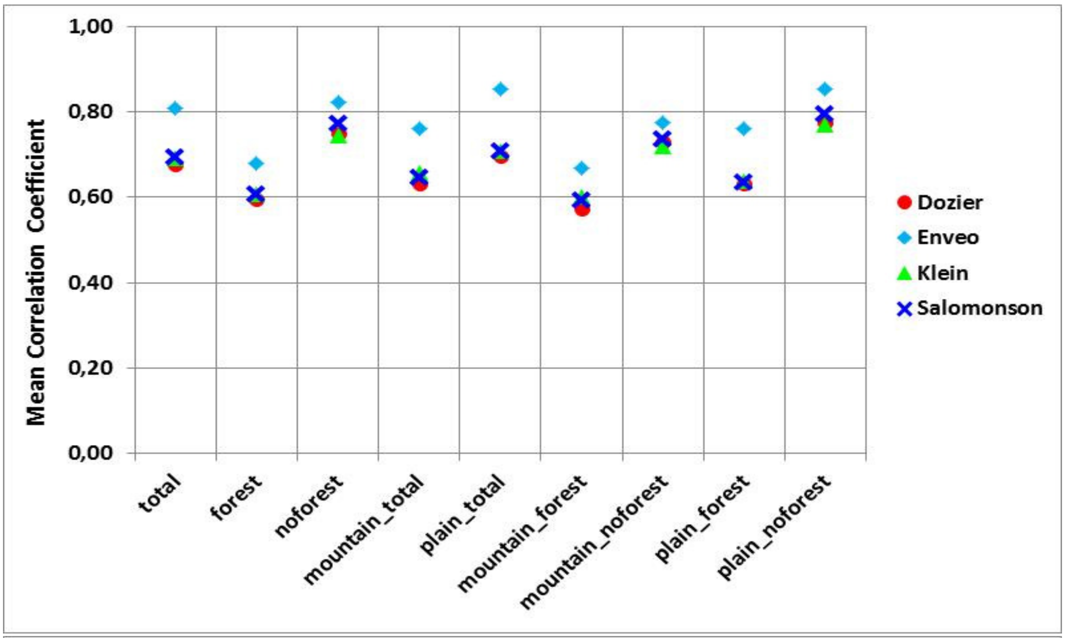
All mean statistical parameters analysed for the GlobSnow-2 SE v2.1 product evaluation with snow maps from Landsat scenes generated by different algorithms are shown in Table 5.2.

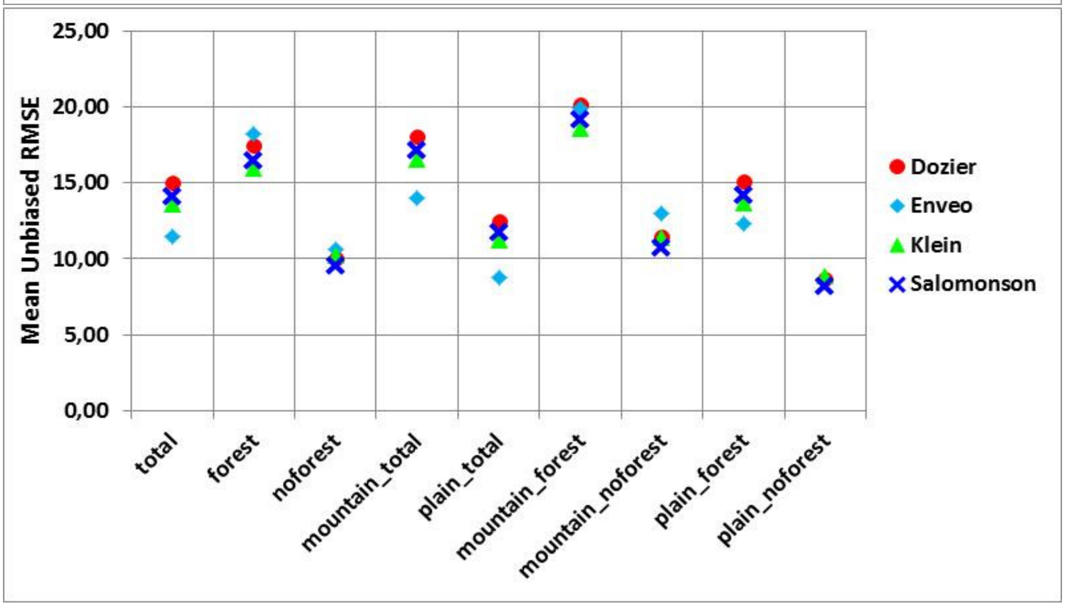
Table 5.2: Mean statistical parameters for all evaluations of the GlobSnow-2 SE v2.1 products with snow maps from selected Landsat scenes generated by different algorithms, considering different surface classes (F = forested, U = non-forested, M = mountain, MF = mountain forested, MU = mountain non-forested, P = plain, PF = plain forested, PU = plain non-forested).

Algorithm	No. of analysed Scenes	Mean Corr. Coefficient	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean Std. Deviation	Class
Dozier	66	0,60	-5,35	19,24	17,48	25,31	F
Enveo	27	0,68	-3,83	19,37	18,18	22,96	F

Algorithm	No. of analysed Scenes	Mean Corr. Coefficient	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean Std. Deviation	Class
Klein	66	0,61	0,72	16,84	15,96	23,52	F
Salomonson	66	0,61	-5,98	18,70	16,43	23,80	F
Dozier	70	0,75	0,23	10,51	10,05	20,62	U
Enveo	33	0,82	-2,15	11,31	10,64	24,19	U
Klein	70	0,74	0,91	10,75	10,20	20,71	U
Salomonson	70	0,77	0,32	10,04	9,54	20,07	U
Dozier	70	0,63	-5,88	19,64	18,04	26,65	M
Enveo	33	0,76	-2,94	14,99	14,03	24,80	M
Klein	70	0,66	-0,73	17,20	16,50	24,75	M
Salomonson	70	0,65	-6,52	19,12	17,13	25,34	M
Dozier	64	0,57	-7,89	22,50	20,12	27,06	MF
Enveo	25	0,67	-3,44	22,43	19,93	25,47	MF
Klein	64	0,60	-1,05	19,45	18,58	24,46	MF
Salomonson	64	0,59	-8,70	22,02	19,11	25,30	MF
Dozier	69	0,73	-0,43	12,19	11,47	20,61	MU
Enveo	33	0,77	-2,67	13,95	12,99	24,30	MU
Klein	69	0,72	0,19	12,12	11,40	20,28	MU
Salomonson	69	0,74	-0,48	11,47	10,74	19,54	MU
Dozier	70	0,70	-2,54	13,13	12,49	21,80	P
Enveo	33	0,85	-1,69	9,26	8,75	21,70	P
Klein	70	0,71	0,96	11,64	11,20	20,85	P
Salomonson	70	0,71	-2,94	12,67	11,75	20,95	P
Dozier	66	0,63	-4,29	16,71	15,14	23,15	PF
Enveo	27	0,76	-1,73	13,41	12,34	19,80	PF
Klein	66	0,64	1,23	14,55	13,68	21,63	PF
Salomonson	66	0,63	-4,91	16,34	14,21	21,88	PF
Dozier	70	0,77	0,38	9,05	8,66	19,95	PU
Enveo	33	0,85	-1,67	9,10	8,59	21,57	PU
Klein	70	0,77	1,03	9,36	8,86	20,06	PU
Salomonson	70	0,79	0,48	8,65	8,20	19,45	PU

In Figure 5.1 the mean statistical values of correlation coefficient, unbiased RMSE and Bias for the evaluation of the GlobSnow-2 SE v2.1 products with snow maps from all Landsat scenes generated with different algorithms are shown for the particular surface classes. This graphic illustrates the similar mean correlation coefficients derived for Dozier, Klein and Salomonson snow maps, but also the mean deviation of all Landsat snow maps from the GlobSnow-2 SE v2.1 products of about 15 % in total, ranging between 8 % for plain non-forested and 23 % for mountainous forested areas. The mean bias values for the intercomparison of the GlobSnow-2 SE v2.1 products with Landsat snow maps generated by Klein's or ENVEO's algorithms are for most of the surface classes significantly smaller than these derived from the comparisons with the Landsat snow maps generated by Dozier's or Salomonson's algorithm.





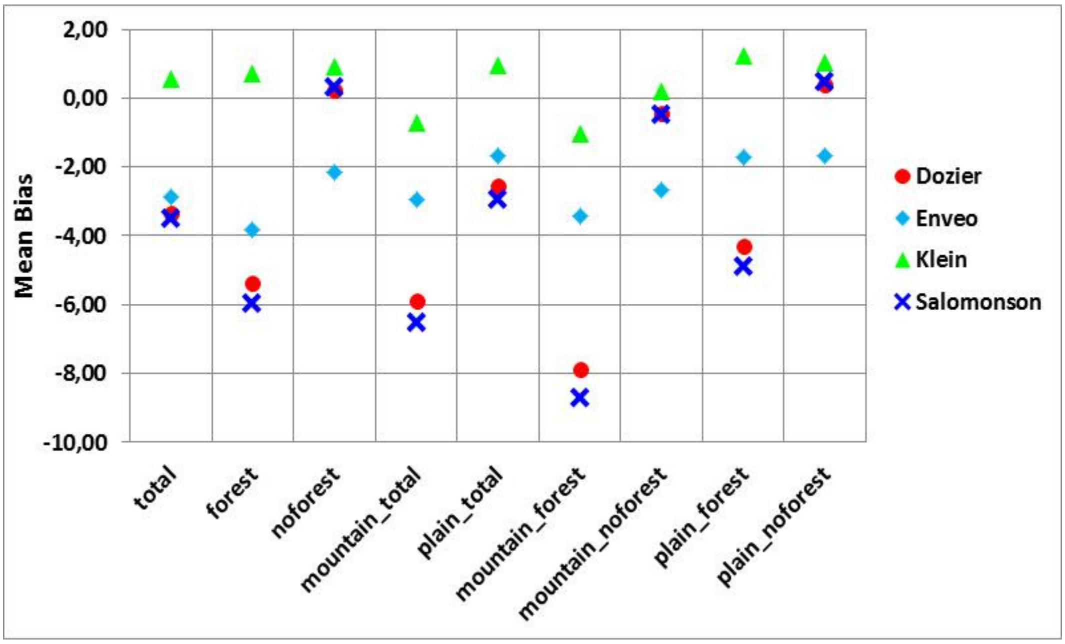


Figure 5.1: Mean Correlation Coefficient (Top), unbiased RMSE (middle) and Bias (bottom) per surface class for the GlobSnow-2 SE v2.1 evaluation with snow maps from all selected Landsat scenes, generated by applying the selected algorithms.

Additionally to the overall mean evaluation results, the detailed evaluation results for 8 snow maps of the selected Landsat scenes, located at different environments and in different climate regions, and generated with different algorithms, are presented. For the results of the statistical analyses only the values for the snow maps generated with Klein's and Salomonson's algorithms are shown, considering also the different surface classes. But the associated scatterplots are shown for all algorithms applied for the snow map generation from Landsat data.

7 of these 8 selected Landsat scenes were acquired in 2003, one was acquired in 2010. 2 scenes were acquired during the main winter months 2003, the remaining were acquired during the melting season, indicating extended areas with fractional snow cover. Further details to the 8 selected Landsat scenes, including exact acquisition date, region name, and detailed location definition by path and row, are provided in the following tables.

The agreement of the snow maps from the 8 selected Landsat scenes with the GlobSnow-2 SE v2.1 products vary in dependence on the location, and on the algorithm used for the generation of the snow map from the Landsat scenes. The comparison of snow maps generated with the Salomonson algorithm with the GlobSnow-2 SE v2.1 products result in correlation coefficients higher than 0.90 in 6 of 8 scenes. The intercomparison pair in Canada has a correlation coefficient of 0.83, and another one in West Russia has a significantly lower value of only 0.62. A similar pattern of the correlation pattern can be observed for the intercomparison of snow maps from Landsat data generated with the Klein algorithm with the GlobSnow-2 SE v2.1 products. Indeed, only 4 of the pairs have a correlation coefficient higher than 0.90, but further 3 pairs have a value equal or greater than 0.80. Only the pair of West Russia has also a significantly lower correlation coefficient of 0.64. The unbiased RMSD shows similar values in most of the intercomparison pairs, each for the Salomonson and for the Klein snow map. A major difference can be observed for the scene over Spain, where the unbiased RMSD for the Salomonson algorithm is 12.44 %, while for the Klein algorithm it is 21.95 %. Also the Bias values show relatively large differences between the intercomparison with snow maps generated by these two algorithms. The Bias values for Salomonson snow maps range between -7.05 and 4.78 for these scenes, and between -1.89 and 11.46 for the Klein snow maps (Table 5.3).

Table 5.3: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the total scenes.

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	36768	0.83	-4.45	22.32	0.80	10.20	25.31
11.05.2003	USA/Rockies	048/022	39355	0.92	-4.41	17.73	0.93	1.47	17.11
16.05.2003	Alaska	172/014	49141	0.92	-2.75	16.13	0.88	8.96	19.80
10.01.2003	Spain	202/033	33217	0.91	4.78	12.44	0.85	11.46	21.95
04.04.2010	Russia West	169/023	44176	0.62	1.29	13.09	0.64	3.62	12.86
17.04.2003	Kazakhstan	161/025	42128	0.96	2.24	6.80	0.96	1.51	6.81
15.05.2003	Russia East	133/021	48867	0.93	-7.05	17.53	0.95	-1.38	14.10
19.02.2003	CH/Alps	194/028	25798	0.91	-3.26	19.77	0.92	-1.89	18.59

Some examples of the associated scatterplots generated for each of the intercomparisons of GlobSnow-2 SE v2.1 products with snow maps from Landsat scene generated by different algorithms are illustrated in Figure 5.2 for mainly plain non-forested area in Kazakhstan, Figure 5.3 for mainly mountainous forested area in the Rocky Mountains, USA, and Figure 5.4 for a scene in Spain, covering all particular surface classes.

The snow maps for mainly plain non-forested areas over Kazakhstan (Figure 5.2), generated by different algorithms from the Landsat scene and resampled to the pixel size of the GlobSnow-2 SE v2.1 products show in general good agreements with the GlobSnow-2 SE v2.1 product, although the resampled products from Landsat show often higher FSC values in the range between 40 and 90 % FSC than the associated GlobSnow-2 SE v2.1 product. The match of the different snow maps are also indicated by the high correlation coefficient of 0.96, the unbiased RMSD of only about 7 % and the Bias values ranging between 1.5 and 2.3 derived from the statistical analyses.

The intercomparison of the resampled snow maps for mountainous forested areas in the Rocky Mountains, USA, generated by different algorithms from the Landsat scene with the associated GlobSnow-2 SE v2.1 product show a wide-spread distribution of the FSC values. Indeed are the correlation coefficients for this scene in the order of 0.92, but this is mainly introduced due to the matches in fully snow covered and snow free areas. The fractional snow cover values from GlobSnow-2 SE v2.1 product compared with snow maps from Landsat scene show large differences for all applied algorithms. This observation is also confirmed by the results of the statistical analyses, with unbiased RMSD in the order of 21 % for the main surface class "mountain forest" and bias values ranging between -6.4 and 1.8.

For the scene over Spain, covering all particular surface classes selected for the discrimination in the GlobSnow-2 SE v2.1 product evaluation the intercomparison with the snow maps from the Landsat scene generated by the different algorithms show partly large differences in the resulting scatterplots (Figure 5.4). This example clearly illustrates the effect of the algorithms selected for the generation of the reference snow map from one Landsat scene. While the match of the GlobSnow-2 SE v2.1 product with the snow map derived by ENVEO's approach show good agreement, with only a few outliers and minor overestimation of FSC from Landsat compared to FSC from AATSR, the intercomparison with snow maps derived by Salomonson's, Klein's and Dozier's algorithm each show partly large differences, with fractional snow cover from Landsat significantly overestimating the FSC from AATSR. The differences in the performance of the selected algorithms applied on the Landsat scene are also reflected by the results of the statistical analyses when comparing the snow maps with the GlobSnow-2 SE v2.1 product. The retrieved unbiased RMSE values for the total area range between 8 % with a Bias of 0.85 for ENVEO's algorithm, and 22 % with a Bias of 11.5 for Klein's algorithm. For snow maps generated with Salomonson's and Dozier's algorithm the retrieved values for unbiased RMSD and Bias for the total area are similar for this scene with 12.4 % and 14.9 % unbiased RMSD and a Bias of 4.8 and 4.4, respectively.

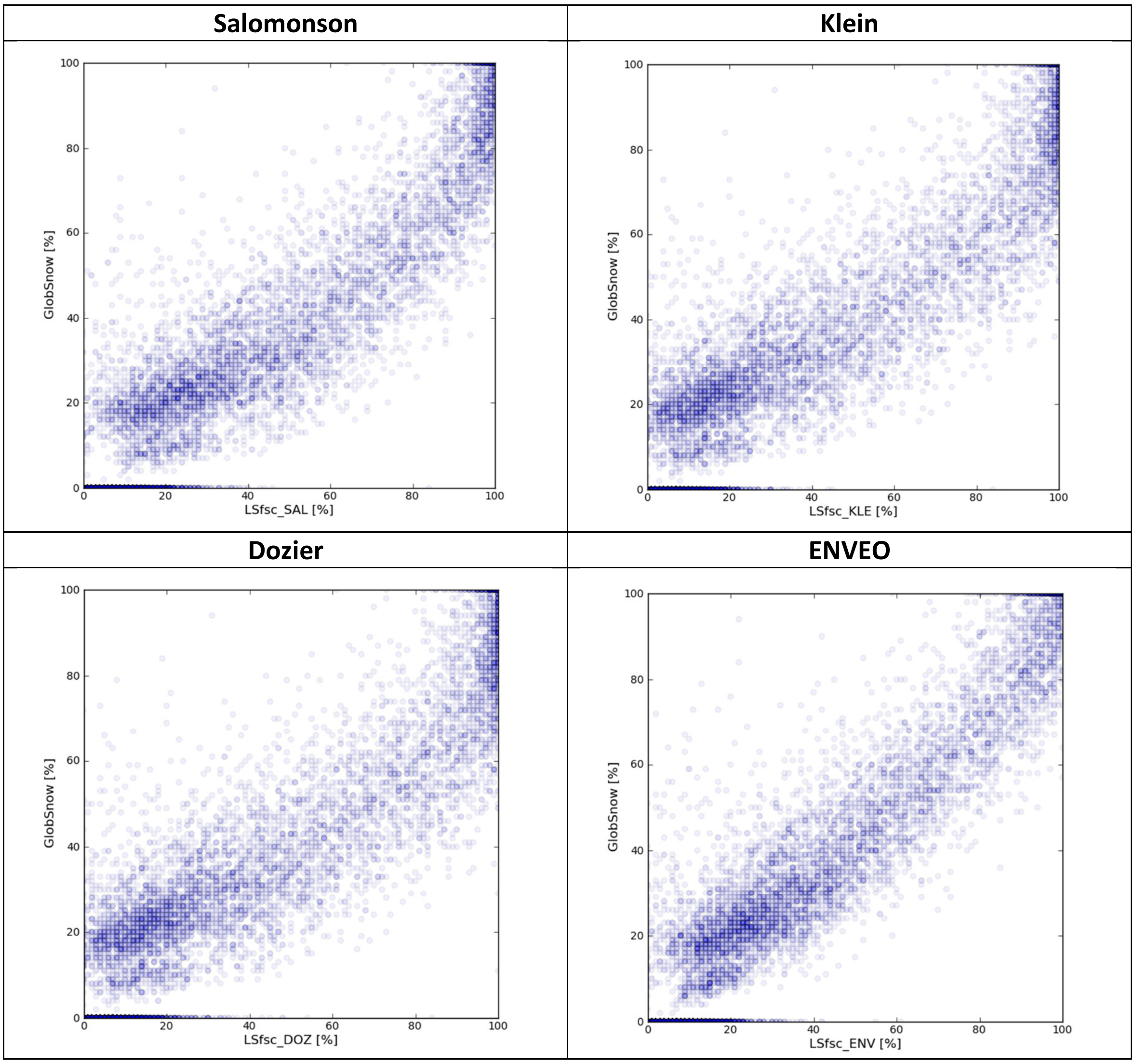


*Figure 5.2: Scatterplots of the intercomparison of the GlobSnow-2 SE v2.1 product with snow maps from Landsat 7 ETM+ scene of 17.04.2003 over **Kazakhstan** generated with different algorithms. Scatterplots are shown for the total area used for the intercomparison.*

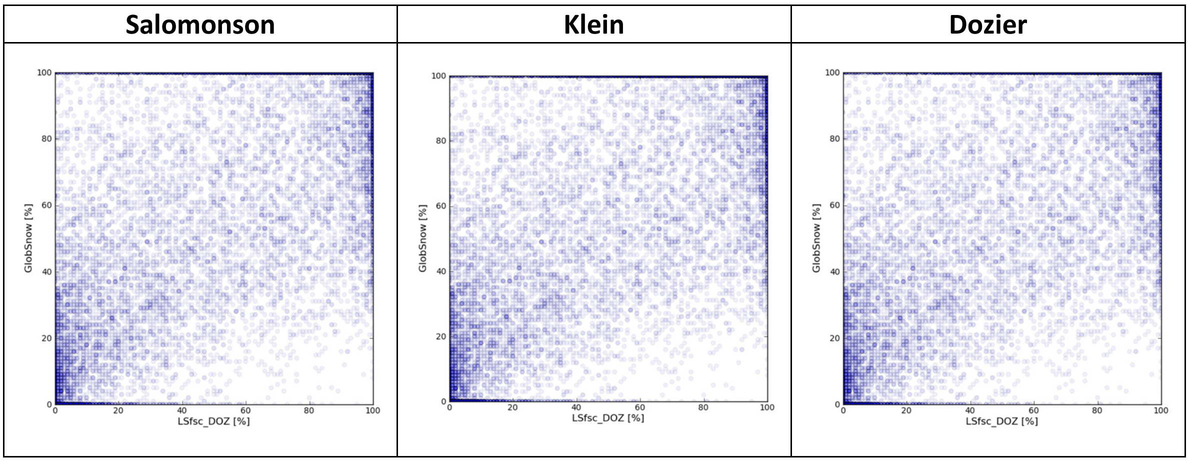


Figure 5.3: Scatterplots of the intercomparison of the GlobSnow-2 SE v2.1 product with snow maps from Landsat 7 ETM+ scene of 2003-05-11 over the ***Rocky Mountains/USA*** *generated with different algorithms. Scatterplots are shown for the total area used for the intercomparison.*

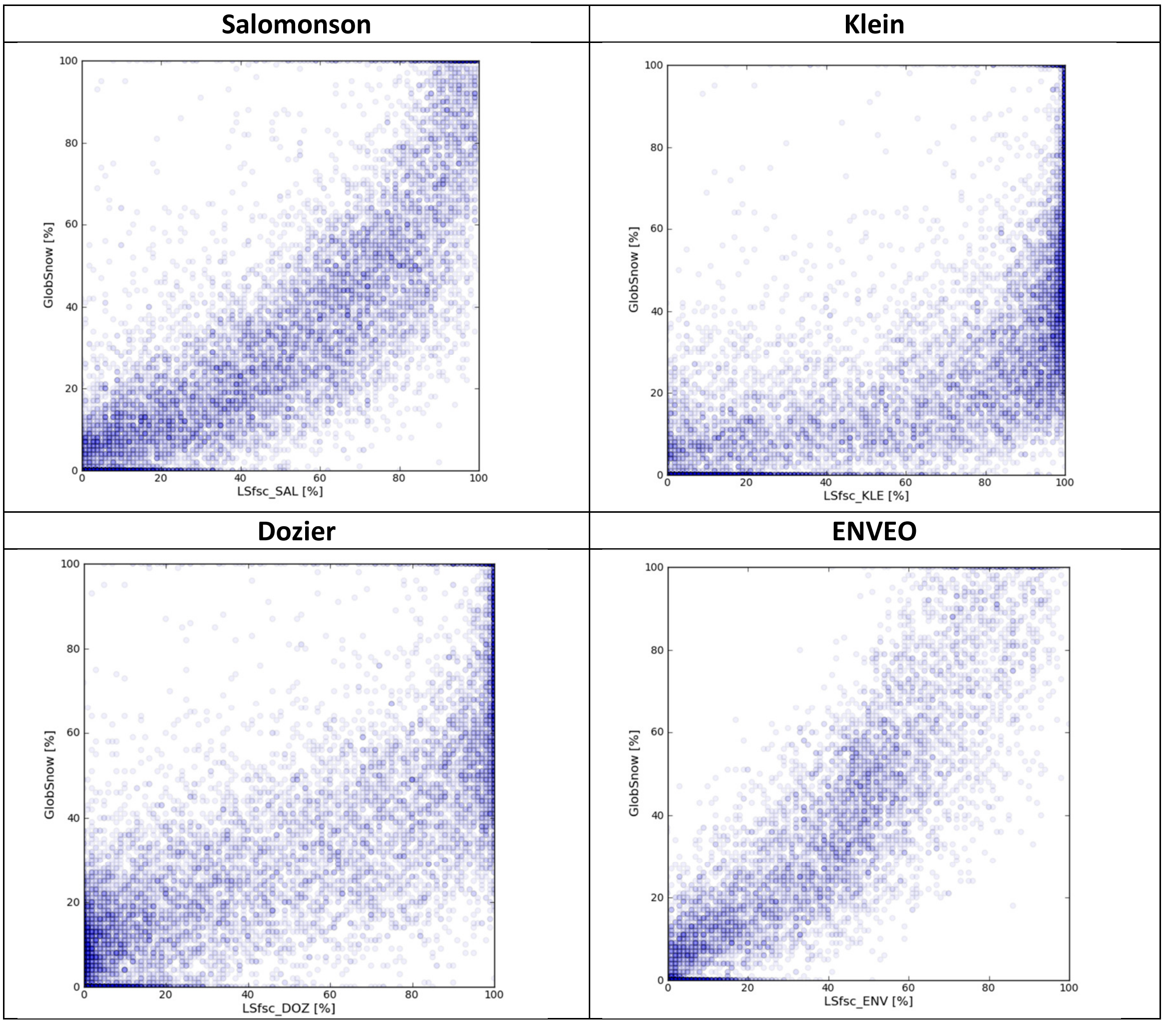


Figure 5.4: Scatterplots of the intercomparison of the GlobSnow-2 SE v2.1 product with snow maps from Landsat 7 ETM+ scene of 2003-01-10 over ***Spain*** *generated with different algorithms. Scatterplots are shown for the total area used for the intercomparison.*

The statistical analyses for the products intercomparison considering particular surface classes (Table 5.4-Table 5.11), as described in Section 4.1.4, show similar patterns as for the total scenes. For some of the classes in the particular scenes the number of pixels is very small, and thus not representative for an objective evaluation. Such cases are marked by grey coloured text in the following tables.

The best matches between the GlobSnow-2 SE v2.1 products and snow maps from Landsat scenes are derived for plain non-forested areas. The unbiased RMSD values for this intercomparisons range between 1.6 % and 19.5 %. For this surface class the snow maps from Landsat data generated with Salomonson better matches the GlobSnow-2 SE v2.1 products than the snow maps generated by Klein's algorithm. This in in agreement with the results presented in Metsämäki et al. (2014). The largest differences are found for mountainous forested areas. For this surface class unbiased RMSD values between 15.8 % and 29.0 % are found, and correlation coefficients ranging between 0.75 and 0.94 for 7 of the scenes, and only 0.22 of the scene of West Russia for each, the Salomonson and the Klein snow map.

Table 5.4: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the surface class "No Forest".

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	100	0.87	-5.93	20.29	0.85	-3.09	21.99
11.05.2003	USA/Rockies	048/022	2048	0.89	-1.73	7.65	0.89	-0.97	7.59
16.05.2003	Alaska	172/014	2848	0.90	6.18	15.43	0.87	12.71	18.03
10.01.2003	Spain	202/033	22965	0.94	4.22	10.44	0.88	9.70	20.15
04.04.2010	Russia West	169/023	34309	0.71	2.98	10.89	0.68	3.42	11.58
17.04.2003	Kazakhstan	161/025	42104	0.96	2.24	6.77	0.96	1.50	6.79
15.05.2003	Russia East	133/021	2563	0.97	-1.82	5.59	0.97	-1.06	5.28
19.02.2003	CH/Alps	194/028	13977	0.98	1.35	8.54	0.98	1.38	8.61

Table 5.5: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the surface class "Forest".

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	36668	0.83	-4.45	22.32	0.80	10.24	25.31
11.05.2003	USA/Rockies	048/022	37307	0.91	-4.56	18.12	0.92	1.60	17.47
16.05.2003	Alaska	172/014	46293	0.92	-3.30	16.01	0.88	8.73	19.88
10.01.2003	Spain	202/033	10252	0.83	6.03	15.97	0.78	15.38	25.09
04.04.2010	Russia West	169/023	9867	0.42	-4.56	17.64	0.52	4.31	16.55
17.04.2003	Kazakhstan	161/025	24	0.80	18.71	19.48	0.81	16.17	19.98
15.05.2003	Russia East	133/021	46304	0.92	-7.33	17.91	0.95	-1.39	14.43
19.02.2003	CH/Alps	194/028	11821	0.81	-8.71	26.68	0.83	-5.76	25.26

Table 5.6: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the surface class "Plain Area, Total".

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	24138	0.85	-2.02	20.66	0.82	12.57	23.76
11.05.2003	USA/Rockies	048/022	15553	0.93	-1.87	11.46	0.93	1.24	11.07
16.05.2003	Alaska	172/014	48764	0.92	-2.72	16.13	0.88	8.96	19.82
10.01.2003	Spain	202/033	26045	0.93	4.06	10.69	0.87	9.75	20.24
04.04.2010	Russia West	169/023	43255	0.63	1.45	12.80	0.65	3.71	12.54
17.04.2003	Kazakhstan	161/025	41326	0.96	2.32	6.62	0.96	1.59	6.62
15.05.2003	Russia East	133/021	24933	0.93	-4.81	14.63	0.95	0.17	11.76
19.02.2003	CH/Alps	194/028	10627	0.95	0.09	4.88	0.96	0.01	4.53

Table 5.7: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the surface class "Plain Area, No Forest".

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	70	0.90	-6.07	18.60	0.88	-3.89	20.38
11.05.2003	USA/Rockies	048/022	145	1.00	-0.81	4.17	1.00	-0.30	4.10
16.05.2003	Alaska	172/014	2845	0.90	6.19	15.43	0.87	12.72	18.02
10.01.2003	Spain	202/033	20358	0.95	3.88	9.94	0.89	9.08	19.47
04.04.2010	Russia West	169/023	33977	0.72	2.97	10.83	0.68	3.42	11.50
17.04.2003	Kazakhstan	161/025	41304	0.96	2.31	6.60	0.96	1.59	6.60
15.05.2003	Russia East	133/021	325	0.99	-1.34	5.29	0.99	-0.82	4.93
19.02.2003	CH/Alps	194/028	8311	0.99	0.25	1.62	0.99	0.05	1.59

Table 5.8: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the surface class "Plain Area, Forest".

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	24068	0.85	-2.01	20.66	0.82	12.61	23.75
11.05.2003	USA/Rockies	048/022	15408	0.93	-1.88	11.50	0.93	1.26	11.11
16.05.2003	Alaska	172/014	45919	0.92	-3.27	16.01	0.88	8.73	19.90
10.01.2003	Spain	202/033	5687	0.85	4.71	13.00	0.80	12.14	22.61
04.04.2010	Russia West	169/023	9278	0.44	-4.08	17.18	0.55	4.76	15.75
17.04.2003	Kazakhstan	161/025	22	0.92	20.18	17.57	0.93	18.05	18.63
15.05.2003	Russia East	133/021	24608	0.93	-4.85	14.71	0.95	0.19	11.83
19.02.2003	CH/Alps	194/028	2316	0.85	-0.47	9.96	0.87	-0.14	9.22

Table 5.9: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the surface class "Mountain, Total".

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	12630	0.78	-9.10	24.53	0.76	5.69	27.48
11.05.2003	USA/Rockies	048/022	23802	0.88	-6.07	20.67	0.89	1.61	20.09
16.05.2003	Alaska	172/014	377	0.94	-5.90	15.75	0.91	9.15	18.09
10.01.2003	Spain	202/033	7172	0.84	7.39	17.12	0.78	17.66	26.37
04.04.2010	Russia West	169/023	921	0.32	-6.28	21.60	0.32	-0.32	23.00
17.04.2003	Kazakhstan	161/025	802	0.84	-1.62	12.33	0.83	-2.81	12.62
15.05.2003	Russia East	133/021	23934	0.91	-9.38	19.84	0.94	-2.99	16.02
19.02.2003	CH/Alps	194/028	15171	0.84	-5.61	25.19	0.86	-3.22	23.84

Table 5.10: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the surface class "Mountain, No Forest".

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	30	0.79	-5.60	23.76	0.77	-1.23	25.26
11.05.2003	USA/Rockies	048/022	1903	0.71	-1.80	7.84	0.71	-1.02	7.79
16.05.2003	Alaska	172/014	3	0.15	-4.67	15.06	0.05	3.33	23.80
10.01.2003	Spain	202/033	2607	0.92	6.90	13.43	0.85	14.60	24.27
04.04.2010	Russia West	169/023	332	0.59	3.95	15.63	0.55	4.02	17.97
17.04.2003	Kazakhstan	161/025	800	0.84	-1.64	12.25	0.82	-2.81	12.59
15.05.2003	Russia East	133/021	2238	0.94	-1.89	5.63	0.95	-1.09	5.33
19.02.2003	CH/Alps	194/028	5666	0.85	2.95	13.10	0.85	3.33	13.15

Table 5.11: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from selected Landsat images for the surface class "Mountain, Forest".

Date	Region	Path / Row	N_{ui}	Salomonson			Klein		
				Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
15.05.2003	Canada	012/024	12600	0.78	-9.11	24.53	0.76	5.71	27.48
11.05.2003	USA/Rockies	048/022	21899	0.87	-6.44	21.39	0.88	1.84	20.81
16.05.2003	Alaska	172/014	374	0.94	-5.91	15.75	0.91	9.20	18.03
10.01.2003	Spain	202/033	4565	0.81	7.67	18.91	0.75	19.41	27.35
04.04.2010	Russia West	169/023	589	0.22	-12.05	22.35	0.22	-2.77	25.07
17.04.2003	Kazakhstan	161/025	2	1.00	2.50	29.50	1.00	-4.50	22.50
15.05.2003	Russia East	133/021	21696	0.90	-10.15	20.60	0.94	-3.19	16.72
19.02.2003	CH/Alps	194/028	9505	0.78	-10.72	28.99	0.80	-7.13	27.63

For the intercomparison with the GlobSnow-2 SE v2.1 product with snow maps from Landsat the performance of the selected algorithms over particular surface classes are crucial for the intercomparison results in case a scene contains one dominant surface class. An example for such a case is shown in Table 5.12 and Figure 5.5 for the intercomparison of the GlobSnow-2 SE v2.1 product with snow maps from a Landsat scene in Alaska, generated by different algorithms.

Table 5.12: Statistical measures for the intercomparison of the GlobSnow-2 SE v2.1 product with snow maps from Landsat scene over Alaska of 16 May 2003 for the total area, and for the main surface class "Forest" in this scene (cf. Figure 5.5).

Class	Salomonson			Klein			Dozier		
	Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD	Corr Coef	Bias	unbiased RMSD
Total	0.92	-2.75	16.13	0.88	8.96	19.80	0.92	-1.63	16.74
Forest	0.92	-3.30	16.01	0.88	8.73	19.88	0.92	-2.16	16.60

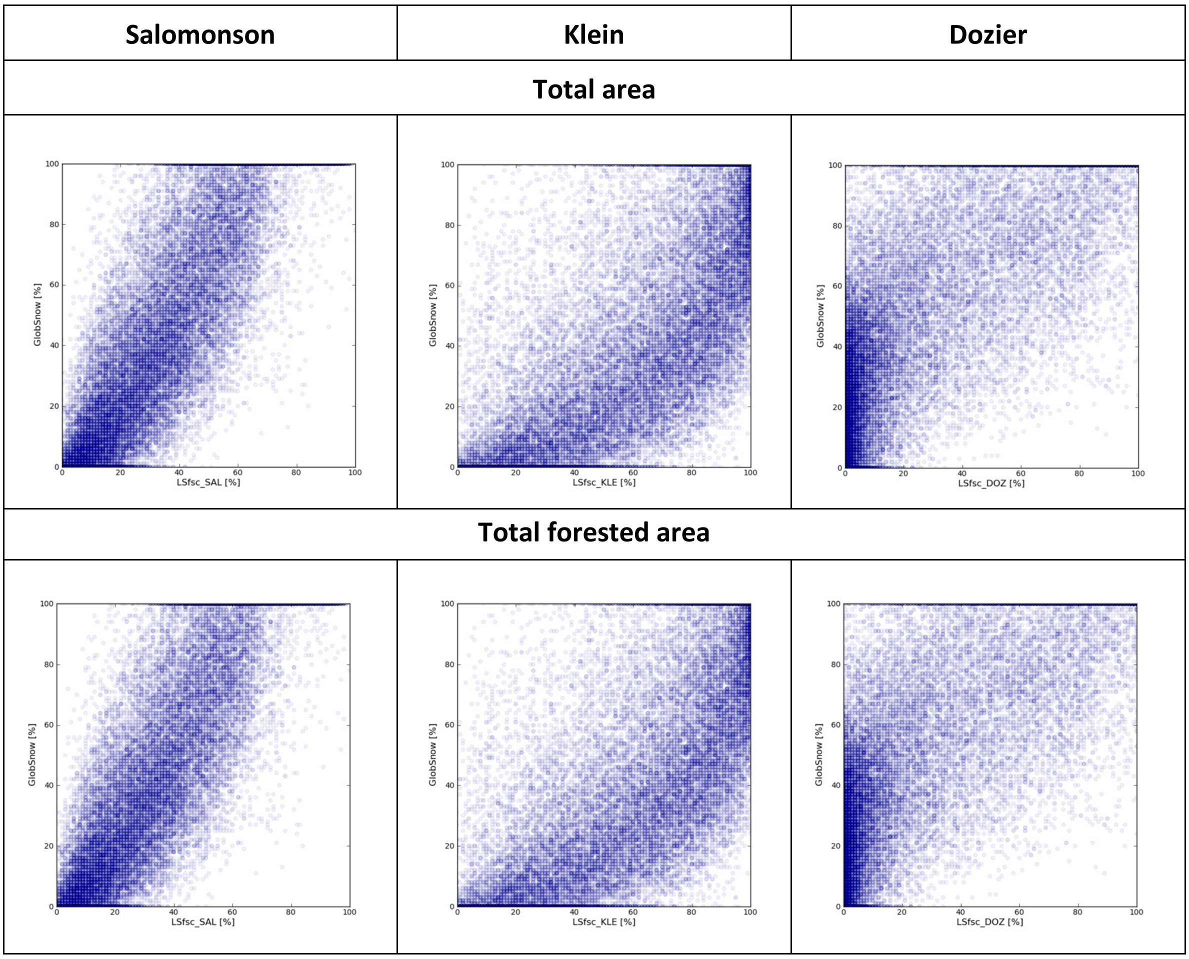


*Figure 5.5: Scatterplots of the intercomparison of the GlobSnow-2 SE v2.1 product with snow maps from Landsat 7 ETM+ scene of 2003-05-16 over **Alaska** generated with different algorithms. Scatterplots are shown for the total area used for the intercomparison (top row), and for the total forested areas on the scene (bottom row).*

The different approaches applied on the Landsat scene show very large differences in the intercomparison with the FSC map from AATSR, but each scatterplot for the total area is very similar to the associated scatterplot generated for the dominant surface class total forested area.

This example also indicates the challenge of mapping snow in forested areas. Although the statistical measures of the intercomparison of the FSC map from AATSR with the snow maps from Landsat scene generated with the algorithms of Salomonson and Dozier show very similar values, the associated scatterplots have completely different distributions. The Salomonson snow map in general underestimates the FSC in forest (Metsämäki et al., 2014), so the apparent overestimations by GlobSnow SE product (Figure 5.5) are not really present. The Dozier snow map also clearly underestimates the FSC from GlobSnow SE v2.1 for FSC values smaller than 10 %, but is anyway wider spread over the full FSC range.

The detailed evaluation results, each for the total area and for particular surface classes, for the GlobSnow-2 SE v2.1 products with all selected Landsat scenes are provided in Appendix G.

Compared to the evaluation of the previous GlobSnow-2 SE v1.2 product data set, the evaluation of the reprocessed data set is based on a significantly larger amount of reference data. Additionally, for the generation of reference snow maps from Landsat data for the evaluation of the reprocessed GlobSnow-2 SE v2.1 product data set multiple algorithms were used, in order to assess the effect of using different approaches for generating a reference data set. Forested and non-forested areas were already discriminated in the evaluation of the GlobSnow-2 SE v1.2 product data set. The detailed evaluation for the surface classes “mountain” and “plain” areas as well as the combination of these two classes with the forested and non-forested areas are new.

The direct intercomparison of the evaluation results for the reprocessed GlobSnow-2 SE v2.1 product data set with the snow maps generated by different algorithms from the selected Landsat scenes with evaluation results derived for the former GlobSnow-2 SE v1.2 products indicate overall a significant improvement of the GlobSnow-2 SE v2.1 products (cf. Table 5.13).

Table 5.13: Intercomparison of differences in the evaluation results for GlobSnow-2 SE v1.2 and for reprocessed GlobSnow-2 SE v2.1 products, each compared with selected Landsat 7 ETM+ (LE7) scenes over European Alps (194/028) of 19 February 2003, Himalaya (145/035) of 17 April 2003, and north-west Alaska (081/011) of 2 May 2003. Bold cursive text indicates the evaluation results of the previous GlobSnow-2 SE v1.2 products, normal text the evaluation results for the reprocessed GlobSnow-2 SE v2.1 products.

Date	Algorithm	LE7 Path	LE7 Row	Nui	Corr. Coef.	BIAS	RMSD	unbiased RMSD	SD	GS SE Version
19.02.2003	***Dozier***	***194***	***27/28***	***53094***	***0,90***	***-4,07***	***21,34***	***20,95***		***1.4***
19.02.2003	Dozier	194	27/28	28104	0,56	-2,55	18,81	18,585	27,85	2.1
19.02.2003	Enveo	194	27/28	11887	0,595	0,295	12,93	12,93	27,99	2.1
19.02.2003	Klein	194	27/28	25019	0,545	-0,93	16,475	16,43	26,83	2.1
19.02.2003	Salomonson	194	27/28	25019	0,545	-3,585	18,2	17,825	28,28	2.1

Date	Algorithm	LE7 Path	LE7 Row	Nui	Corr. Coef.	BIAS	RMSD	unbiased RMSD	SD	GS SE Version
17.04.2003	***Dozier***	***145***	***35/36***	***58569***	***0,95***	***0,53***	***8,14***	***8,12***		***1.4***
17.04.2003	Dozier	145	35	10418	0,98	-1,16	6,53	6,42	31,14	2.1
17.04.2003	Enveo	145	35	9636	0,99	-0,36	3,63	3,62	29,69	2.1
17.04.2003	Klein	145	35	10312	0,98	-1,13	6,42	6,31	31,05	2.1
17.04.2003	Salomonson	145	35	10312	0,99	-0,59	5,24	5,21	30,94	2.1
02.05.2003	***Dozier***	***81***	***10-12***	***694412***	***0,54***	***-4,63***	***12,34***	***11,44***		***1.4***
02.05.2003	Dozier	81	11	67700	0,65	-2,92	9,25	8,77	11,45	2.1
02.05.2003	Enveo	81	11	67700	0,59	-4,82	11,15	10,05	13,01	2.1
02.05.2003	Klein	81	11	67006	0,65	-2,93	9,26	8,78	11,47	2.1
02.05.2003	Salomonson	81	11	67006	0,65	-3,01	8,45	7,89	10,52	2.1

5.2 Validation against Kompsat-2 snow maps

Elisabeth Ripper and Gabriele Bippus (ENVEO)

The intercomparison with snow maps generated from Kompsat-2 data gives information on the GlobSnow-2 SE v2.1 product performance in complex terrain. The used scenes are located in multiple climate regions all on the northern hemisphere. Each snow map from the Kompsat-2 scenes is resampled to the pixel size of the GlobSnow-2 SE v2.1 products (cf. Section 3.3.3). Not all of the Kompsat-2 scenes were acquired exactly on the same date as a GlobSnow-2 SE v2.1 product is available, but the delay in the scene acquisitions is within 2 days. As all scenes are over mountainous areas at high altitudes, the effect of the acquisition delay should be negligible.

The quality of the manually generated snow maps from Kompsat-2 scenes with the high spatial resolution was assessed by the analysts for each scene (cf. Appendix D). In Table 5.14 the quality assessments for the particular scenes user for intercomparison with the GlobSnow-2 SE v2.1 products are summarized. These should be considered for the interpretation of the validation results.

The number of pixels used for the validation of the GlobSnow-2 SE v2.1 products with resampled snow maps from Kompsat-2 scenes is in general small due to the small spatial coverage of Kompsat-2 scenes. For the selected intercomparison pairs the statistical analyses were performed, resulting in Correlation Coefficients ranging between -0.15 and 0.77, unbiased RMSD values between 1.06 % and 29.92 %, and Bias values between -10.29 and 8.56. The results of the statistical analyses for all used scenes are shown in Table 5.15.

Table 5.14: Quality assessment of snow maps from Kompsat-2 scenes used for validation exercises with the GlobSnow-2 SE v2.1 products.

Acquisition Date	Region	Assessment of quality of snow map from Kompsat-2 scene
06.06.2010	Japan-MtNorikura	Quite accurate above the tree line, inaccuracies in forested areas
08.04.2011	Norway-Oppland-Gausdal-Liomseter	Quite accurate, with marginal misclassifications
05.03.2009	USA-Ca-Yosemite	Quite accurate
29.10.2008	Tibet (033438)	Very accurate
29.10.2008	Tibet (033440)	Very accurate
23.03.2009	Norway-Troms-Bardu-Skadjoaivvit	Very accurate
23.03.2009	Norway-Troms-Bardu-Altevann	Very accurate
20.06.2010	Kashmir	Accurate, some underestimations at patchy snow areas

In two cases, the scenes in Norway of 23 March 2009, the resampled fractional snow cover from Kompsat-2 scenes and the GlobSnow-2 SE v2.1 products had very small differences in the order of a thousandth, resulting in a Correlation Coefficient close to zero. As the products match very well, as also indicated by the unbiased RMSD and the Bias (cf. Table 5.15), but the correlation coefficient is misleading, this parameter has been manually set to “nan” in these two cases.

Table 5.15: Statistical analyses for the GlobSnow-2 SE v2.1 products with resampled snow maps from Kompsat-2 images.

Date of KS2 acquisition	Date of GS-2 SE v2.1 product	Region	N_{ui}	Corr Coef	Bias	unbiased RMSD
06.06.2010	06.06.2010	Japan-MtNorikura	115	0.43	-10.29	23.13
08.04.2011	09.04.2011	Norway-Oppland-Gausdal-Liomseter	261	-0.15	0.25	10.26
08.04.2011	07.04.2011	Norway-Oppland-Gausdal-Liomseter	345	-0.14	-1.30	8.76
05.03.2009	07.03.2009	USA-Ca-Yosemite	197	-0.10	2.58	9.76
29.10.2008	29.10.2008	Tibet (033438)	163	0.71	1.60	17.60
29.10.2008	29.10.2008	Tibet (033440)	156	0.57	-1.24	20.53
23.03.2009	22.03.2009	Norway-Troms-Bardu-Skadjoaivvit	639	nan	0.13	1.06
23.03.2009	22.03.2009	Norway-Troms-Bardu-Altevann	608	nan	1.75	8.95
20.06.2010	20.06.2010	Kashmir	91	0.77	8.56	29.92

Figure 5.6 illustrates the results of the statistical analyses for the snow maps from all selected Kompsat-2 scenes used for the intercomparison with the GlobSnow-2 SE v2.1 products, including unbiased RMSD, Bias and Number of pixels used for the intercomparisons.

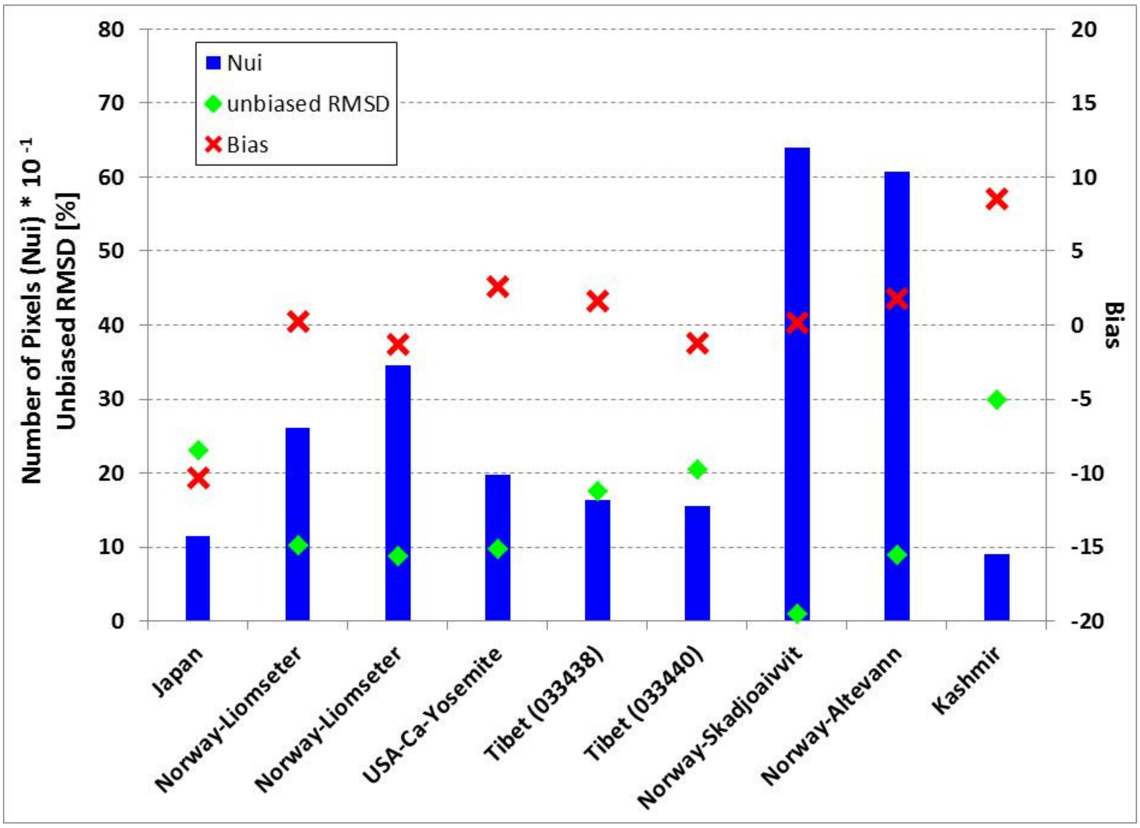


Figure 5.6: Statistical analyses, including number of pixels (Nui), unbiased RMSD and Bias, for the intercomparison of the GlobSnow-2 SE v2.1 products with the snow maps from the selected Kompsat-2 scenes in mountainous regions.

5.3 Intercomparison with MOD10_L2

Gabriele Bippus and Elisabeth Ripper (ENVEO)

Intercomparison of the GlobSnow-2 SE v2.1 products on a hemispheric scale has been performed with the MOD10_L2 products for the years 2003, 2004 and 2010. For the intercomparison of these two products difference maps (cf. Section 4.4.3) for the winter season 2003/2004, and for the period February – April for each of the selected years have been generated. Additionally, the statistical analyses described in Section 4.3 were used for assessing the compliance of these two fractional snow cover products, considering also different surface classes as described in Section 4.1.4.

Figure 5.7 shows the number of pixels with at least one difference in the daily FSC products in the period 1 October 2003 – 31 May 2004, as well as the mean absolute deviation per pixel for the total area. Figure 5.8 shows the associated statistical analyses for this period for the total area, including correlation coefficients, number of pixels and unbiased RMSD.

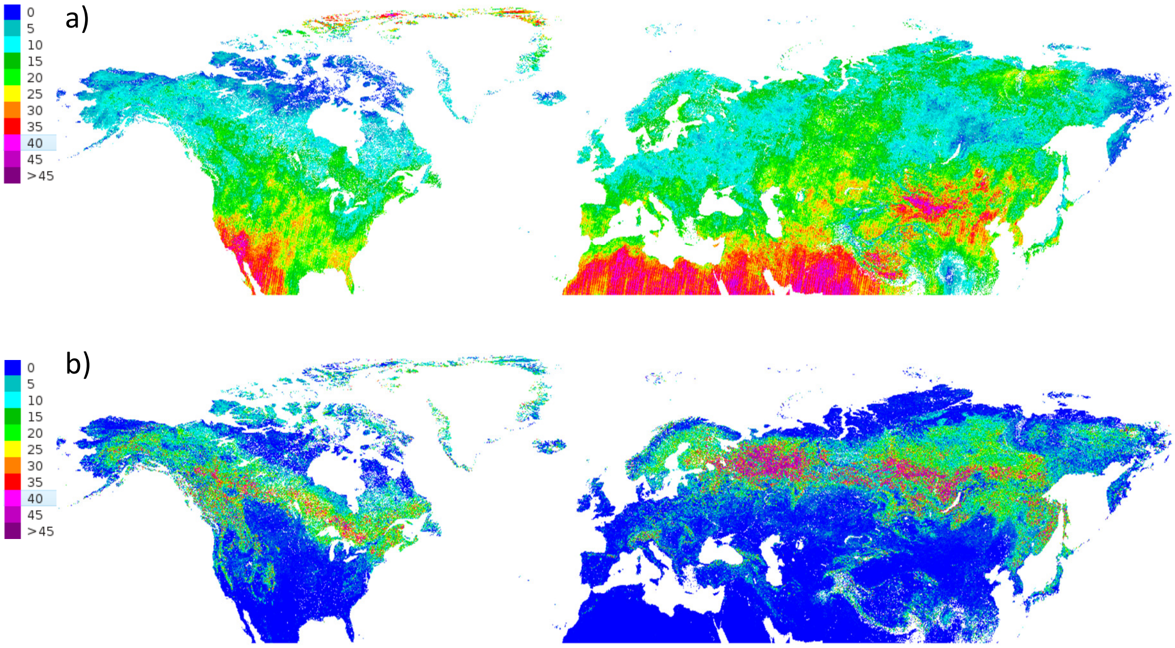


Figure 5.7: a) Number of pixels with differences in FSC for the period 1 Oct 2003-31 May 2004. b) Mean absolute deviation of the daily snow difference maps for the total area generated from GlobSnow-2 SE v2.1 and MOD10_L2 products for the selected period.

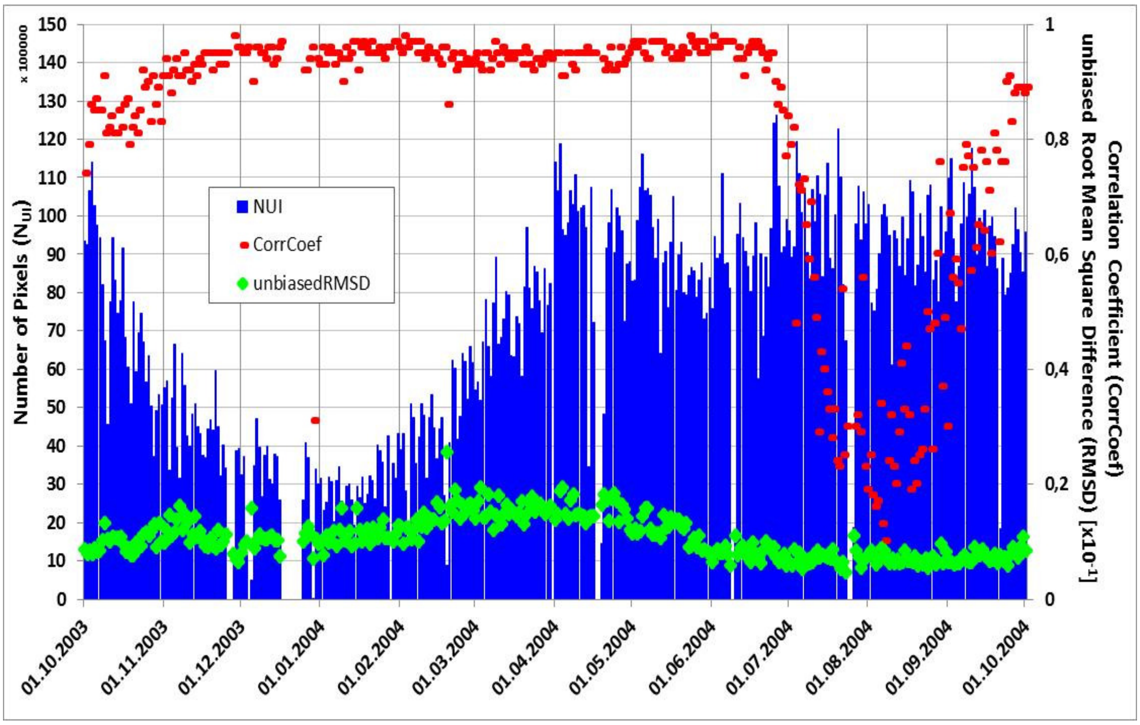
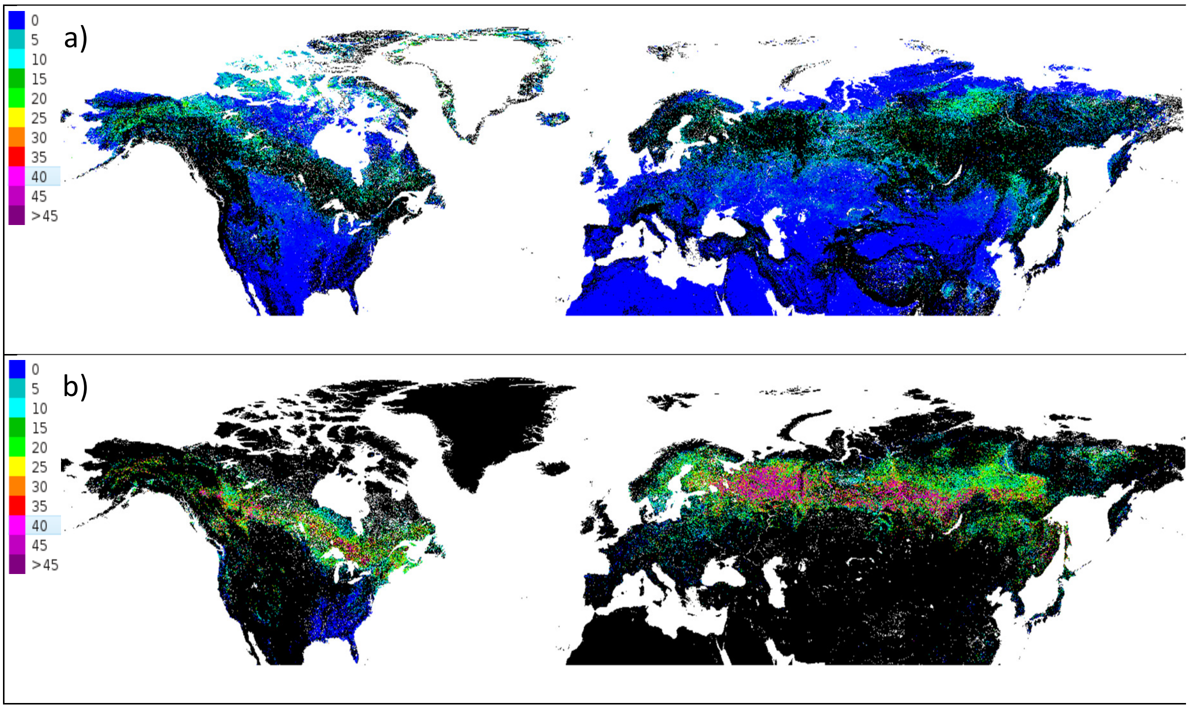


Figure 5.8: Daily statistical analyses, including number of pixels (Nui), correlation coefficient (CorrCoef), and unbiased RMSD for the intercomparison of the total areas of GlobSnow-2 SE v2.1 product and the MOD10_L2 product for the period 1 October 2003 to 1 October 2004.



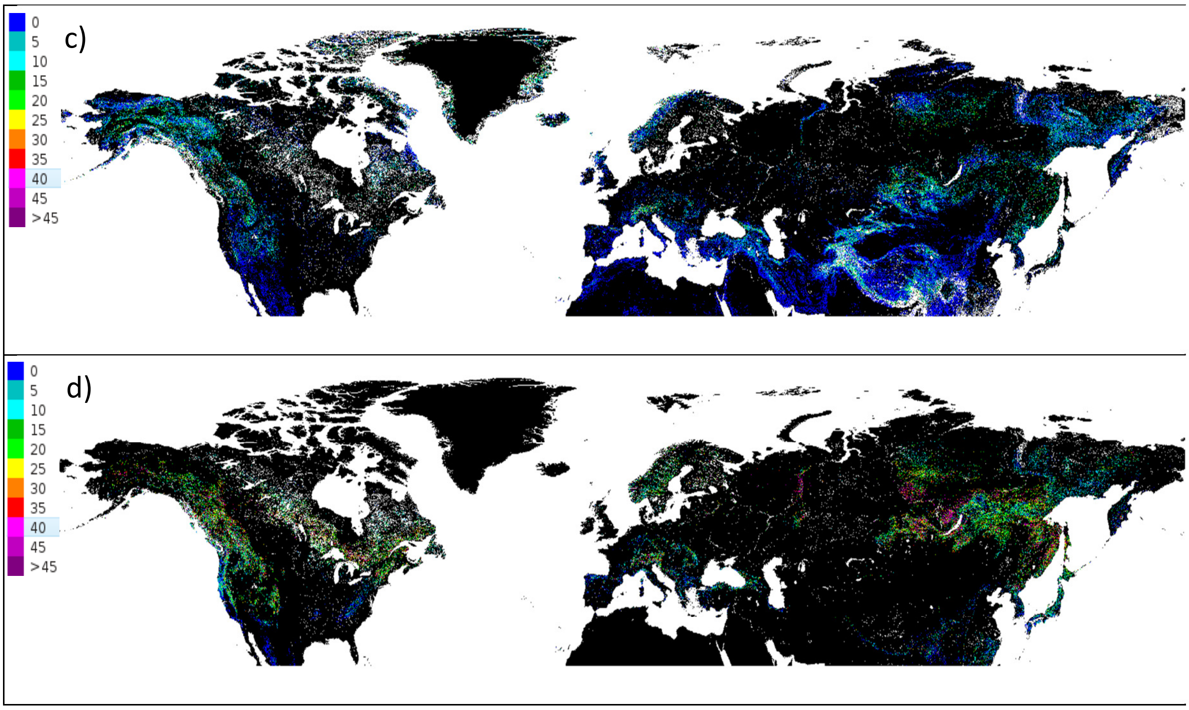
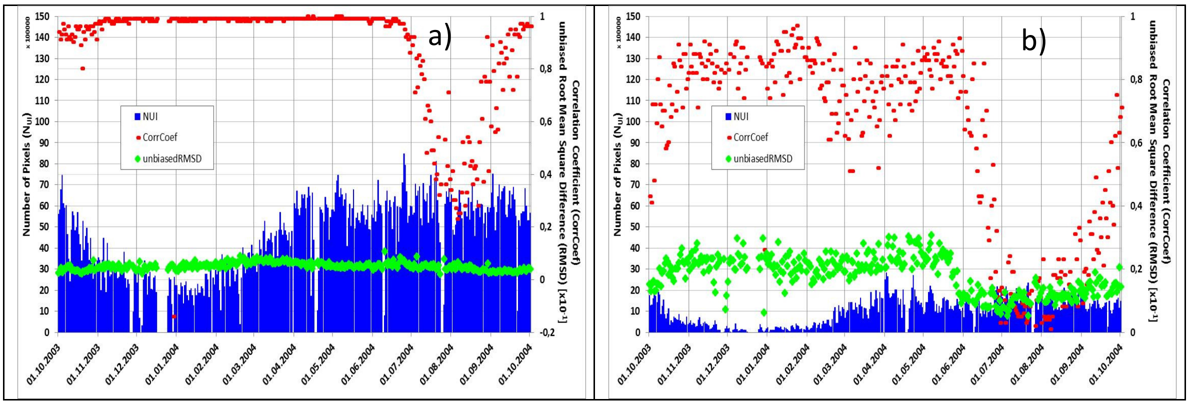


Figure 5.9: Mean absolute deviation of the daily snow difference (SE v2.1 – MOD10_L2) maps for different surface classes generated from GlobSnow-2 SE v2.1 and MOD10_L2 products for the period 1 Oct 2003-31 Mai 2004. a) plain un-forested areas, b) plain forested areas; c) mountainous un-forested areas; d) mountainous forested areas. Black areas indicate any other surface class. For differences the color code used in Figure 5.7 is applied.

Figure 5.9 shows the mean absolute deviations for the different surface classes, generated from the daily snow products of the period 1 October 2003 – 31 May 2004. In Figure 5.10 the statistical analyses for this intercomparison are shown for the particular surface classes. Major differences in the FSC products are found in forested areas, each in plain and in mountainous terrain.



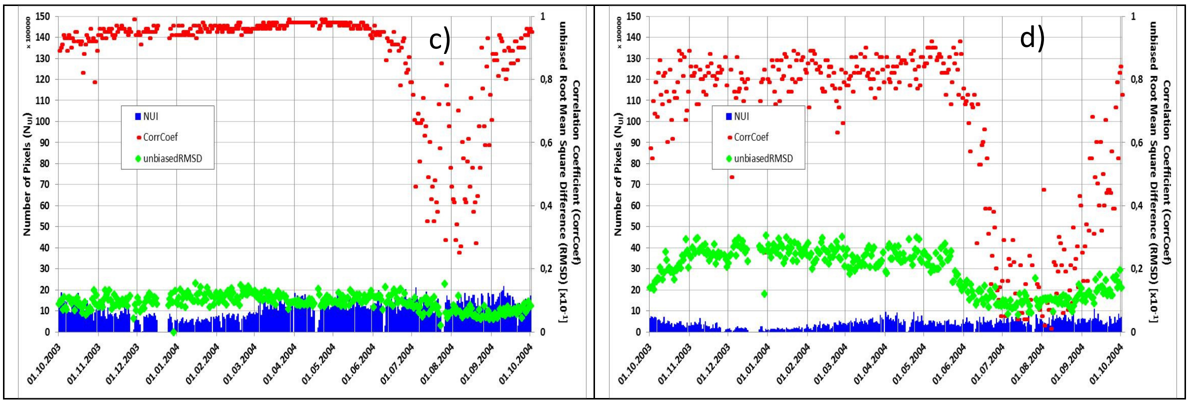


Figure 5.10: Daily statistical analyses for the intercomparison of the different surface classes of GlobSnow-2 SE v2.1 product and the MOD10_L2 product for the period 1 October 2003 to 1 October 2004: a) plain non-forested areas, b) plain forested areas; c) mountainous non-forested areas; d) mountainous forested areas. Value ranges of the axes are identical to those in Figure 5.8.

The mean annual values derived from the daily statistical analyses for different surface classes indicate a good agreement of these two products in general (cf. Table 5.16). The mean correlation coefficient is about 0.81 in all selected years, with high correlations for non-forested areas (plain and mountainous), and lower correlations for forested areas (plain and mountain). The mean unbiased RMSD values for the total area for the selected years are in the order of 11 %, with values for the particular surface classes ranging between 5 % for plain non-forested areas, and 20 % for mountainous forested areas. The mean absolute biases for the total areas are in the order of 2.5, ranging between 0.42 for plain non-forested areas and 11.8 for plain forested areas. The mean standard deviations for the total area are in the order of 28 %, ranging from about 25 % for plain non-forested areas to about 33 % for mountainous forested areas.

The full results of the statistical analyses of the intercomparison of GlobSnow-2 SE v2.1 products with the MOD10_L2 fractional snow products for the years 2003, 2004 and 2010 over the total area are reported in the Appendix H. The analyses for particular surface classes for these years were performed and available at ENVEO. For keeping the document readable these daily results are not reported in detail.

Table 5.16: Annual mean values of the statistical parameters for the intercomparison of GlobSnow-2 SE v2.1 with MOD10_L2 products for the years 2003, 2004 and 2010, for the total (T) area, as well as for particular surface classes (F = forest, U = non-forested, M = mountain, P = plain, MF = mountain forested, MU = mountain non-forested, PF = plain forested, PU = plain non-forested).

Year	Mean Corr Coefficient	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean Std. Deviation	Class
2003	**0,81**	**2,5378**	**11,7308**	**11,1398**	**28,4134**	**T**
	0,60	11,0365	22,8121	19,0837	31,6811	F
	0,88	0,4454	6,6582	6,5885	26,8617	U

Year	Mean Corr Coefficient	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean Std. Deviation	Class
	0,79	3,3879	14,9470	14,3592	30,6860	M
	0,80	2,2887	10,4071	9,9005	27,6761	P
	0,60	10,3787	23,0693	19,9699	32,3443	MF
	0,87	0,5749	9,8979	9,8295	29,2859	MU
	0,59	11,4368	22,3546	18,1417	30,9492	PF
	0,88	0,4187	5,4465	5,3738	25,8825	PU
2004	**0,82**	**2,5088**	**11,4842**	**10,8789**	**29,3183**	**T**
	0,63	11,3377	22,9554	19,1314	32,8529	F
	0,89	0,4798	6,4750	6,3984	27,4100	U
	0,82	3,1302	14,3833	13,8952	31,8310	M
	0,82	2,3012	10,2311	9,7013	28,2100	P
	0,64	10,3648	22,6939	19,6357	33,3349	MF
	0,88	0,5375	9,6417	9,5782	30,2732	MU
	0,63	11,7948	22,6461	18,3119	31,9871	PF
	0,89	0,4646	5,2677	5,1853	26,2324	PU
2010	**0,81**	**2,3937**	**11,0105**	**10,4527**	**27,3735**	**T**
	0,61	10,4277	21,6751	18,0872	30,6807	F
	0,88	0,4659	6,4450	6,3709	26,0812	U
	0,81	3,1096	13,9691	13,4379	29,8192	M
	0,80	2,1926	9,8255	9,3418	26,5377	P
	0,62	9,9302	22,0015	19,0175	31,8692	MF
	0,87	0,5730	9,4672	9,4018	28,3159	MU
	0,61	10,8171	21,2786	17,1967	29,6038	PF
	0,88	0,4425	5,3397	5,2610	25,1488	PU

5.4 Intercomparison with CryoLand Pan-European FSC product

Gabriele Bippus and Elisabeth Ripper (ENVEO)

The intercomparison of the GlobSnow-2 SE v2.1 product with the Pan-European Fractional Snow Cover product of the EU FP7 project CryoLand was performed for the years 2003, 2004 and 2010. The daily difference maps of the two products have been generated for the winter season 2003/04 and for the period February – April of each selected year. The mean of the daily difference map for the winter season 2003/04, from 1 October 2003 to 31 September 2004, for the total area as well as for particular surface classes are shown in Figure 5.11.

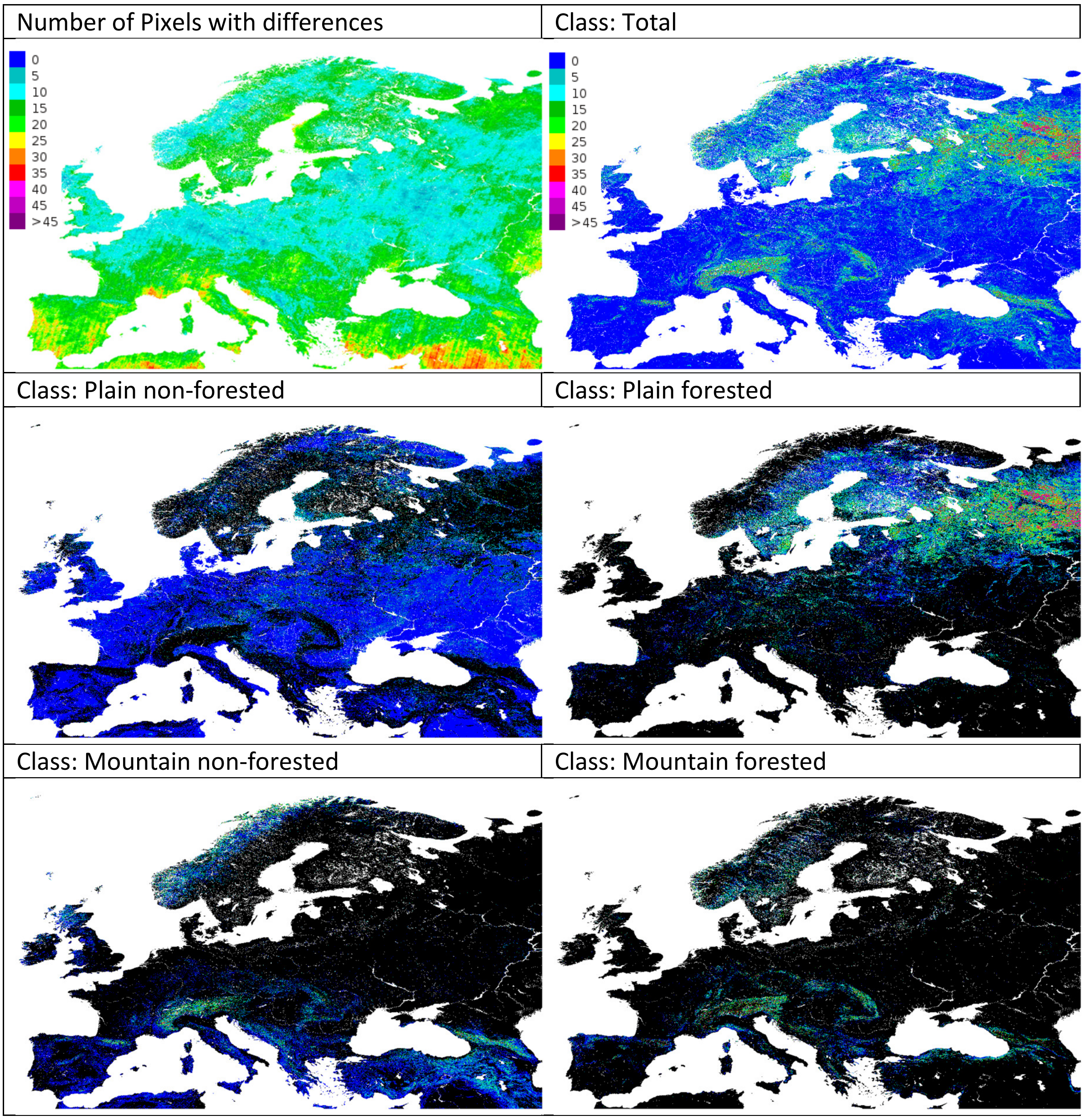


Figure 5.11: Mean absolute difference maps for particular surface classes for the Pan-European area generated from the daily difference maps of GlobSnow-2 SE v2.1 versus CryoLand Pan-European FSC products for the period 1 October 2003 - 31 May 2004.

Additionally to the snow difference maps the statistical analyses (cf. Section 4.3) for the daily intercomparisons of the two products have been performed for each surface class.

The intercomparison of the GlobSnow-2 SE v2.1 products with the CryoLand Pan-European FSC product shows partly major differences in the products, although basically the same approach is applied, but on different input data, including regionally adjusted transmissivity data. The mean correlation coefficients for the selected years are each in the order of 0.65 for the total area, ranging between 0.49 for mountainous forested areas and 0.77 for mountainous non-forested areas. The mean unbiased RMSD derived for the intercomparison of the GlobSnow-2 SE v2.1

products with the CryoLand Pan-European FSC products for the total area are in the order of 10 % for all years, with the minimum unbiased RMSD for plain non-forested areas, and the maximum value for forested areas in all years. The mean Bias ranges between 0.9 and 1.3, also with a minimum mean Bias for plain non-forested areas and a maximum mean Bias for forested areas in all years. The mean annual standard deviations for these years are in the order of 23 % for the total area, ranging from about 17 % for plain non-forested areas to 27 % for the total forested area.

The mean annual values of these statistical analyses are summarized in Table 5.17.

Table 5.17: Annual mean values of the statistical parameters for the intercomparison of GlobSnow-2 SE v2.1 with CryoLand Pan-European FSC products for the years 2003, 2004 and 2010, for the total (T) area, as well as for particular surface classes (F = forest, U = non-forested, M = mountain, P = plain, MF = mountain forested, MU = mountain non-forested, PF = plain forested, PU = plain non-forested).

Year	Mean Corr. Coefficient	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean Std. Deviation	Class
2003	**0,66**	**1,1089**	**9,9566**	**9,8280**	**22,9278**	**T**
	0,50	4,3261	18,4296	17,6837	26,8942	F
	0,74	0,2631	5,8260	5,7975	19,9780	U
	0,69	1,6421	11,5946	11,4287	24,2097	M
	0,63	0,8332	8,3185	8,2093	20,5234	P
	0,49	4,6935	18,2422	17,4373	26,0893	MF
	0,77	0,6433	8,1625	8,1044	22,8179	MU
	0,50	3,4818	16,6338	15,9966	24,9933	PF
	0,70	0,1340	4,3554	4,3316	17,2148	PU
2004	**0,65**	**1,2843**	**10,1559**	**10,0189**	**23,8209**	**T**
	0,51	4,5497	18,8393	18,0743	27,4698	F
	0,74	0,4042	6,0043	5,9719	20,7952	U
	0,69	1,6023	11,2656	11,1086	24,1490	M
	0,62	1,0511	8,5854	8,4653	21,8403	P
	0,49	4,3671	17,8479	17,1305	26,1348	MF
	0,77	0,7886	8,1735	8,1074	22,5101	MU
	0,52	3,9491	17,3113	16,6244	25,7366	PF
	0,69	0,2693	4,5169	4,4909	18,4209	PU
2010	**0,65**	**0,8916**	**9,3555**	**9,2591**	**22,4741**	**T**
	0,51	3,6528	17,0889	16,4997	26,0013	F

Year	Mean Corr. Coefficient	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean Std. Deviation	Class
	0,73	0,1251	5,7303	5,7072	19,8170	U
	0,69	1,2239	10,6653	10,5574	23,6628	M
	0,61	0,7178	7,9738	7,8833	20,6238	P
	0,51	3,6186	16,7116	16,1729	26,1673	MF
	0,76	0,4440	7,8482	7,8062	21,7200	MU
	0,51	3,2835	15,7227	15,1298	24,5653	PF
	0,68	0,0358	4,4379	4,4148	17,7768	PU

Compared to the mean annual analyses of the intercomparison of the GlobSnow-2 SE v2.1 products with the CryoLand Pan-European FSC products the matches of the products during the winter and spring season is different. The mean monthly values, as shown in Table 5.18, show significantly higher correlation coefficients, all higher than 0.90 for the months January to April, and a clearly decreased value of only about 0.85 in May, when the melting period started in all regions of the Pan-European area, also on high altitudes. The mean unbiased RMSD for the winter months are slightly higher than the annual means, in the order of 12 %, with small mean Bias values ranging between 0.95 and 2.43. The mean values for May are slightly better than the annual mean with unbiased RMSD in the order of 8 %, and mean Bias values between 0.90 and 1.96. Also the mean standard deviation decreases in May significantly compare to the winter months, from mean values in the order of about 40 % for January to April to about 20 % in May in all selected years.

Table 5.18: Mean monthly statistical analyses for the winter and spring season of the years 2003, 2004 and 2010 for the intercomparison of the GlobSnow-2 SE v2.1 products with the CryoLand Pan-European FSC product for the total Pan-European area.

Year	Month	Mean Corr Coef	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean SDTV
2003	Jan	0,91	1,2829	14,5106	14,3697	37,3458
	Feb	0,95	1,2682	13,0682	12,8923	42,4536
	Mar	0,97	1,8531	11,6500	11,4404	45,1835
	Apr	0,96	2,0803	11,0713	10,7920	43,7373
	May	0,81	1,1721	8,3596	8,1982	19,6654
2004	Jan	0,92	1,7752	13,4548	13,2881	37,3539
	Feb	0,95	1,4526	11,9730	11,8607	41,3915
	Mar	0,97	1,4710	10,3020	10,1507	43,7097
	Apr	0,97	2,4323	11,2792	10,9415	44,8892

Year	Month	Mean Corr Coef	Mean BIAS	Mean RMSD	Mean unbiased RMSD	Mean SDTV
	May	0,85	1,9642	10,2326	9,9835	21,7219
2010	Jan	0,91	0,9546	13,6179	13,5254	36,6918
	Feb	0,95	1,2568	12,6789	12,5132	44,0157
	Mar	0,97	1,2884	10,3619	10,2423	43,9874
	Apr	0,96	1,6640	9,9060	9,6793	38,3590
	May	0,84	0,8981	7,6081	7,5123	20,4355

As illustrated in Figure 5.12, the daily unbiased RMSD during the period from March to April 2004 ranges between 6 % and 18 %, with a mean value of 10.52 %.

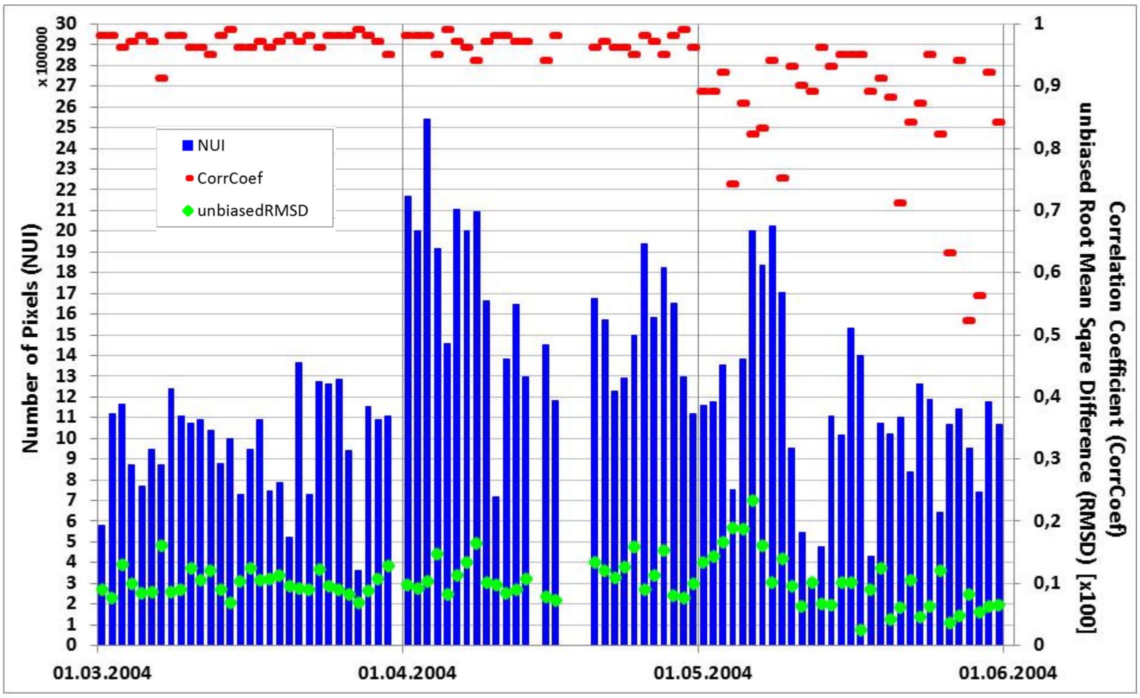


Figure 5.12: Daily statistical analyses, including number of pixels (Nui), correlation coefficient (CorrCoef), and unbiased RMSD for the intercomparison of the total areas of GlobSnow-2 SE v2.1 product and the CryoLand Pan-European FSC product for the period March to May 2004.

Also the retrieved daily correlation coefficients for the intercomparison of these 2 products during this period are quite high, in most cases between 0.93 and 1.00. From February until end of April large areas located in northern latitudes and at high elevations are usually fully snow covered, which is in most cases well matched by both products. In May usually the melting season starts for these regions, resulting in patchy snow areas within one GlobSnow-2 pixel. The GlobSnow-2 SE v2.1 products and the CryoLand Pan-European FSC products classify partly different fractional snow cover values, as also indicated by the statistical analyses and the snow difference maps.

The daily statistical analyses for the two snow products for different surface classes during the main winter season in 2004 show relatively stable correlation coefficients and unbiased RMSD values for plain and mountainous non-forested areas (cf. Figure 5.13). For forested plain or mountainous areas, the statistical values show a higher daily variability during the winter season. With the beginning of the melting season the correlation of the snow products decreases for all surface classes. The largest decrease in the correlation coefficient is observed for mountainous forested areas, followed by plain forested areas. The smallest decrease in the correlation of the two snow maps also in the melting season was found for non-forested plain areas.

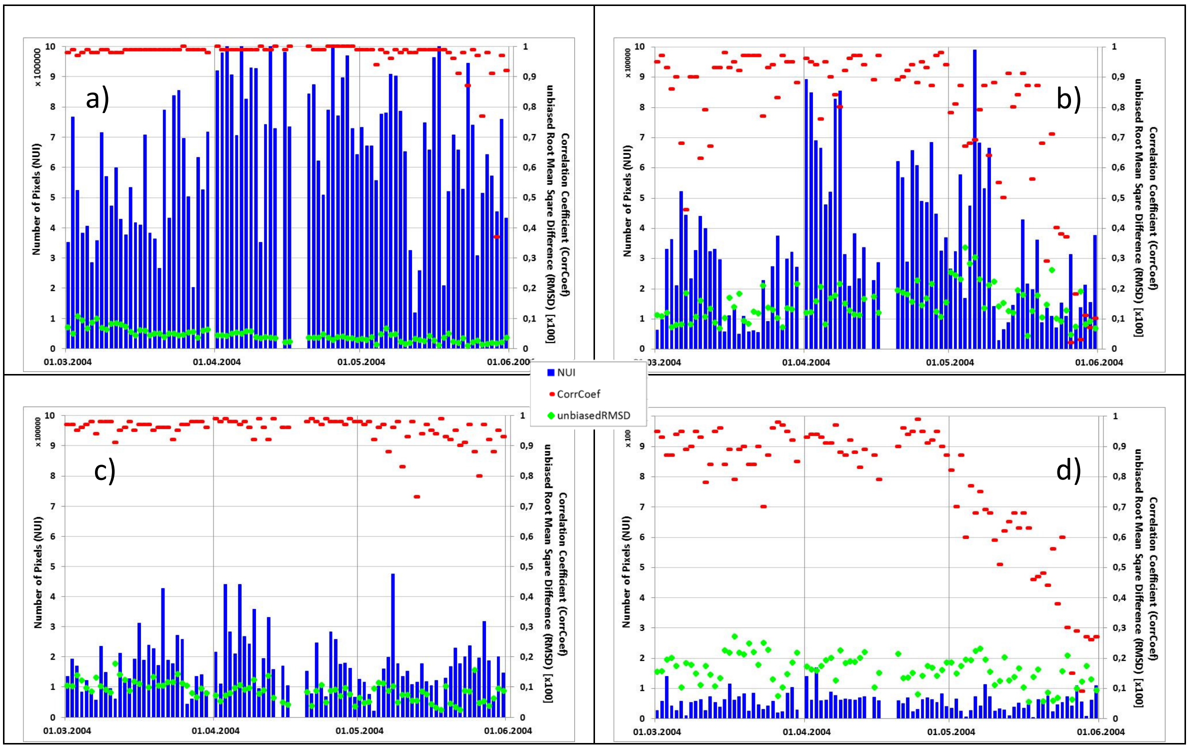


Figure 5.13: Daily statistical analyses for the intercomparison of the different surface classes of GlobSnow-2 SE v2.1 product and the CryoLand Pan-European FSC product for the period 1 March 2004 to 31 May 2004: a) plain non-forested areas, b) plain forested areas; c) mountainous non-forested areas; d) mountainous forested areas.

The full results of the daily statistical analyses derived for the intercomparison of the GlobSnow-2 SE v2.1 products with the CryoLand Pan-European FSC products for the selected years for the total area are provided in Appendix I. The statistical analyses for the particular surface types were performed, and results are available at ENVEO. In order to keep the document readable the detailed daily statistical analyses for the particular surface classes are not reported here.

5.5 Validation against Finnish snow course data

Sari Metsämäki (SYKE)

Validation against Finnish Snow course observations (fraction of snow-covered area within radius of 25m from the observer's location) is carried out for year 2003-2011, excluding years 2001 and 2002 where the identified geolocation error with ATSR-2 were too severe. Due to narrow swath width of AATSR and ATSR-2, Finland is not covered daily. The data gaps, frequent cloud cover over Finland and the fact that snow courses are visited only once per month, results in rather small number of comparison pairs for analyses. The number is still reduced because only those snow courses at distance >500m from water bodies were used for analysis. This is because the contribution of ice-covered lakes to the observed reflectance, and consequently to the gained FSC, would distort the results. Finally, 118 observations were available for validation. The statistical measures are provided for those 118 comparison pairs but also separately for cases where fractional snow (not full snow cover) is observed at the snow course. This is to assess the accuracy for fractional snow retrievals particularly, since full snow cover is typically quite well identified, and the high number of full snow cover observations would have too high weight in the resulting measures. 69 comparison pairs for fractional snow cover were obtained. The gained statistical measures are presented in Table 5.19.

Table 5.19: Statistical measures derived for the GlobSnow-2 SE v2.1 product evaluation with Finnish snow course data.

Statistical measure	**Evaluation result**
RMSE	0.16
RMSE (fractional)	0.21
Unbiased RMSE	0.12
Unbiased RMSE (fractional)	0.21
Correlation coefficient	0.84
Correlation coefficient (fractional)	0.81
Bias	0.02
Bias (fractional)	0.05

The results indicate that fractional snow can be retrieval with accuracy < 21% in general. There is also an indication of slight overestimations. This is probably due to i) too low transmissivity values assigned for forested pixels or ii) effect of atmosphere over the forested pixels; forest is a dark target, meaning that the increase of reflectance due to atmosphere has a strong impart to the FSC retrieval. It is also possible that some of the overestimations are due to presence of unidentified clouds, whereas some of the underestimations are due the unidentified cloud shadows, which decrease the reflectance and thus decrease the retrieved FSC.

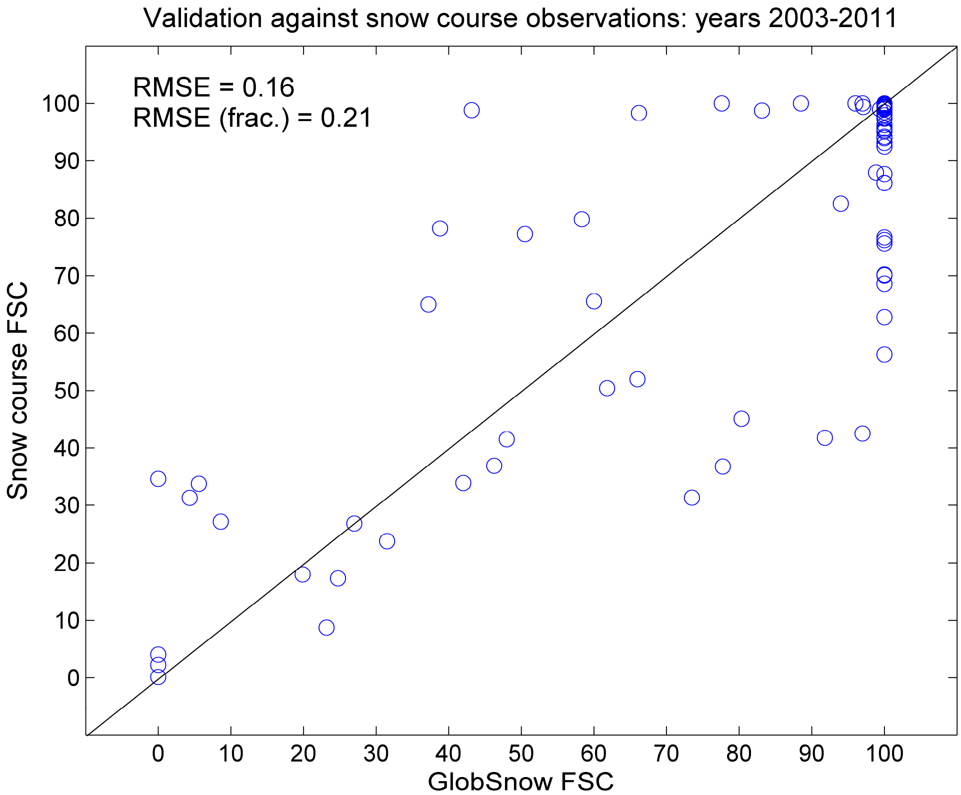


Figure 5.14: GlobSnow v2.1 SE (FSC) against fractional snow cover observations from the Finnish Snow courses.

5.6 Finnish weather station e-codes

Kristin Böttcher (SKYE)

Daily binary snow cover was evaluated for 1999, 2000, 2003 and 2006 based on Finnish weather station e-codes. Fractional Snow Cover was converted to binary snow cover based on the thresholds SE0, SE15 and SE50. E-code observations can be directly compared to thresholds SE0 and SE50. SE15 is not directly comparable with e-codes; the actual snow cover for e-code 4 and 5 may be lower or higher than 15% (e-code 4: open terrain snow free and some snow is observed in forest; e-code5: 0 < fractional snow cover < 0.5).

Table 5.20 summarizes the performance of GlobSnow SE v2.1 products for observations from all years. The overall accuracy (HR) ranged between 0.92 and 0.95. Highest PODsnow (0.97) was observed for SE50, followed by SE0 and SE15. PODno-snow was high (≥ 0.94) for all thresholds.

When analysing the snow season only (February to mid-June), FARsnow was lower than for the whole year (0.02 for SE0 and 0.04 for SE50); 144 out of 308 cases of false snow detection with SE0 occurred in summer. The number of false snow detection decreased to 69 out of 401 cases when using the threshold SE50. The highest proportions of false snow detection in summer were obtained for 2000 and 2003.

Table 5.20: Binary metrics from validation against snow e-codes describing the snow coverage at Finnish weather stations in 1999, 2000, 2003 and 2006 (N=8688).

Threshold for judging the pixel as 'snow' is FSC>0 (SE0) and e-code 4-9

estim. / in-situ	snow	no-snow	#in-situ		POD	FAR	HR	KSS
Snow	2737	350	3087	**Snow**	0.89	0.10	0.92	0.83
Non-snow	308	5293	5601	**no-snow**	0.95	0.06		

Threshold for judging the pixel as 'snow' is FSC≥0.15 (SE15) and e-code 4-9

estim. / in-situ	snow	no-snow	#in-situ		POD	FAR	HR	KSS
Snow	2694	393	3087	**Snow**	0.87	0.08	0.93	0.83
Non-snow	247	5354	5601	**no-snow**	0.96	0.07		

Threshold for judging the pixel as 'snow' is FSC≥0.50 (SE50) and e-code 6-9

estim. / in-situ	snow	no-snow	#in-situ		POD	FAR	HR	KSS
Snow	2232	64	2296	**Snow**	0.97	0.15	0.95	0.91
Non-snow	401	5991	6392	**no-snow**	0.94	0.01		

The results of the evaluation for single years are provided in the Appendix E.1 and shown in Figure 5.15.

Statistical parameters varied only slightly between years. Best overall performance was obtained for threshold SE50. Performance for SE0 and SE15 was somewhat similar. PODsnow was higher for SE0 than for SE15, but performance based on SE15 was better regarding PODnosnow. As mentioned above, SE15 is not directly comparable with e-codes. FARsnow in 2000 was higher than in other years. Many cases of false snow detection (58/91 for SE0) occurred during summer, probably due to undetected clouds, but also the number of reference snow observations (absolute value and compared to no-snow observations) was lowest for that year.

Results for the evaluation of GlobSnow SE product v2.1 for 2003 based on threshold SE50 were stable compared to the earlier product version 1.2 (reported in D11). The number of observations decreased in v2.1 from N=1478 to 1338. Performance improved slightly for all statistical parameters when using threshold SE15 and SE0 in product version 2.1.

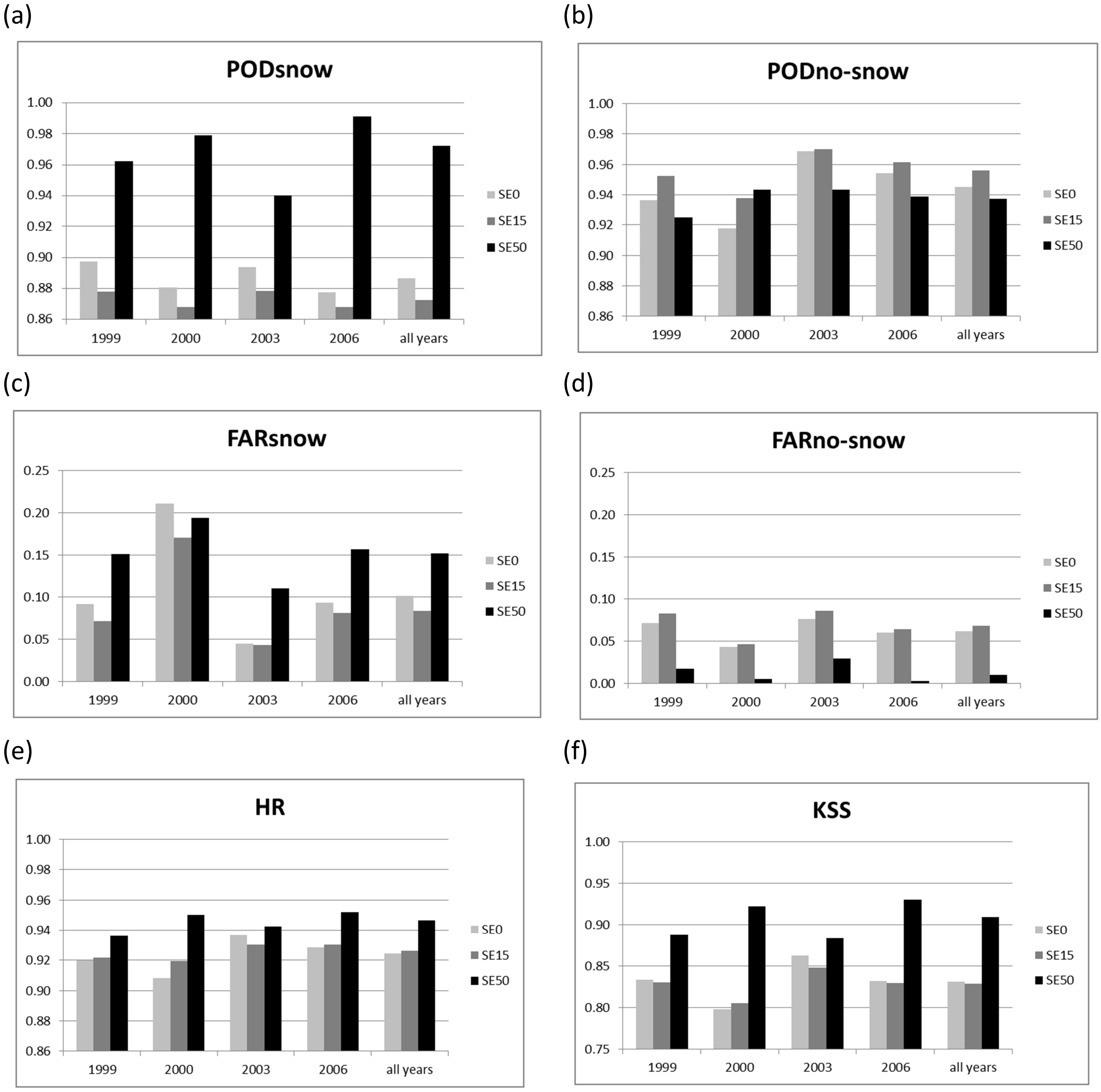


Figure 5.15: Yearly statistical parameters for binary snow maps applying thresholds SE0, SE15, SE50: (a) PODsnow, (b) PODno-snow, (c) FARsnow, (d) FARno-snow, (e) HR and (f) KSS.

For the comparison of the performance of SE products from the two different sensors, we combined evaluation results for years 1999 and 2000 for ATSR-2 and years 2003 and 2006 for AATSR in Table 5.21. Performance was very similar for both sensors. The overall accuracy (HR) was only 1% higher for AATSR than for ATSR-2 for all three thresholds.

Table 5.21: Binary metrics from validation against snow e-codes, describing the snow coverage at Finnish weather stations, for ATSR-2 (years 1999, 2000, N=3596) and AATSR separately (years 2003 and 2006, AATSR, N=5092).

Threshold for judging the pixel as 'snow' is FSC≥0.50 (SE50) and e-code 6-9

ATSR-2

estim. / in-situ	snow	no-snow	#in-situ		POD	FAR	HR	KSS
Snow	30	899	929	**Snow**	0.97	0.17	0.94	0.90
Non-snow	178	2489	2667	**no-snow**	0.93	0.01		

AATSR

estim. / in-situ	snow	no-snow	#in-situ		POD	FAR	HR	KSS
Snow	1333	34	1367	Snow	0.98	0.14	0.95	0.92
Non-snow	223	3502	3725	no-snow	0.94	0.01		

Threshold for judging the pixel as 'snow' is FSC> 0 (SE0) and e-code 4-9

ATSR-2

estim. / in-situ	snow	no-snow	#in-situ		POD	FAR	HR	KSS
Snow	1120	135	1255	**Snow**	0.89	0.13	0.92	0.82
Non-snow	170	2171	2341	**no-snow**	0.93	0.06		

AATSR

estim. / in-situ	snow	no-snow	#in-situ		POD	FAR	HR	KSS
Snow	1617	215	1832	Snow	0.88	0.08	0.93	0.84
Non-snow	138	3122	3260	no-snow	0.96	0.06		

Threshold for judging the pixel as 'snow' is FSC≥0.15 (SE15) and e-code 4-9

ATSR-2

estim. / in-situ	snow	no-snow	#in-situ		POD	FAR	HR	KSS
Snow	1098	157	1255	Snow	0.87	0.10	0.92	0.82
Non-snow	128	2213	2341	no-snow	0.95	0.07		

AATSR								
estim. / in-situ	**snow**	**no-snow**	**#in-situ**		**POD**	**FAR**	**HR**	**KSS**
Snow	1596	236	1832	Snow	0.87	0.07	0.93	0.83
Non-snow	119	3141	3260	no-snow	0.96	0.07		

5.7 Snow depth measurements (ground data)

5.7.1 Austria

Rainer Unger (ZAMG)

This section presents the validation results from AATSR time series (SE product v2.0) compared with in-situ observation data over Austria. The performance the AATSR SE product v2.0 product is summarized as statistical parameters in various tables. The parameters were calculated for each station over the entire validation period and for each year individually (temporal analysis, see APPENDIX G.1).

The following statistics were calculated (formulas in Section 4.2): the accuracy as hit rate (HR), the probability of detection for snow (PODsnow) and no snow events (PODno-snow) and equivalently the false alarm ratio for snow (FARsnow) and no snow (FARno-snow). Additionally, the Kuiper’s skill score (KSS) was computed. For certain periods individual statistical parameters could not be calculated due to invalid mathematical operations (e.g. division by zero) and are marked with “nan”.

The validation was performed based on the in-situ measurements at the ZAMG Snow sites as described in Section 2.3.3). Binary snow cover information was derived from daily FSC data sets (DFSC) from AATSR for the years 2003, 2004, 2006 and 2010. Therefore two different thresholds were implemented to determine a pixel as snow covered or snow free, respectively: ≥ 15% and ≥ 50% FSC. A second threshold had to be set for the ground based snow depth measurements to define the site as snow covered or snow free. In general, a snow day is defined as a day with a snow depth larger than a certain threshold (Foppa and Seiz, 2012; WMO, 2009). Different thresholds are published in the literature, ranging from varying thresholds for each altitude zone (Marty, 2008) to e.g. 15 cm for the alpine topography (Hüsler et al., 2012). In this study two thresholds were implemented: ≥ 1cm (standard of MeteoSwiss) and ≥ 15 cm (Hüsler et al. 2012). On a daily basis the classified snow covered pixel was compared with the snow or no-snow information from the in-situ snow depth measurements. Contingency matrices for each station were designed to calculate different statistical indices and scores as described in Section 4.2. The entire set of statistical parameters for each station site is calculated for each threshold combination separately (SE15_SD01, SE15_SD15, SE50_SD01, SE50_SD15).

The number of point versus pixel comparisons used for the AATSR validation varied from station to station resulting in a total of 5805 data pairs over the time period depending on cloud cover and other limitations from the algorithm or missing/invalid data. The following four tables summarize the performance of the AATSR time series (SE product v2.0) for the years 2003, 2004, 2006 and 2010 at each selected stations (Table 5.23 to Table 5.26). Each table represents one FSC and in-situ threshold combination and the sum and scores calculated over all sites from the total number of hits, missed events, false alarms and true negatives. Table 5.22 presents a summary of the statistical outcome of the four different threshold combinations in the first place.

Referring to Table 5.22 it is eye-catching, that KSS has rather low values for any threshold combination (0.17 to 0.41) but is strongest for the SE15_SD15 combination (0.41). It can be also seen that PODsnow and KSS have very similar values. This is a consequence of the fact that for rare events, the KSS is strongly dominated by the PODsnow. It also has to be mentioned that true negatives are by far the most common category leading to a high POD for snow free events and a low POD for snow covered pixels.

PODsnow and FARsnow should always be used in conjunction with each other to take into account false alarms and missed events. That means that high FAR values are driven by the number of observed hits in relation to the number of false alarms and vice versa for low FAR values. Hence FAR is particularly low in the SE15_SD01 and SE50_SD01 threshold combinations, whereas PODno-snow is always close to 1, independently of the threshold combination. This is a result of the high portion of snow-free events in both datasets.

Concerning the overall accuracy in terms of Hit Rate (HR) over Austria, the SE product v2.0 indicates that between 86 and 90 Percent of all snow events were correctly detected by the algorithm. The best values are found for the SE15_SD15 threshold combination. However it is important to point out that snow-free events are by far the most common category. This fact is highly influencing the results, particularly the Hit Rate. A good Hit Rate could therefore lead to misinterpretation of the results.

In summary, there exists no ideal threshold combination. However the best performance at all validation sites is yielded with a threshold combination of 15% FSC and an in-situ snow depth ≥ 1 cm (SE15_SD01). Table 5.23 to Table 5.26 show in depth results of the validation at all sites.

Table 5.22: Mean Statistics for 4 threshold combinations based on AATSR (2003, 04, 06, 10) and all ZAMG validation sites

Threshold Combination	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
SE15_SD01	317	654	70	4764	0.38	0.99	0.18	0.12	0.88	0.36
SE15_SD15	217	415	170	5003	0.44	0.97	0.44	0.08	0.90	0.41
SE50_SD01	156	815	16	4818	0.18	1.00	0.09	0.14	0.86	0.18
SE50_SD15	99	533	73	5100	0.19	0.99	0.42	0.09	0.90	0.17

Table 5.23: Statistics at each ZAMG validation site based on AATSR (2003, 04, 06, 10) for FSC ≥ 15% and in-situ ≥ 1cm (SE15_SD01)

Stat.ID	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
1600	8	12	1	114	0.40	0.99	0.11	0.10	0.90	0.39
5000	8	8	1	118	0.50	0.99	0.11	0.06	0.93	0.49
5010	8	8	1	118	0.50	0.99	0.11	0.06	0.93	0.49
5871	5	5	4	121	0.50	0.97	0.44	0.04	0.93	0.47
6300	8	9	1	117	0.47	0.99	0.11	0.07	0.93	0.46

Stat.ID	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
6515	8	10	1	116	0.44	0.99	0.11	0.08	0.92	0.44
6610	8	41	1	85	0.16	0.99	0.11	0.33	0.69	0.15
7000	5	10	4	116	0.33	0.97	0.44	0.08	0.90	0.30
7110	8	21	1	105	0.28	0.99	0.11	0.17	0.84	0.27
7202	6	22	3	104	0.21	0.97	0.33	0.17	0.81	0.19
7502	8	9	1	117	0.47	0.99	0.11	0.07	0.93	0.46
9010	8	14	1	112	0.36	0.99	0.11	0.11	0.89	0.35
9641	8	19	1	107	0.30	0.99	0.11	0.15	0.85	0.29
9800	7	13	2	113	0.35	0.98	0.22	0.10	0.89	0.33
9901	8	20	1	106	0.29	0.99	0.11	0.16	0.84	0.28
10502	8	16	1	110	0.33	0.99	0.11	0.13	0.87	0.32
10600	8	6	1	120	0.57	0.99	0.11	0.05	0.95	0.56
11110	8	8	1	118	0.50	0.99	0.11	0.06	0.93	0.49
11800	7	10	2	116	0.41	0.98	0.22	0.08	0.91	0.39
11801	6	9	3	117	0.40	0.98	0.33	0.07	0.91	0.38
12200	8	21	1	105	0.28	0.99	0.11	0.17	0.84	0.27
12210	7	31	2	95	0.18	0.98	0.22	0.25	0.76	0.16
13110	7	17	2	109	0.29	0.98	0.22	0.13	0.86	0.27
13300	7	10	2	116	0.41	0.98	0.22	0.08	0.91	0.39
13700	7	11	2	115	0.39	0.98	0.22	0.09	0.90	0.37
14310	8	28	1	98	0.22	0.99	0.11	0.22	0.79	0.21
14400	7	10	2	116	0.41	0.98	0.22	0.08	0.91	0.39
14800	8	28	1	98	0.22	0.99	0.11	0.22	0.79	0.21
15000	8	14	1	112	0.36	0.99	0.11	0.11	0.89	0.35
15403	8	21	1	105	0.28	0.99	0.11	0.17	0.84	0.27
15500	8	26	1	100	0.24	0.99	0.11	0.21	0.80	0.23
16402	7	3	2	123	0.70	0.98	0.22	0.02	0.96	0.68
16600	7	4	2	122	0.64	0.98	0.22	0.03	0.96	0.62
17000	5	28	4	98	0.15	0.96	0.44	0.22	0.76	0.11
17900	6	7	3	119	0.46	0.98	0.33	0.06	0.93	0.44
18000	8	7	1	119	0.53	0.99	0.11	0.06	0.94	0.53
18600	7	4	2	122	0.64	0.98	0.22	0.03	0.96	0.62
18800	8	20	1	106	0.29	0.99	0.11	0.16	0.84	0.28
18900	7	4	2	122	0.64	0.98	0.22	0.03	0.96	0.62
20000	8	20	1	106	0.29	0.99	0.11	0.16	0.84	0.28
20100	8	30	1	96	0.21	0.99	0.11	0.24	0.77	0.20
20210	7	9	2	117	0.44	0.98	0.22	0.07	0.92	0.42
21100	8	31	1	95	0.21	0.99	0.11	0.25	0.76	0.19
All Sites	**317**	**654**	**70**	**4764**	**0.38**	**0.99**	**0.18**	**0.12**	**0.88**	**0.36**

Table 5.24: Statistics at each ZAMG validation site based on AATSR (2003, 04, 06, 10) for FSC ≥ 15% and in-situ ≥ 15cm (SE15_SD15)

Stat.ID	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
1600	5	7	4	119	0.42	0.97	0.44	0.06	0.92	0.38
5000	0	0	9	126	nan	0.93	1.00	0.00	0.93	nan
5010	5	5	4	121	0.50	0.97	0.44	0.04	0.93	0.47
5871	0	0	9	126	nan	0.93	1.00	0.00	0.93	nan
6300	5	4	4	122	0.56	0.97	0.44	0.03	0.94	0.52
6515	3	2	6	124	0.60	0.95	0.67	0.02	0.94	0.55
6610	8	39	1	87	0.17	0.99	0.11	0.31	0.70	0.16
7000	3	5	6	121	0.38	0.95	0.67	0.04	0.92	0.33
7110	7	14	2	112	0.33	0.98	0.22	0.11	0.88	0.32
7202	6	15	3	111	0.29	0.97	0.33	0.12	0.87	0.26
7502	6	3	3	123	0.67	0.98	0.33	0.02	0.96	0.64
9010	6	11	3	115	0.35	0.97	0.33	0.09	0.90	0.33
9641	7	15	2	111	0.32	0.98	0.22	0.12	0.87	0.30
9800	3	5	6	121	0.38	0.95	0.67	0.04	0.92	0.33
9901	6	16	3	110	0.27	0.97	0.33	0.13	0.86	0.25
10502	5	9	4	117	0.36	0.97	0.44	0.07	0.90	0.32
10600	6	3	3	123	0.67	0.98	0.33	0.02	0.96	0.64
11110	1	1	8	125	0.50	0.94	0.89	0.01	0.93	0.44
11800	4	4	5	122	0.50	0.96	0.56	0.03	0.93	0.46
11801	4	4	5	122	0.50	0.96	0.56	0.03	0.93	0.46
12200	8	13	1	113	0.38	0.99	0.11	0.10	0.90	0.37
12210	7	27	2	99	0.21	0.98	0.22	0.21	0.79	0.19
13110	6	6	3	120	0.50	0.98	0.33	0.05	0.93	0.48
13300	3	3	6	123	0.50	0.95	0.67	0.02	0.93	0.45
13700	4	1	5	125	0.80	0.96	0.56	0.01	0.96	0.76
14310	8	19	1	107	0.30	0.99	0.11	0.15	0.85	0.29
14400	4	6	5	120	0.40	0.96	0.56	0.05	0.92	0.36
14800	8	21	1	105	0.28	0.99	0.11	0.17	0.84	0.27
15000	6	10	3	116	0.38	0.97	0.33	0.08	0.90	0.35
15403	6	15	3	111	0.29	0.97	0.33	0.12	0.87	0.26
15500	7	19	2	107	0.27	0.98	0.22	0.15	0.84	0.25
16402	1	0	8	126	1.00	0.94	0.89	0.00	0.94	0.94
16600	3	1	6	125	0.75	0.95	0.67	0.01	0.95	0.70
17000	5	24	4	102	0.17	0.96	0.44	0.19	0.79	0.13
17900	3	2	6	124	0.60	0.95	0.67	0.02	0.94	0.55
18000	3	5	6	121	0.38	0.95	0.67	0.04	0.92	0.33
18600	5	2	4	124	0.71	0.97	0.44	0.02	0.96	0.68
18800	8	12	1	114	0.40	0.99	0.11	0.10	0.90	0.39
18900	3	1	6	125	0.75	0.95	0.67	0.01	0.95	0.70
20000	8	15	1	111	0.35	0.99	0.11	0.12	0.88	0.34

Stat.ID	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
20100	8	23	1	103	0.26	0.99	0.11	0.18	0.82	0.25
20210	5	4	4	122	0.56	0.97	0.44	0.03	0.94	0.52
21100	8	24	1	102	0.25	0.99	0.11	0.19	0.81	0.24
All Sites	**217**	**415**	**170**	**5003**	**0.44**	**0.97**	**0.44**	**0.08**	**0.90**	**0.41**

Table 5.25: Statistics at each ZAMG validation site based on AATSR (2003, 04, 06, 10) for FSC ≥ 50% and in-situ ≥ 1cm (SE50_SD01)

Stat.ID	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
1600	4	16	0	115	0.20	1.00	0.00	0.12	0.88	0.20
5000	4	12	0	119	0.25	1.00	0.00	0.09	0.91	0.25
5010	4	12	0	119	0.25	1.00	0.00	0.09	0.91	0.25
5871	3	7	1	124	0.30	0.99	0.25	0.05	0.94	0.29
6300	4	13	0	118	0.24	1.00	0.00	0.10	0.90	0.24
6515	4	14	0	117	0.22	1.00	0.00	0.11	0.90	0.22
6610	4	45	0	86	0.08	1.00	0.00	0.34	0.67	0.08
7000	3	12	1	119	0.20	0.99	0.25	0.09	0.90	0.19
7110	4	25	0	106	0.14	1.00	0.00	0.19	0.81	0.14
7202	3	25	1	106	0.11	0.99	0.25	0.19	0.81	0.10
7502	4	13	0	118	0.24	1.00	0.00	0.10	0.90	0.24
9010	4	18	0	113	0.18	1.00	0.00	0.14	0.87	0.18
9641	4	23	0	108	0.15	1.00	0.00	0.18	0.83	0.15
9800	3	17	1	114	0.15	0.99	0.25	0.13	0.87	0.14
9901	4	24	0	107	0.14	1.00	0.00	0.18	0.82	0.14
10502	4	20	0	111	0.17	1.00	0.00	0.15	0.85	0.17
10600	4	10	0	121	0.29	1.00	0.00	0.08	0.93	0.29
11110	4	12	0	119	0.25	1.00	0.00	0.09	0.91	0.25
11800	4	13	0	118	0.24	1.00	0.00	0.10	0.90	0.24
11801	3	12	1	119	0.20	0.99	0.25	0.09	0.90	0.19
12200	4	25	0	106	0.14	1.00	0.00	0.19	0.81	0.14
12210	4	34	0	97	0.11	1.00	0.00	0.26	0.75	0.11
13110	3	21	1	110	0.13	0.99	0.25	0.16	0.84	0.12
13300	3	14	1	117	0.18	0.99	0.25	0.11	0.89	0.17
13700	3	15	1	116	0.17	0.99	0.25	0.11	0.88	0.16
14310	4	32	0	99	0.11	1.00	0.00	0.24	0.76	0.11
14400	4	13	0	118	0.24	1.00	0.00	0.10	0.90	0.24
14800	4	32	0	99	0.11	1.00	0.00	0.24	0.76	0.11
15000	4	18	0	113	0.18	1.00	0.00	0.14	0.87	0.18
15403	4	25	0	106	0.14	1.00	0.00	0.19	0.81	0.14
15500	4	30	0	101	0.12	1.00	0.00	0.23	0.78	0.12
16402	3	7	1	124	0.30	0.99	0.25	0.05	0.94	0.29
16600	3	8	1	123	0.27	0.99	0.25	0.06	0.93	0.26

Stat.ID	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
17000	2	31	2	100	0.06	0.98	0.50	0.24	0.76	0.04
17900	3	10	1	121	0.23	0.99	0.25	0.08	0.92	0.22
18000	4	11	0	120	0.27	1.00	0.00	0.08	0.92	0.27
18600	3	8	1	123	0.27	0.99	0.25	0.06	0.93	0.26
18800	4	24	0	107	0.14	1.00	0.00	0.18	0.82	0.14
18900	3	8	1	123	0.27	0.99	0.25	0.06	0.93	0.26
20000	4	24	0	107	0.14	1.00	0.00	0.18	0.82	0.14
20100	4	34	0	97	0.11	1.00	0.00	0.26	0.75	0.11
20210	3	13	1	118	0.19	0.99	0.25	0.10	0.90	0.18
21100	4	35	0	96	0.10	1.00	0.00	0.27	0.74	0.10
All Sites	**156**	**815**	**16**	**4818**	**0.18**	**1.00**	**0.09**	**0.14**	**0.86**	**0.18**

Table 5.26: Statistics at each ZAMG validation site based on AATSR (2003, 04, 06, 10) for FSC ≥ 50% and in-situ ≥ 15cm (SE50_SD15)

Stat.ID	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
1600	2	10	2	121	0.17	0.98	0.50	0.08	0.91	2
5000	0	0	4	131	nan	0.97	1.00	0.00	0.97	0
5010	2	8	2	123	0.20	0.98	0.50	0.06	0.93	2
5871	0	0	4	131	nan	0.97	1.00	0.00	0.97	0
6300	2	7	2	124	0.22	0.98	0.50	0.05	0.93	2
6515	0	5	4	126	0.00	0.97	1.00	0.04	0.93	0
6610	4	43	0	88	0.09	1.00	0.00	0.33	0.68	4
7000	1	7	3	124	0.13	0.98	0.75	0.05	0.93	1
7110	3	18	1	113	0.14	0.99	0.25	0.14	0.86	3
7202	3	18	1	113	0.14	0.99	0.25	0.14	0.86	3
7502	3	6	1	125	0.33	0.99	0.25	0.05	0.95	3
9010	2	15	2	116	0.12	0.98	0.50	0.11	0.87	2
9641	3	19	1	112	0.14	0.99	0.25	0.15	0.85	3
9800	2	6	2	125	0.25	0.98	0.50	0.05	0.94	2
9901	2	20	2	111	0.09	0.98	0.50	0.15	0.84	2
10502	2	12	2	119	0.14	0.98	0.50	0.09	0.90	2
10600	3	6	1	125	0.33	0.99	0.25	0.05	0.95	3
11110	0	2	4	129	0.00	0.97	1.00	0.02	0.96	0
11800	2	6	2	125	0.25	0.98	0.50	0.05	0.94	2
11801	2	6	2	125	0.25	0.98	0.50	0.05	0.94	2
12200	4	17	0	114	0.19	1.00	0.00	0.13	0.87	4
12210	4	30	0	101	0.12	1.00	0.00	0.23	0.78	4
13110	2	10	2	121	0.17	0.98	0.50	0.08	0.91	2
13300	2	4	2	127	0.33	0.98	0.50	0.03	0.96	2
13700	2	3	2	128	0.40	0.98	0.50	0.02	0.96	2
14310	4	23	0	108	0.15	1.00	0.00	0.18	0.83	4

Stat.ID	Hit	Miss	False	True	POD snow	POD no-snow	FAR snow	FAR no-snow	HR	KSS
14400	2	8	2	123	0.20	0.98	0.50	0.06	0.93	2
14800	4	25	0	106	0.14	1.00	0.00	0.19	0.81	4
15000	2	14	2	117	0.13	0.98	0.50	0.11	0.88	2
15403	2	19	2	112	0.10	0.98	0.50	0.15	0.84	2
15500	3	23	1	108	0.12	0.99	0.25	0.18	0.82	3
16402	0	1	4	130	0.00	0.97	1.00	0.01	0.96	0
16600	2	2	2	129	0.50	0.98	0.50	0.02	0.97	2
17000	2	27	2	104	0.07	0.98	0.50	0.21	0.79	2
17900	2	3	2	128	0.40	0.98	0.50	0.02	0.96	2
18000	2	6	2	125	0.25	0.98	0.50	0.05	0.94	2
18600	3	4	1	127	0.43	0.99	0.25	0.03	0.96	3
18800	4	16	0	115	0.20	1.00	0.00	0.12	0.88	4
18900	0	4	4	127	0.00	0.97	1.00	0.03	0.94	0
20000	4	19	0	112	0.17	1.00	0.00	0.15	0.86	4
20100	4	27	0	104	0.13	1.00	0.00	0.21	0.80	4
20210	3	6	1	125	0.33	0.99	0.25	0.05	0.95	3
21100	4	28	0	103	0.13	1.00	0.00	0.21	0.79	4
All Sites	**99**	**533**	**73**	**5100**	**0.19**	**0.99**	**0.42**	**0.09**	**0.90**	**0.17**

5.7.2 Switzerland (based on in-situ snow depth measurements)

Nando Foppa and Fabio Fontana (MeteoSwiss)

The following two chapters present the validation results from ATSR and AATSR time series (SE product v2.0) compared with in-situ observation data over Switzerland. Each of the chapters is divided in two sections: an analysis focusing on the individual station sites and a temporal analysis over the entire time period of ATSR and AATSR, respectively. In addition a third chapter summarizes and discusses the performance of the SE product v2.0 over the entire period 1995-2012.

The performance of the ATSR and AATSR SE product v2.0 is visualized and summarized as statistical parameters in various tables. The following statistics were calculated (formulas in Section 4.2): the accuracy as hit rate (ACC), the probability of detection for snow (POD) and no snow events (PODns) and equivalently the false alarm ratio for snow (FAR) and no snow (FARns). Additionally, the probability of false detection (POFD) and the Kuiper's skill score (KSS) were computed. For certain periods individual statistical parameters could not be calculated due to invalid mathematical operations (e.g. division by zero) and are marked with a dash.

The validation was performed based on the in-situ measurements at the potential Swiss GCOS Snow sites as described in Section 2.3.3.2. Binary snow cover information was derived from daily FSC data sets (DFSC) from ATSR and AATSR for the years 1995-2002, and 2002-2012, respectively. As defined in Section 3.1.4, two different thresholds were implemented to determine a pixel as snow covered or snow free, respectively: ≥ 15% and ≥ 50% FSC. A second threshold had to be set for the ground based snow depth measurements to define the site as snow covered or snow free. In general, a snow day is defined as a day with a snow depth larger than a certain threshold (Foppa and Seiz, 2012; WMO, 2009). Different thresholds are published in the literature, ranging from varying thresholds for each altitude zone (Marty, 2008) to e.g. 15 cm for the alpine topography (Hüsler et al., 2012). In this study two thresholds were implemented: ≥ 1cm (standard of MeteoSwiss) and ≥ 15 cm (Hüsler et al. 2012). On a daily basis the classified snow covered pixel was compared with the snow or no-snow information from the in-situ snow depth measurements. Contingency matrices for each station were designed to calculate different statistical indices and scores as described in Section 4.2.

The entire set of statistical parameters for each station site is calculated for each threshold combination separately (15_1, 15_15, 50_1, 50_15) and listed in Appendix E.3.

5.7.2.1 ATSR SE product v2.0

Fabio Fontana and Nando Foppa (MeteoSwiss)

The number of data pairs used for the ATSR validation varied from station to station resulting in a total 2012 data pairs over the time period 1995-2002 excluding the year 2001 (see Section 3.1) and depending on cloud cover and other limitations from the algorithm or missing/invalid data.

Figure 5.16 illustrates the KSS at each validation site for each threshold combination separately. The KSS score is as a complementary measure using all elements in the contingency table. It discriminates detected snow events from incorrectly defined snow events.

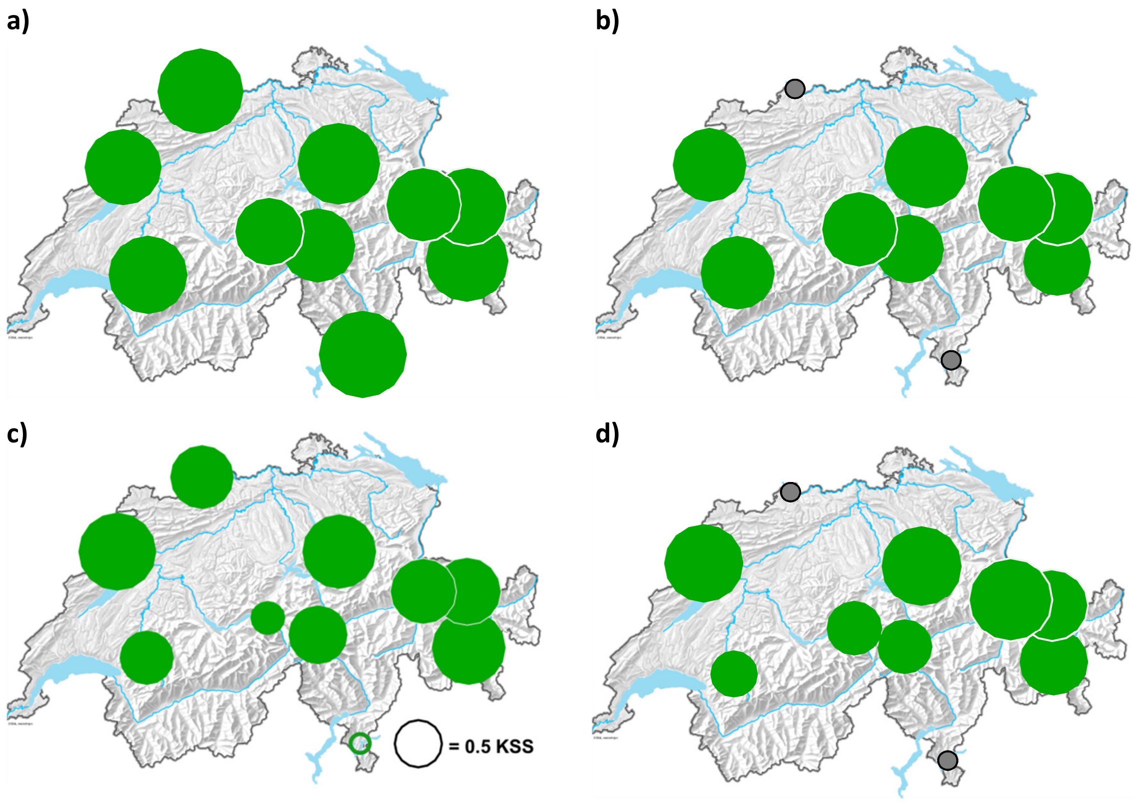


Figure 5.16: KSS for each validation site for the period 1995-2002 (excluding 2001) and for each threshold combination: a) 15_1, b) 15_15, c) 50_1, d) 50_15. Grey dots refer to no values and circles to zero or negative KSS values. The KSS values of each site can be found in Appendix E.3.

Its expression is identical to PODsnow – POFD and ranges from -1 to 1, whereas 0 indicates no skill and perfect score is 1.0. This score is independent of the event and non-event distribution and not affected by the size of the validation set. KSS is calculated over the entire period excluding the year 2001. The absolute values for each station site are listed in Appendix E.3.

The overall KSS is highest for the 15_1 threshold combination (0.88) and decreases to 0.73 when FSC binary threshold is set to 50% (50_1 and 50_15). Highest KSS values over all station sites are obtained for the threshold combination 15_1 (Figure 5.16 a). The two lowland urban sites in the Eastern Jura (BAS) and in Alpine South Side (LUG) show KSS values ranging from 0.98 (LUG 15_1) to 0.0 (LUG 50_1) or indicate no values (grey dots). Both sites do almost not miss any snow event but represent high false alarm rates of 1.0 (LUG 15_15) and 1.0 (BAS 50_15), respectively. Largest changes in KSS over the various threshold combinations can be seen for the inner-alpine site of Meiringen (MEI), from 0.86 (15_15) to 0.39 (50_1) due to a decrease in the number of hits in conjunction with a larger number of missed snow events.

Figure 5.17 shows the time series of selected scores from 1995 to 2002 for each threshold combination based on ATSR data. The statistical parameters were calculated for each year based on the contingency table including all ten in-situ observation sites. For the sake of completeness we included the year 2001 in the plots. It is, however, obvious, that the year 2001 shows remarkable scores such as highest false alarm ratios or lowest KSS values over the entire period.

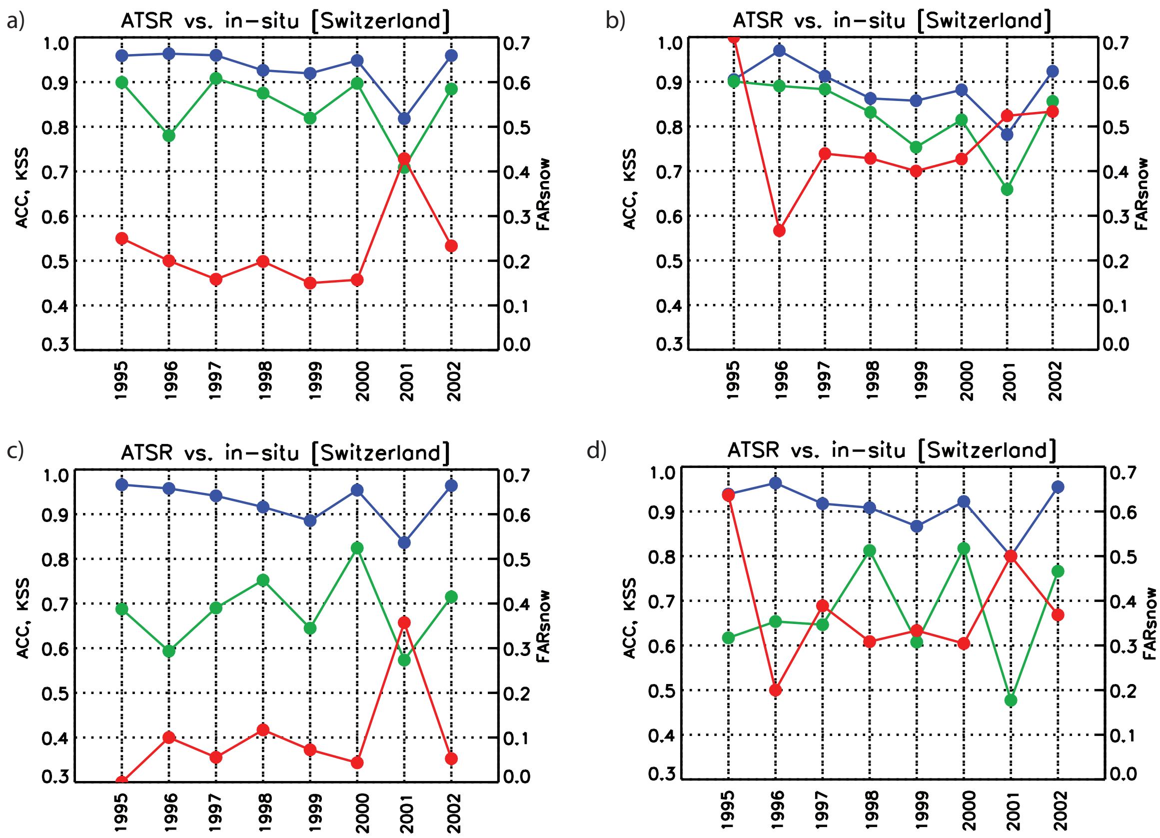


Figure 5.17: Time series of selected scores from 1995-2002 for ATSR: Accuracy (blue), Kuiper's Skill Score (green) and False Alarm Ration for Snow (FAR_snow (red) for all four threshold combination 15_1 (a), 15_15 (b), 50_1 (c) and 50_15 (d).

In general, the inter-annual variability of KSS (green line) is smaller when the threshold for the binary classification is set to 15% (Figure 5.17 a, b) instead of 50% (Figure 5.17 c, d). The accuracy (blue line) is for all the years and all the threshold combinations at least 0.80. ACC shows a continuous decrease from 1995 to 1999 for all threshold combinations. This could be explained by increasing difference between the total number of observations and the sum of hits and true negatives over this period. The false alarm ratio shows highest values over the entire time range when a threshold combination of 50_1 (c) is chosen. Remarkable is the false alarm ratio of 0.70 for the year 1995 (b) and of 0.64 (d), respectively. These values result from the difference between the absolute counts of hits and false alarms (Appendix E.3). Overall, we conclude that the 15_1 combination represents the best performance between SE product v2.0 and in-situ for ATSR.

5.7.2.2 AATSR SE product v2.0

Fabio Fontana and Nando Foppa (MeteoSwiss)

The number of point versus pixel comparisons used for the AATSR validation varied from station to station resulting in a total of 3826 data pairs over the time period 2002-2012 depending on cloud cover and other limitations from the algorithm or missing/invalid data.

The entire set of statistical parameters for each validation site is calculated for each threshold combination separately and listed in the Appendix E.3. Figure 5.18 a-d illustrates the KSS at the selected sites for each threshold combination. The KSS score can also be interpreted as (accuracy for events)+(accuracy for non-events)-1.

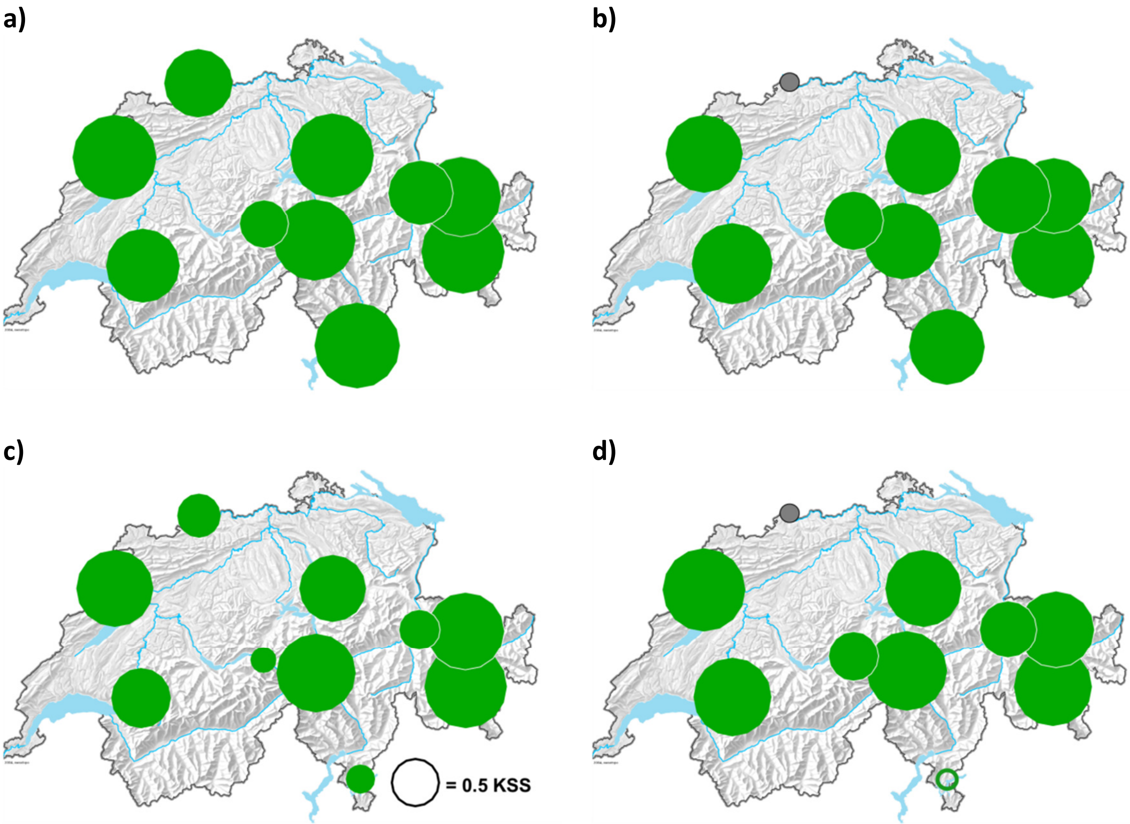


Figure 5.18: KSS for each validation site for the period 2002-2012 for each threshold combination: a) 15_1, b) 15_15, c) 50_1, d) 50_15. Grey dots refer to no values and circles to zero or negative KSS values. The KSS values of each site can be found in Appendix E.3.

The highest KSS values are determined at individual sites when the threshold combination is set to 15_1 (a) and 15_15 (b) (0.96 and 0.94, respectively). At certain station sites the KSS remains rather stable such as in the western part of Switzerland (Western Jura, Western alpine north slope) (LCF, CHD) and the inner-alpine sites (Engadine, Central Alpine north slope) (SAM, AND) as well as at the middle altitude zone of EIN and the highest site WFJ. The two lowland sites BAS and LUG show large differences between the threshold combinations as well as at the inner-alpine sites MEI and CHU. Both sites are located within alpine valleys at an altitude of 559 and 556 masl, respectively and surrounded by a high elevation gradient. These two stations show lowest KSS values for the threshold combination 50_1 (c), resulting in an increase of PODsnow due to the domination of missed events over hits.

Figure 5.19 shows the time series of selected scores from 2002 to 2012 for each threshold combination based on AATSR data. The statistical parameters were calculated for each year based on the contingency table including all ten in-situ observation sites.

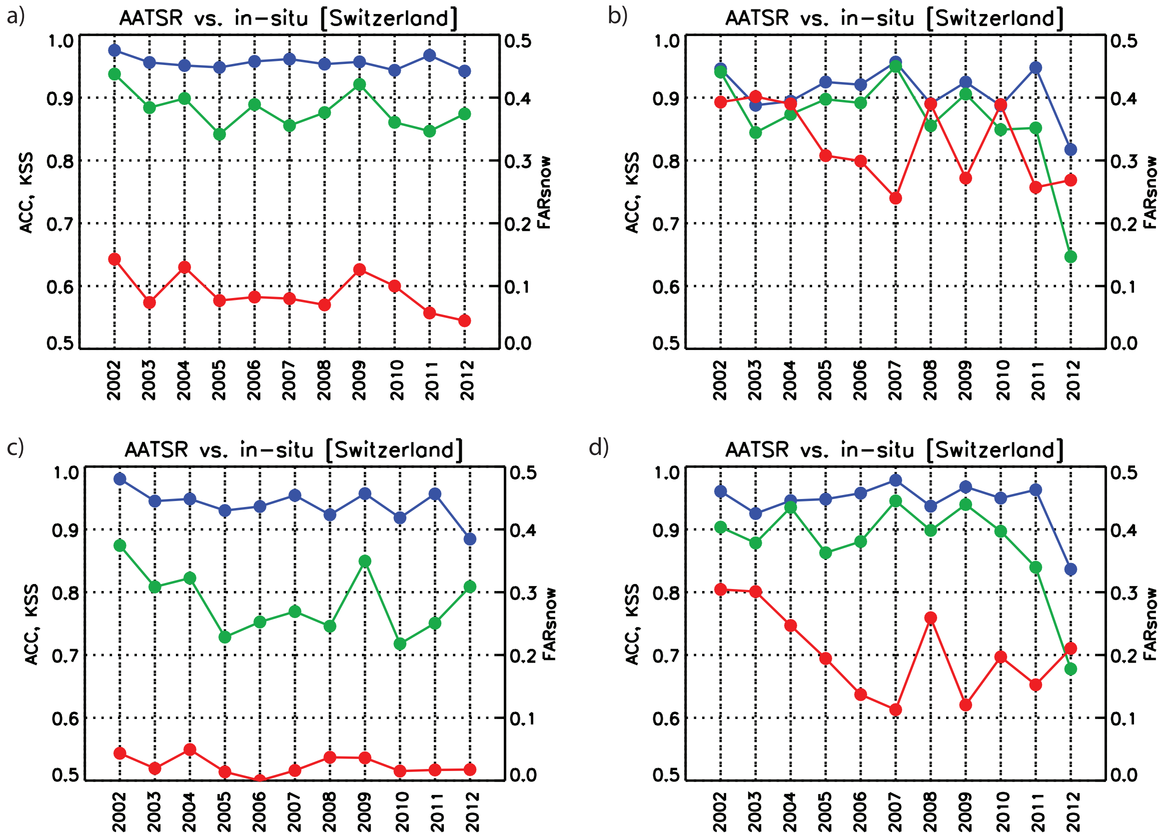


Figure 5.19: Time series of selected scores from 1995-2002 for AATSR: Accuracy (blue), Kuiper's Skill Score (green) and False Alarm Ration for Snow (FARsnow (red) for all four threshold combination 15_1 (a), 15_15 (b), 50_1 (c) and 50_15 (d). Note the different y-axis scaling when compared to Figure 5.17.

Remarkable is the relatively small inter-annual variation of the accuracy (blue dots) and the KSS (green dots) when the threshold 15_1 is defined. When the in-situ threshold is set to ≥ 15 cm, the accuracy and the KSS decreases significantly for the year 2012 (b, d) and increases for the threshold combinations 15_1 and 50_1, respectively (a, c). Small values of the false alarm ratio over the entire period are obvious for the threshold combination 50_1 (c). In contrary, with an increase of the in-situ threshold to 15cm FARsnow is substantially higher over the entire period compared to the threshold of 1cm snow depth. From 2002 to 2007 the false alarm ration decreases constantly for 15_15 and 50_15, respectively (b, d). This could be explained by the decreasing proportion of the amount of false alarms and hits. The tables in the appendix E.3.2 include all yearly statistical parameters for each threshold combination. Overall, we conclude that the 15_1 combination represents the best agreement between SE product v2.0 and in-situ for AATSR.

5.8 Model data (snow extent)

Rainer Unger (ZAMG)

5.8.1 Austria (2003, 2004, 2006)

The following tables summarize the performance of the AATSR (SE product v2.1) for each day of data availability for the Globsnow-2 FSC (15 and 50 % thresholds) and model data (1 and 15 cm thresholds) and averaged over 3 years of comparison (2003, 2004 and 2006). Results for single years are provided in the Appendix F.1. The statistical parameters were calculated according to the in-situ validation procedure. The four threshold combinations are SE15_SD01, SE15_SD15, SE50_SD01 and SE50_SD15.

The following statistics were calculated (formulas Section 4.2): the accuracy as Hit Rate (HR), the probability of detection for snow (PODsnow) and no snow events (PODno-snow) and equivalent the False Alarm Ratio for snow (FARsnow) and no snow (FARno-snow). Additionally, the Kuiper's Skill Score (KSS) was computed. For specific data pairs individual statistical parameters could not be calculated due to invalid mathematical operations (e.g. division by zero). These days have been excluded from the validation.

The KSS score is a complementary measure using all elements in the contingency table. It discriminates detected snow events from incorrectly defined snow events. The score ranges from 1- to 1, whereas 0 indicates no skill and 1 a perfect score. The KSS is independent of the event and non-event distribution and not affected by the size of the validation set. Therefore it's a good indicator of the overall performance of the validation. According to the KSS values, the SE15_SD01 threshold combination (see Table 5.27) has the best performance. KSS ranges between 0.26 and 0.48 depending on the applied landcover mask. If no mask is applied, the KSS is 0.39.

PODsnow and FARsnow should always be used in conjunction with each other to take into account false alarms and missed events. High FAR values are driven by the number of observed hits in relation to the number of false alarms and vice versa for low FAR values. PODsnow has its highest values in the SE15_SD15 combination, ranging between 0.87 and 0.92, depending on the applied landcover mask. On the other hand it also show the highest False Alarm Rate for snow covered pixels (FARsnow), ranging between 0.46 and 0.52, again depending on landcover type. The best performance is again found within the SE15_SD01 threshold combination. PODsnow ranges between 0.78 and 0.85 and FARsnow between 0.17 and 0.26.

Table 5.27: Austria: Statistics based on AATSR (SE product v2.1) and model snow depth data (multiannual average for FSC ≥ 15% and model snow depth ≥ 1 cm)

PODsnow	PODno-snow	FARsnow	FARno-snow	HR	KSS	class
0.79	0.73	0.23	0.28	0.85	0.52	**total**
0.78	0.68	0.18	0.35	0.85	0.46	**forest**
0.82	0.74	0.22	0.25	0.87	0.56	**noforest**
0.85	0.75	0.26	0.18	0.90	0.59	**plain_total**
0.83	0.75	0.24	0.22	0.89	0.58	**plain_forest**
0.80	0.80	0.22	0.17	0.91	0.60	**plain_noforest**
0.79	0.68	0.19	0.36	0.84	0.47	**mountain_total**
0.83	0.63	0.17	0.39	0.85	0.46	**mountain_forest**
0.80	0.70	0.18	0.33	0.86	0.50	**mountain_noforest**

Table 5.28: Austria: Statistics based on AATSR (SE product v2.1) and model snow depth data (multiannual average for FSC ≥ 15% and model snow depth ≥ 15 cm)

PODsnow	PODno-snow	FARsnow	FARno-snow	HR	KSS	class
0.88	0.52	0.48	0.21	0.74	0.40	**total**
0.87	0.42	0.48	0.27	0.69	0.29	**forest**
0.89	0.56	0.52	0.19	0.76	0.45	**noforest**
0.90	0.59	0.48	0.21	0.80	0.50	**plain_total**
0.89	0.52	0.51	0.20	0.73	0.42	**plain_forest**
0.92	0.58	0.47	0.19	0.81	0.50	**plain_noforest**
0.89	0.44	0.48	0.24	0.71	0.33	**mountain_total**
0.88	0.38	0.48	0.25	0.67	0.26	**mountain_forest**
0.91	0.48	0.46	0.23	0.72	0.39	**mountain_noforest**

Table 5.29: Austria: Statistics based on AATSR (SE product v2.1) and model snow depth data (multiannual average for FSC ≥ 50% and model snow depth ≥ 1 cm)

PODsnow	PODno-snow	FARsnow	FARno-snow	HR	KSS	class
0.69	0.82	0.18	0.34	0.84	0.52	**total**
0.71	0.73	0.18	0.37	0.85	0.43	**forest**
0.72	0.81	0.17	0.31	0.85	0.53	**noforest**
0.73	0.79	0.16	0.35	0.85	0.52	**plain_total**
0.70	0.78	0.20	0.31	0.85	0.49	**plain_forest**
0.74	0.77	0.18	0.34	0.85	0.51	**plain_noforest**
0.70	0.79	0.18	0.33	0.84	0.49	**mountain_total**
0.70	0.71	0.19	0.39	0.83	0.41	**mountain_forest**
0.72	0.80	0.15	0.34	0.84	0.51	**mountain_noforest**

Table 5.30: Austria: Statistics based on AATSR (SE product v2.1) and model snow depth data (multiannual average for FSC ≥ 50% and model snow depth ≥ 15 cm)

PODsnow	PODno-snow	FARsnow	FARno-snow	HR	KSS	class
0.80	0.59	0.46	0.24	0.75	0.39	**total**
0.82	0.46	0.45	0.34	0.71	0.28	**forest**
0.82	0.61	0.41	0.25	0.79	0.43	**noforest**
0.85	0.61	0.40	0.25	0.80	0.46	**plain_total**
0.82	0.55	0.41	0.31	0.78	0.37	**plain_forest**
0.85	0.63	0.43	0.21	0.80	0.48	**plain_noforest**
0.81	0.53	0.42	0.29	0.74	0.34	**mountain_total**
0.83	0.43	0.41	0.35	0.73	0.26	**mountain_forest**
0.81	0.59	0.47	0.22	0.76	0.40	**mountain_noforest**

Focusing on the detection of pixels not covered by snow, the performance of the validation is very similar to the snow covered ones. The best performing combination of PODno-snow and FARno-snow is found in the SE15_SD15 threshold combination with FAR values significantly lower than in the other threshold combinations. FARno-snow values are ranging between 0.19 and 0.27, whereas PODno-snow values range between 0.38 and 0.59.

Concerning the overall accuracy in terms of Hit Rate (HR) over Austria, the SE product v2.1 indicates that between 84 and 91 Percent of all snow events were correctly detected by the algorithm. These values are found for the SE15_SD01 threshold combination. Hit Rate is lower for the other threshold combinations, ranging approximately between 67 and 85 Percent.

Generally, the differences of all of the statistical values between the masked pixels (landcover masks) are only marginal for any threshold combination and for any year. No significant statistical outliers are found in the scores when different landcover masks are applied. That could indicate the good performance of the transmissivity map of the AATSR SCAmod product.

5.8.2 Carpathian Region (2003, 2004, 2006, 2010)

The GlobSnow SE v2.1 product (based on AATSR) validation against snow model data for the Carpathians shows very similar outcomes than for the Austrian domain.

The overall accuracy in terms of Hit Rate (HR) is highest for the SE15_SD01 threshold combination with values around 93 percent. It is also constant throughout the various classes (see Table 5.31).

The SE15_SD01 combination also leads to the highest Kuiper's Skill Scores (KSS) of all threshold combinations, with values ranging from 0.59 to 0.74. The variance between classes is again very little. Combining POD and FAR on can detect POD values for snow covered pixels between 0.59 and 0.74 and a zero FAR for the SE15_SD01 combination. On the other hand POD on not snow covered pixels is 1 with a FARno-snow between 0.13 and 0.21. Thus validation results of AVHRR SCAmod data are very similar to AATSR SCAmod data with no significant discrepancies depending on land us classification (forest, no forest) but differences between the various threshold settings. Eventually, the ≥ 50 % FSC and ≥ 4 cm snow depth combination shows the best result in terms of contingency statistics with modeled snow depth data.

Table 5.31: Carpathians: Statistics based on AATSR (SE product v2.1) and model snow depth data (multiannual average for FSC ≥ 15% and model snow depth ≥ 1 cm)

PODsnow	PODno-snow	FARsnow	FARno-snow	HR	KSS	class
0.74	1	0	0.17	0.94	0.74	**total**
0.63	1	0	0.16	0.93	0.63	**forest**
0.63	1	0	0.14	0.94	0.63	**noforest**
0.72	1	0	0.13	0.95	0.72	**plain_total**
0.59	1	0	0.14	0.94	0.59	**plain_forest**
0.70	1	0	0.21	0.92	0.70	**plain_noforest**
0.74	1	0	0.20	0.94	0.74	**mountain_total**
0.65	1	0	0.21	0.91	0.65	**mountain_forest**
0.67	1	0	0.16	0.94	0.67	**mountain_noforest**

Table 5.32: Carpathians: Statistics based on AATSR (SE product v2.1) and model snow depth data (multiannual average for FSC ≥ 15% and model snow depth ≥ 15 cm)

PODsnow	PODno-snow	FARsnow	FARno-snow	HR	KSS	class
0.82	0.63	0.45	0.10	0.78	0.45	**total**
0.74	0.71	0.55	0.05	0.79	0.45	**forest**
0.74	0.71	0.58	0.04	0.78	0.45	**noforest**
0.81	0.65	0.52	0.07	0.77	0.46	**plain_total**
0.70	0.71	0.59	0.03	0.78	0.42	**plain_forest**
0.79	0.66	0.43	0.11	0.79	0.45	**plain_noforest**
0.82	0.62	0.41	0.12	0.79	0.44	**mountain_total**
0.75	0.68	0.46	0.10	0.79	0.43	**mountain_forest**
0.78	0.69	0.52	0.06	0.79	0.48	**mountain_noforest**

Table 5.33: Carpathians: Statistics based on AATSR (SE product v2.1) and model snow depth data (multiannual average for FSC ≥ 50% and model snow depth ≥ 1 cm)

PODsnow	PODno-snow	FARsnow	FARno-snow	HR	KSS	class
0.66	1	0	0.26	0.90	0.66	**total**
0.45	1	0	0.25	0.87	0.45	**forest**
0.50	1	0	0.23	0.89	0.50	**noforest**
0.66	1	0	0.20	0.92	0.66	**plain_total**
0.43	1	0	0.23	0.88	0.43	**plain_forest**
0.55	1	0	0.33	0.84	0.55	**plain_noforest**
0.66	1	0	0.30	0.89	0.66	**mountain_total**
0.44	1	0	0.34	0.81	0.44	**mountain_forest**
0.53	1	0	0.25	0.88	0.53	**mountain_noforest**

Table 5.34: Carpathians: Statistics based on AATSR (SE product v2.1) and model snow depth data (multiannual average for FSC ≥ 50% and model snow depth ≥ 15 cm)

PODsnow	PODno-snow	FARsnow	FARno-snow	HR	KSS	class
0.75	0.63	0.44	0.17	0.77	0.38	**total**
0.56	0.75	0.53	0.11	0.79	0.31	**forest**
0.63	0.73	0.57	0.08	0.79	0.37	**noforest**
0.75	0.64	0.51	0.12	0.77	0.39	**plain_total**
0.55	0.74	0.57	0.08	0.80	0.30	**plain_forest**
0.65	0.70	0.43	0.20	0.78	0.35	**plain_noforest**
0.74	0.62	0.40	0.21	0.77	0.36	**mountain_total**
0.54	0.74	0.46	0.20	0.78	0.28	**mountain_forest**
0.66	0.72	0.50	0.12	0.79	0.38	**mountain_noforest**

For the Carpathian region there is a clear signal, that the FSC ≥ 15% and snow depth ≥ 1 cm combination (SE15_SD01) shows the best performance in terms of binary statistics. Even though a more detailed landcover masking was applied, SE v2.1 shows quite better performance than the SE v1.2, when validated against modelled snow depth in the Carpathian domain.

The full evaluation results for the Carpathian region are provided in Appendix F.2.

5.9 Comparison of AATSR SCAmod with AVHRR SE (European Alps)

This section introduces the results for the inter-satellite comparison over the European Alps for the product version 2.1 and compares the results with the previous version (v1.2). Again, the results are shown separately for the two threshold values (15% and 50%). Even though the AVHRR SPARC SE is taken as a reference here, this is considered a comparison with regard to data set merging rather than a validation. Therefore the following results should be interpreted with care as also the AVHRR SPARC SE suffers from some (partly the same) inaccuracies and cannot be taken as a true reference. Due to limited reprocessing, only the years 2003, 2004, 2006, and 2010 are re-validated and used for the comparison here. Hence, the results of version 1.2 can slightly differ from the previous validation report. The full comparison results, considering also particular surface classes, are provided in Appendix J.

5.9.1 Results for threshold value 15%:

Selected results for the temporal comparison of AVHRR SE and GlobSnow SE v2.1 for the threshold of 15% are displayed in Figure 5.20. The plot presents the monthly mean contingency table statistics averaged over four validation years.

Generally, the differences between the same landcover in plain area and in mountains are very similar. HR shows values above 0.7 over the whole year but slightly decreases during the snow season. While the HR for non-forested areas (mountain and plain) remains constantly high over the course of the year (i.e. 0.89 in January and 0.99 in August), the seasonal differences increase for the forested areas (HR of 0.7 in January and 0.99 in August) and are also found in the total dynamic of HR over the course of the year. The annual behaviour for PODsnow shows an opposite behaviour than the HR. It is found to be high during winter (around 0.9 for all landcover classes, also forests) and decreases during the summer months, particularly for the non-forested areas. The reason for this is assumed to be caused by a known slight overestimation (artefact) of snow by the AVHRR SE product, which has been optimized and validated for winter but not for summer months (see Hüsler et al. 2012). During summer, the higher values of POD snow for the forested areas is caused by the snowline lying mostly higher elevated than the treeline during this season. Therefore, the high winter values remain indicative for the comparison. As a summary, the KSS is moving around a value of 0.6 over the year. While it is slightly higher for non-forested areas than for forested areas during winter, this behaviour is opposed during the snowfree season for the reasons outlined before.

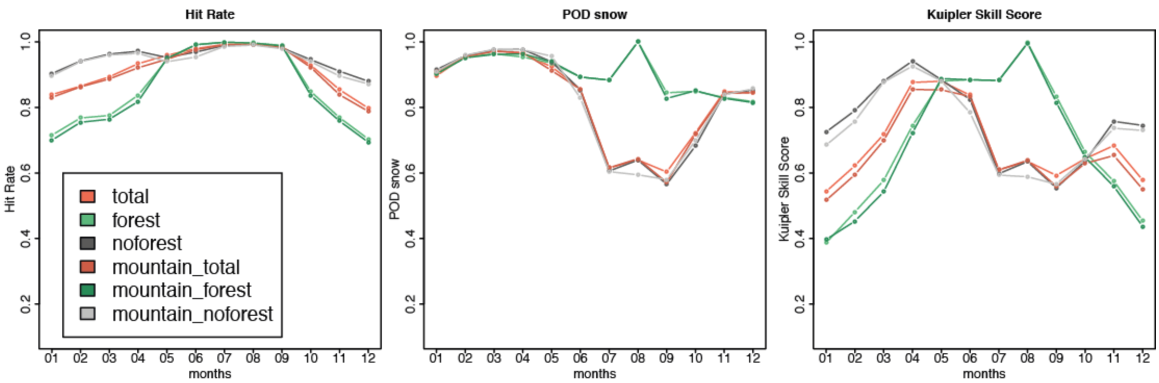


Figure 5.20: Hit rate (left panel), POD snow (center panel), and Kuiper Skill Score (right panel) monthly mean values for the years 2003, 2004, 2006, and 2010 for all validation classes (see legend). Results apply to a SCA threshold of 15%.

The spatial analyses (Figure 5.21 and Figure 5.24) at annual resolution display the most occurring value (see legend in Figure 5.21) over the course of the full year. Generally, these values indicate a very high spatial agreement between the two snow products. Most of the pixel values aggregated over a full year (here 2004) show either both “snow” or both “snowfree” conditions. However, small differences occur in forested regions, particularly found in lower lying areas and the South Eastern part of the Alps, where GlobSnow-2 SE indicates snow while AVHRR SE shows snowfree conditions in the majority of the cases during the year 2004. As expected, also all the contingency table measurements indicate a high agreement (mean KSS of 0.92) and – most importantly – remain constant over all validation years. The bias values are interpreted as a slight underestimation of snow cover by AVHRR SE when using a GlobSnow-2 SE v2.1 SCA threshold of 15%. However, these values tend to improve when using a SCA threshold of 50% (see section below).

Table 5.35: Annual accuracy measure values for spatial comparison indicated in Figure 5.21 for all validation years for the Alpine Region. Results apply to a SCA threshold of 15%.

Year	HR	BIAS	KSS	POD snow	FAR snow
2003	0.98	0.96	0.97	0.99	0.05
2004	0.95	0.93	0.92	0.97	0.09
2006	0.98	0.98	0.95	0.97	0.04
2010	0.98	0.97	0.96	0.98	0.04
Mean	0.97	0.96	0.95	0.98	0.06

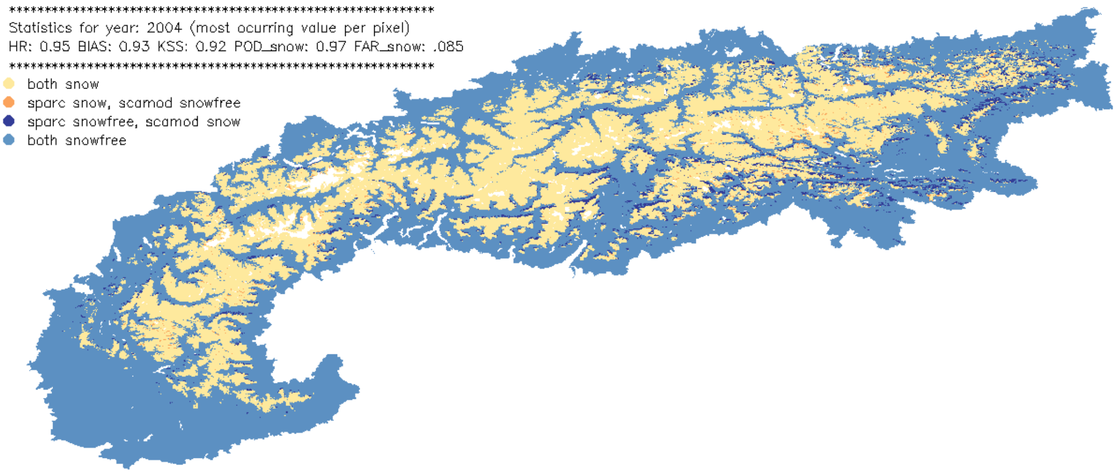


Figure 5.21: Spatial comparison between AVHRR SE and GlobSnow-2 SE v2.1 for the Alpine Region. Pixel values indicate most occurring value during the course of the year 2004. Results apply to a SCA threshold of 15%.

5.9.2 Comparison to v1.2 for threshold value 15%:

The comparison of the GlobSnow SE v1.2 and v2.1 for a cut off value of 15% generally shows some improvement for the reprocessed version (v2.1). Figure 5.22 displays the differences in HR, POD snow, and KSS for the two versions of the GlobSnow SE product. Difference values for HR are very low and indicate slightly higher (better) values for non-forested regions and slightly lower values of forested regions in winter for the v2.1 product. Overall, PODsnow as well as KSS show a significant improvement for the v2.1 except for KSS in DJF for the forested regions.

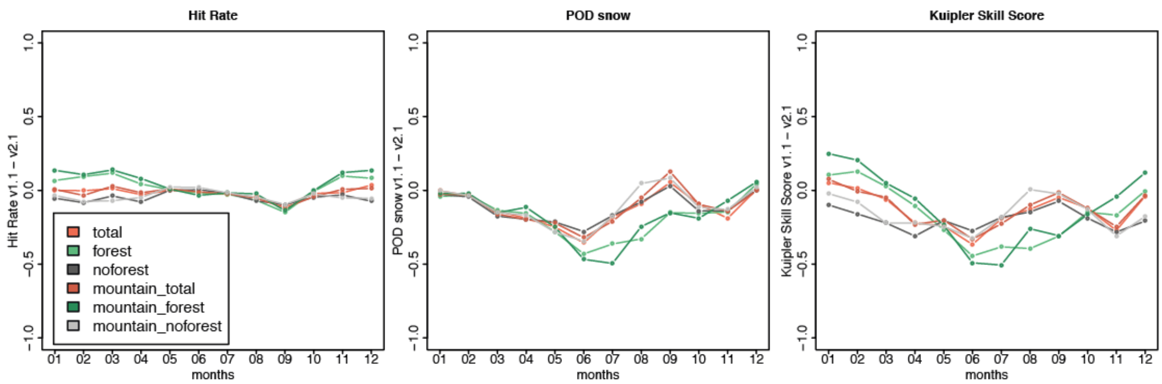


Figure 5.22: Differences between GS-2 v1.2 and GS-2 v2.1 in Hit rate (left panel), POD snow (centre panel), and Kuiper Skill Score (right panel) monthly mean values for the years 2003, 2004, 2006, and 2010 for all validation classes (see legend). Results apply to a SCA threshold of 15%.

The differences in the annually summarized values are shown in Table 5.36 and only indicate negligible differences between the two product versions. However, all values show an improvement except for the bias in 2003.

Table 5.36: Differences between GS-2 v1.2 and GS-2 v2.1 in annual accuracy measure values for spatial comparison for all validation years for the Alpine Region. Results apply to a SCA threshold of 15%.

Year	HR	BIAS	KSS	POD snow	FAR snow
2003	0.00	0.03	-0.03	-0.03	0.00
2004	-0.01	-0.01	-0.02	0.00	0.01
2006	-0.01	-0.01	-0.02	-0.02	0.03
2010	-0.02	-0.01	-0.03	-0.02	0.03
Mean Diff	-0.01	0.00	-0.03	-0.02	0.02

5.9.3 Results for threshold value 50%

The results for the SCA threshold of 50% are generally very similar to the results presented for the threshold of 15% for all land cover classes. The PODsnow (see Figure 5.23) is slightly lower during the summer which is, however, not assumed indicative for the reason of known deficiencies of AVHRR SE in summer (see comments above). The remarkable peak in August for POD snow and KSS for both thresholds is explained by the slightly higher availability of clear-sky coincident overpasses.

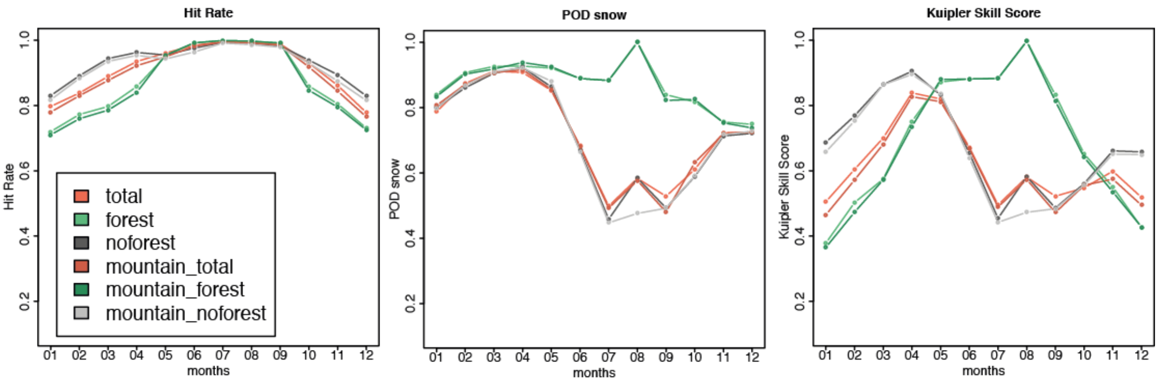


Figure 5.23: Hit rate (left panel), POD snow (center panel), and Kuiper Skill Score (right panel) monthly mean values for the years 2003, 2004, 2006, and 2010 for all validation classes (see legend). Results apply to a SCA threshold of 50%.

Table 5.37: Annual accuracy measure values for spatial comparison indicated in Figure 5.24 for all validation years for the Alpine Region. Results apply to a SCA threshold of 50%.

Year	HR	BIAS	KSS	POD snow	FAR snow
2003	0.98	0.96	0.97	0.99	0.05
2004	0.95	0.93	0.92	0.97	0.09
2006	0.98	0.98	0.95	0.97	0.04
2010	0.98	0.97	0.96	0.98	0.04
Mean	0.97	0.96	0.95	0.98	0.06

The spatial comparison for the year 2004 (Figure 5.24) shows a gentle but insignificant decrease of the „AVHRR SE snowfree, GlobSnow SE snow“-case in the transition zone while the number of „AVHRR SE snow, GlobSnow SE snow“-case marginally increases in comparison to the 15%-threshold.

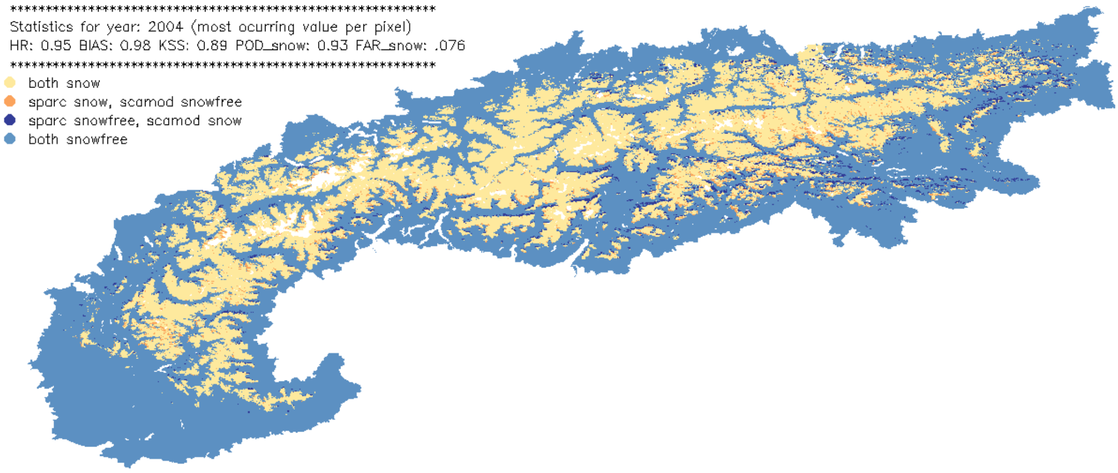


Figure 5.24: Spatial comparison between AVHRR SE and GlobSnow SE for the Alpine Region. Pixel values indicate most occurring value during the course of the year 2004. Results apply to a SCA threshold of 50%.

5.9.4 Comparison to v1.2 for threshold value 50%

Similarly to the threshold of 15%, the comparison of the GlobSnow SE v1.2 and v2.1 for a cut off value of 50% generally shows some improvement for the reprocessed version (v2.1). Figure 5.25 presents the differences in HR, PODsnow, and KSS for the two versions of the GlobSnow SE product. Difference values for HR are very low and indicate insignificantly higher (better) values for non-forested value and slightly lower values of forested regions in winter for the v2.1 product. Finally, POD snow as well as KSS show a significant improvement for the v2.1 and confirm the influence of geolocation on the accuracy of the SE product.

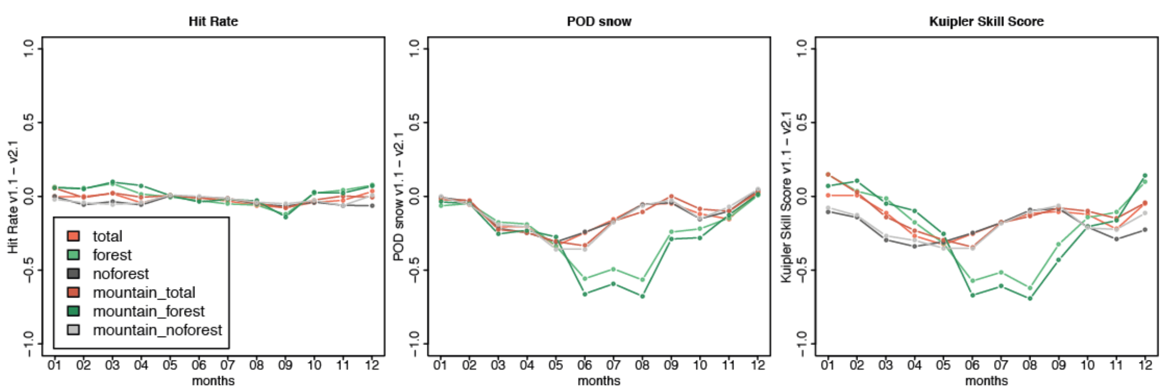


Figure 5.25: Differences between GS-2 v1.2 and GS-2 v2.1 in Hit rate (left panel), POD snow (centre panel), and Kuiper Skill Score (right panel) monthly mean values for the years 2003, 2004, 2006, and 2010 for all validation classes (see legend). Results apply to a SCA threshold of 50%.

The differences in the annually summarized values are shown in Table 5.38. As for the threshold of 15%, only marginal differences can be found. These, however, point to an improvement of the agreement between AVHRR SE and GlobSnow SE v2.1 product for all investigated years. Especially the differences in KSS and PODsnow indicate an increase in accuracy in the reprocessed version of the GlobSnow SE product. HR and FAR snow remain very close and the Bias values are slightly shifted towards an underestimation of snow by AVHRR SE.

Table 5.38: Differences between GS-2 v1.2 and GS-2 v2.1 in annual accuracy measure values for spatial comparison for all validation years for the Alpine Region. Results apply to a SCA threshold of 50%.

Year	HR	BIAS	KSS	POD snow	FAR snow
2003	-0.02	0.04	-0.11	-0.12	-0.01
2004	-0.02	0.07	-0.07	-0.07	0.00
2006	-0.03	0.02	-0.09	-0.09	0.01
2010	-0.03	0.03	-0.08	-0.08	0.03
Mean Diff	-0.02	0.04	-0.09	-0.09	0.04

In summary of Section 5.9, the detailed visual investigation of all the difference images (from all coincident overpasses over the region of interest) reveals the expected pattern: Low-lying snowfree areas as well as the higher altitude sites are found to be in very good agreement, the transition zones around the snowline (especially during spring and autumn) indicate the highest differences in the two snow products. The differences are mainly attributed to forested areas that are not equally well detected in both the products and remain a problem in optical remote sensing in general. Furthermore, sparse illumination at north-facing slopes during winter causes another region of uncertainty. However, the results in DEL-11, where the two products were compared using regression-based analyses, indicated a good agreement between the products over time and space and are considered slightly more representative than the “validation” procedure here.

The comparison between the two product versions of GlobSnow SE (v1.2 and v2.1) shows an improvement of v2.1 with respect to AVHRR SE. Even though the snow detection with SCAmod remained the same, the improvement in almost all accuracy parameters indicates a certain influence of small pixel shifts in the validation – especially over the complex terrain of the European Alps.

5.10 Consistency check (algorithm and data) using ATSR-2 and AATRS data

Finland

Kristin Böttcher (SYKE)

FSC estimates from AATSR and ATSR-2 showed good correspondence for observations in 2003 over Finland (R2=0.91, N=174597). However, observations were highly scattered (Figure 5.26).

This is most probably due to geolocation differences between the products from different sensors.

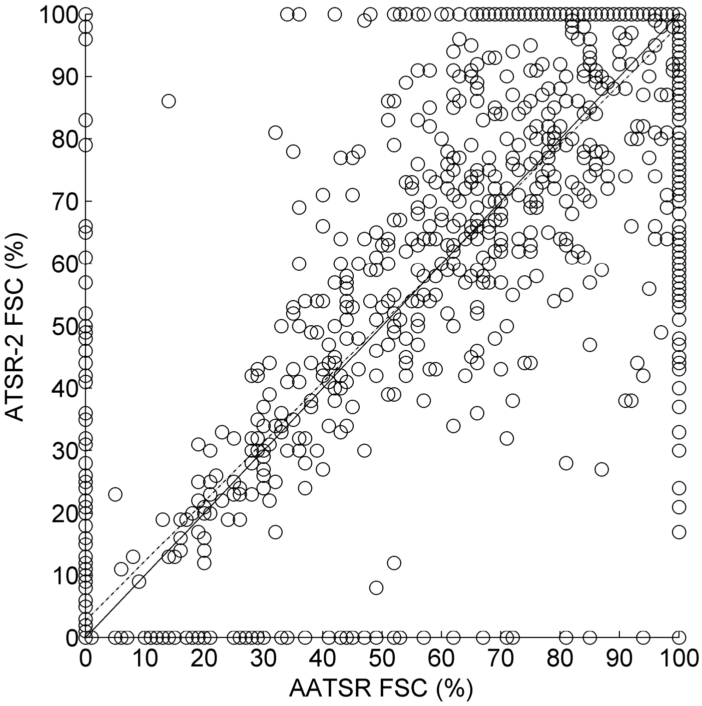


Figure 5.26: Scatterplots of FSC estimates from ATSR-2 and AATSR for 2003. Note that only every 50th observation is shown in the scatter plot.

Results for the validation based on Finnish weather station e-codes are summarized in Appendix E. Overall performance (HR) was the same for both products. More valid observations were retained from AATSR based products than from ATSR-2. PODsnow was a slightly higher for ATSR-2 when applying thresholds SE0 and SE15, but PODnosnow was lower compared to AATSR based products.

5.11 ATSR & AATSR SE product v2.0 (1995-2012)

Nando Foppa and Fabio Fontana (MeteoSwiss)

The following four tables summarize the performance of the combined ATSR/AATSR time series (SE product v2.0) from 1995 to 2012 at each selected stations (Table 5.39 to Table 5.42).

Each table represents one FSC and in-situ threshold combination and the sum and scores calculated over all sites from the total number of hits, missed events, false alarms and true negatives. The statistical indices are based on a total of 5847 data pairs.

Comparing the ATSR and AATSR validation results separately, we conclude that the threshold combination 15_1 leads to highest KSS scores (0.63 to 0.97) over all stations including lowland and highest alpine sites. This conclusion is emphasized when both data sets are combined (see Table 5.39). If the binary threshold is set to ≥ 50% snow cover and the in-situ one to ≥ 1cm, the number of missed events increases considerably at the urban sites located at lowland regions

(BAS, LUG). This effect could be related to a relatively low number of observed snow events, which are usually short-lived. A similar outcome with an increase of the number of missed events is found at the inner-alpine valleys on middle altitudes, probably referred to the high elevation gradients at these sites (MEI, CHU).

Table 5.39: Statistics at each validation site based on A/ATSR 1995-2012 (excl. 2001) for FSC ≥ 15% and in-situ ≥ 1cm.

Site	HIT	MISS	FALSE	TRUE	ACC	POD snow	PODno snow	FAR snow	FARno snow	POFD	KSS
SAM	234	6	14	351	0.97	0.98	0.96	0.06	0.02	0.04	0.94
LUG	16	0.0	24	798	0.97	1.00	0.97	0.60	0.00	0.03	0.97
WFJ	265	26	2	100	0.93	0.91	0.98	0.01	0.21	0.02	0.89
LCF	109	3	17	367	0.96	0.97	0.96	0.13	0.01	0.04	0.93
AND	225	8	23	302	0.94	0.97	0.93	0.09	0.03	0.07	0.89
CHU	53	13	28	534	0.93	0.80	0.95	0.35	0.02	0.05	0.75
MEI	63	30	23	498	0.91	0.68	0.96	0.27	0.06	0.04	0.63
EIN	122	6	5	426	0.98	0.95	0.99	0.04	0.01	0.01	0.94
BAS	18	3	13	511	0.97	0.86	0.98	0.42	0.01	0.02	0.83
CHD	135	18	16	442	0.94	0.88	0.97	0.11	0.04	0.03	0.85
All sites	**1240**	**113**	**165**	**4329**	**0.95**	**0.92**	**0.96**	**0.12**	**0.03**	**0.04**	**0.88**

Table 5.40: Statistics at each validation site based on A/ATSR 1995-2012 (excl. 2001) for FSC ≥ 15% and in-situ ≥ 15cm.

Site	HIT	MISS	FALSE	TRUE	ACC	POD snow	PODno snow	FAR snow	FARno snow	POFD	KSS
SAM	168	0	80	357	0.87	1.00	0.82	0.32	0.00	0.18	0.82
LUG	1	0	39	798	0.95	1.00	0.95	0.98	0.00	0.05	0.95
WFJ	254	13	13	113	0.93	0.95	0.90	0.05	0.10	0.10	0.85
LCF	63	0	63	370	0.87	1.00	0.85	0.50	0.00	0.15	0.85
AND	201	6	47	304	0.91	0.97	0.87	0.19	0.02	0.13	0.84
CHU	11	0	70	547	0.89	1.00	0.89	0.86	0.00	0.11	0.89
MEI	22	4	64	524	0.89	0.85	0.89	0.74	0.01	0.11	0.74
EIN	70	0	57	432	0.90	1.00	0.88	0.45	0.00	0.12	0.88
BAS	0	0	31	514	0.94	-	0.94	1.00	0.00	0.06	-
CHD	101	2	50	458	0.91	0.98	0.90	0.33	0.00	0.10	0.88
All sites	**891**	**25**	**514**	**4417**	**0.91**	**0.97**	**0.90**	**0.37**	**0.01**	**0.10**	**0.87**

Table 5.41: Statistics at each validation site based on A/ATSR 1995-2012 (excl. 2001) for FSC ≥ 50% and in-situ ≥ 1cm.

Site	HIT	MISS	FALSE	TRUE	ACC	POD snow	PODno snow	FAR snow	FARno snow	POFD	KSS
SAM	221	19	8	357	0.96	0.92	0.98	0.03	0.05	0.02	0.90
LUG	5	11	3	819	0.98	0.31	1.00	0.38	0.01	0.00	0.31
WFJ	246	45	0	102	0.89	0.85	1.00	0.00	0.31	0.00	0.85
LCF	98	14	2	382	0.97	0.88	0.99	0.02	0.04	0.01	0.87

Site	HIT	MISS	FALSE	TRUE	ACC	POD snow	PODno snow	FAR snow	FARno snow	POFD	KSS
AND	195	38	6	319	0.92	0.84	0.98	0.03	0.11	0.02	0.82
CHU	35	31	8	554	0.94	0.53	0.99	0.19	0.05	0.01	0.52
MEI	31	62	4	517	0.89	0.33	0.99	0.11	0.11	0.01	0.33
EIN	99	29	1	430	0.95	0.77	1.00	0.01	0.06	0.00	0.77
BAS	12	9	3	521	0.98	0.57	0.99	0.20	0.02	0.01	0.57
CHD	102	51	7	451	0.91	0.67	0.98	0.06	0.10	0.02	0.65
All sites	**1044**	**309**	**42**	**4452**	**0.94**	**0.77**	**0.99**	**0.04**	**0.06**	**0.01**	**0.76**

Table 5.42: Statistics at each validation site based on A/ATSR 1995-2012 (excl. 2001) for FSC ≥ 50% and in-situ ≥ 15cm.

Site	HIT	MISS	FALSE	TRUE	ACC	POD snow	PODn snow	FAR snow	FARno snow	POFD	KSS
SAM	166	2	63	374	0.89	0.99	0.86	0.28	0.01	0.14	0.84
LUG	0	1	8	829	0.99	0.00	0.99	1.00	0.00	0.01	-0.01
WFJ	240	27	6	120	0.92	0.90	0.95	0.02	0.18	0.05	0.85
LCF	63	0	37	396	0.93	1.00	0.91	0.37	0.00	0.09	0.91
AND	180	27	21	330	0.91	0.87	0.94	0.10	0.08	0.06	0.81
CHU	8	3	35	582	0.94	0.73	0.94	0.81	0.01	0.06	0.67
MEI	16	10	19	569	0.95	0.62	0.97	0.54	0.02	0.03	0.58
EIN	66	4	34	455	0.93	0.94	0.93	0.34	0.01	0.07	0.87
BAS	0	0	15	530	0.97	-	0.97	1.00	0.00	0.03	-
CHD	83	20	26	482	0.92	0.81	0.95	0.24	0.04	0.05	0.75
All sites	**822**	**94**	**264**	**4667**	**0.94**	**0.90**	**0.95**	**0.24**	**0.02**	**0.05**	**0.84**

Overall, we observed a good agreement with a KSS varying between 0.88 (15_1) and 0.76 (50_1) for all stations over the entire period. It can be seen that the POFD is very close to zero for 15_1, while PODsnow and KSS basically take the same values. This is a consequence of the fact that for relatively rare events, the KSS, which is the difference between PODsnow and POFD, is completely dominated by the PODsnow (as POFD is almost zero due to the high number of "true negatives").

Concerning the overall accuracy (ACC) over Switzerland, the SE product v2.0 indicates that 95% of all snow events were correct detected by the algorithm (15_1). The accuracy ranges in between 0.98 (EIN) and 0.87 (LCF), depending on the threshold combination. The variation of ACC between the validation sites representing varying landcover, topography and snow distribution is smallest and highest when a threshold combination of 15% FSC and an in-situ snow depth of ≥ 1cm is chosen (15_1). However, ACC could be misleading since it is highly dependent on the most common category (e.g. snow covered in high mountainous landscapes and snow free in the lowland plains). PODsnow and FAR should be used in conjunction with each other to take into account false alarms and missed events, respectively. Relatively high FAR values (e.g. 0.27 to 0.86) are driven by the absolute number of observed hits in relation to the number of false alarms. This is mostly the case when the in-situ snow depth threshold increases to 15cm (e.g. CHU, MEI, EIN, SAM). Likewise, no significant changes of FAR is observed for the station sites WFJ and AND. In general, FAR is smallest when 50_1 is chosen, representing a conservative threshold for the binary satellite-based snow cover classification.

Overall, the investigation revealed a good performance at all station sites, particularly when a threshold combination of 15% FSC and an in-situ snow depth of ≥ 1cm is chosen (15_1). We can conclude that the assessment of the performance of the SE product v2.0 is sensitive to the selection of the threshold combination. However, a uniform distribution of reference sites along a horizontal and vertical scale, such as the selected validation sites, allows us to draw conclusions on the overall performance. Overall, we conclude that the variation of the accuracy between the different in-situ sites representing varying landcover, topography and snow distribution, is smallest and highest when a threshold combination of 15% FSC and an in-situ snow depth of ≥1cm is chosen. In general, our validation results show a strong performance of the SE product v2.0 over the mountainous regions of Switzerland.

5.12 Trend Analysis

Eirik Malnes and Heidi Hindberg (Norut)

Based on the time series from the Globsnow-2 Snow cover fraction product v2.1 (GS2-SE v2.1) and the partially overlapping time series of MODIS snow cover fraction products (MOD10A1-product) we have made an assessment of the two products ability to capture the overall trends in the snow cover fraction for an extended area. The two time series AATSR and MODIS cover the periods 1995-2012 and 2000-2013, respectively. When using the GlobSnow SE version 2.1 we used the period 2003-2011 for comparison since this period are common for the two datasets and cover entire years.

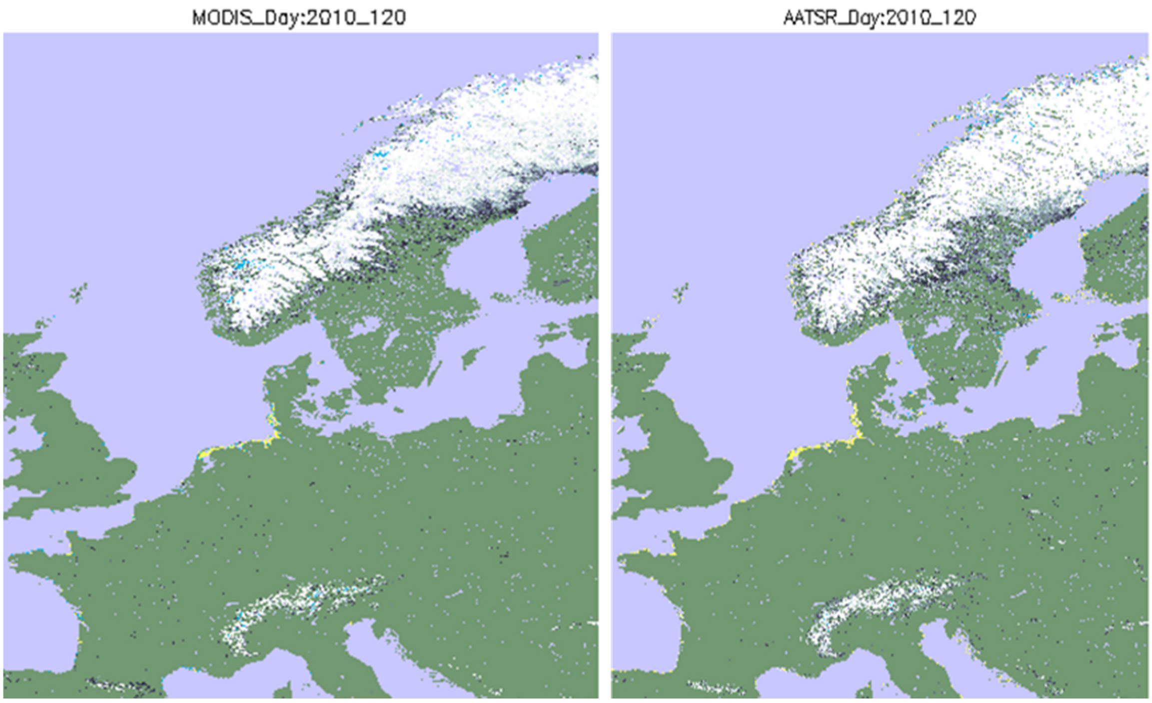


Figure 5.27: Snow cover fraction for Europe for April 30, 2010 (DOY=120) for MODIS (left) and AATSR (right).

In order to obtain a direct comparison of the trends in snow cover fraction we first use temporal interpolation to obtain cloud free snow maps for the areas under investigation. By using straight-forward pixel-to-pixel interpolation between cloud-free pixels we obtain cloud free estimates for the snow cover fraction. The trend analysis is subsequently performed by estimating the total weighted snow cover fraction within the area 42°-72°N and 5°W to 30°E covering most of Europe (Figure 5.27). This area was selected based on the common area between a remapped MOD10A1 dataset readily available at Norut covering Europe.

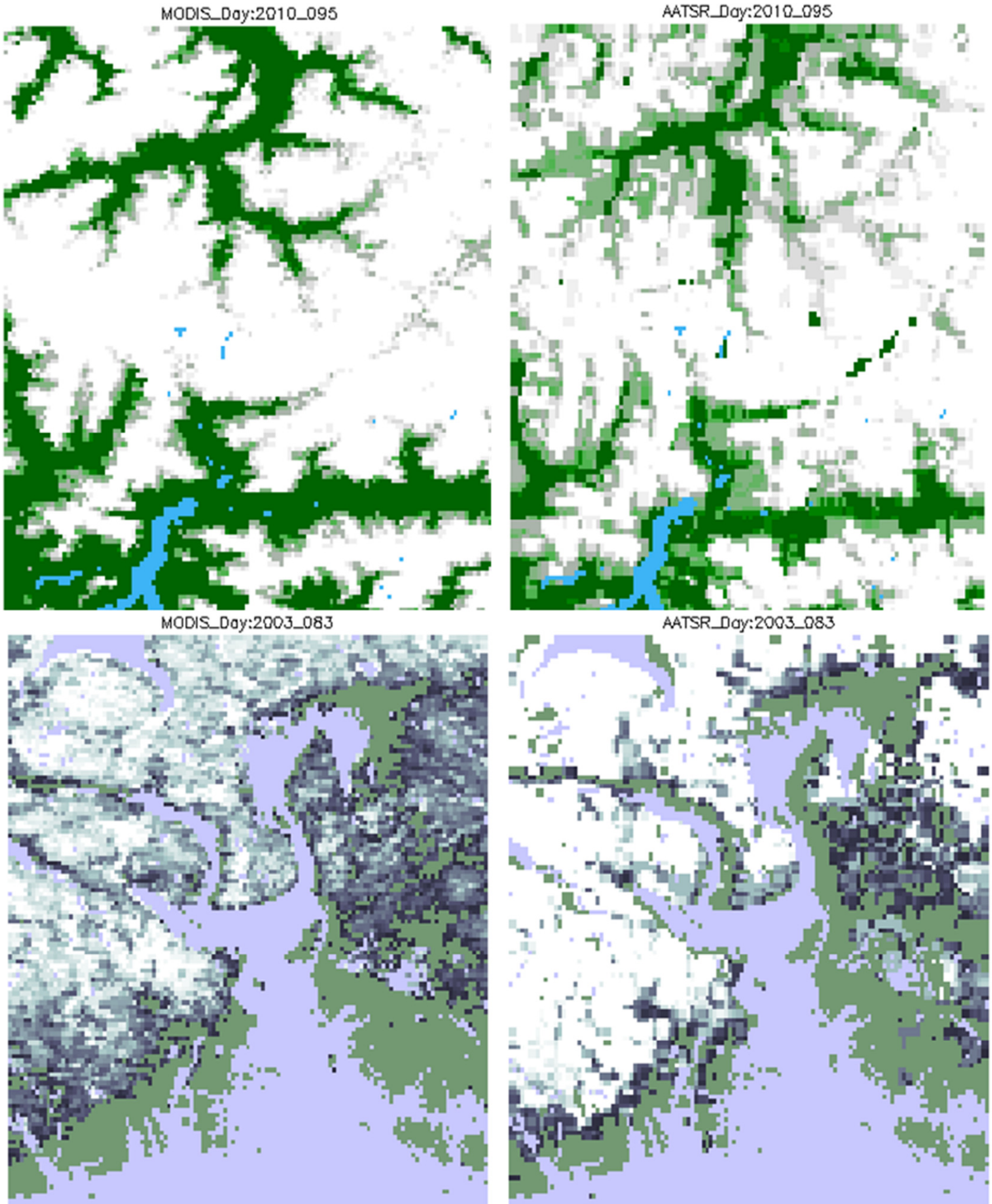


Figure 5.28: Top: Detailed comparison for an area in South-Tyrol (46ºN, 11ºE), Italy for MODIS (left) and AATSR (right) for April 5th in 2010 (DOY=95). Bottom: Comparison for an area south of Oslo, Norway (59ºN, 10ºE) for March 24, 2003 (DOY=95).

We have also studied the ability for this multi-temporal aggregation algorithm to capture smaller areas properly (typically 1°x1°-areas in latitude and longitude) for specific days (Figure 5.28). The inter-comparison shows good overall agreement between MODIS and AATSR, although the differences in spatial resolution and effects due to lower temporal resolution in the AATSR dataset are also clearly visible.

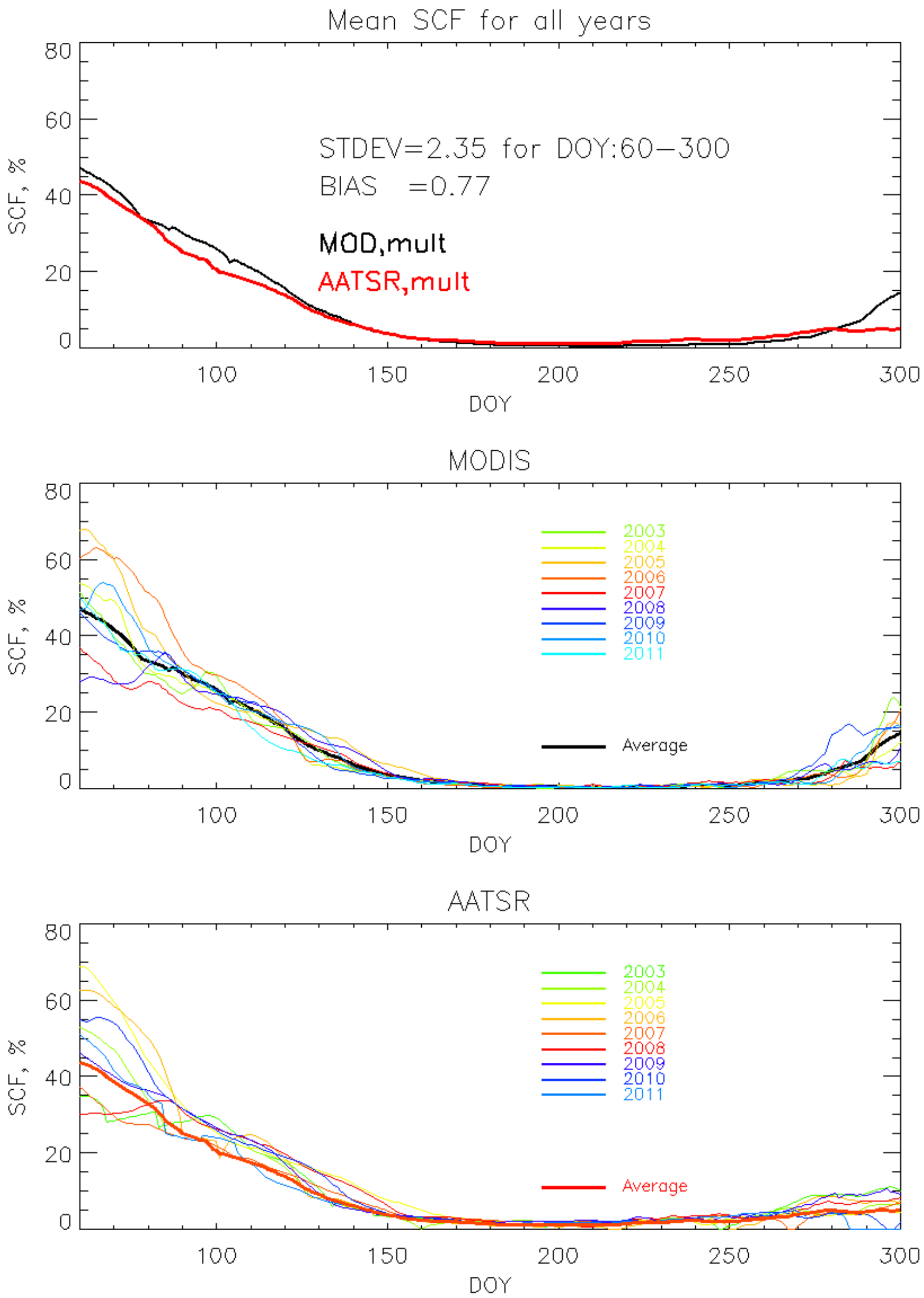


Figure 5.29: Snow cover fraction vs day of year (DOY) for MODIS and AATSR datasets for Europe. Top panel: Comparison between MODIS and AATSR average snow fraction vs. DOY. Middle panel: MODIS total snow fraction for individual years used in the average. Lower panel: AATSR total snow fraction for individual years used in the average.

To assess the overall trend in the two datasets we calculate the total snow cover fraction for the whole area for each day. This yields continuous snow depletion curves per year (Figure 5.29). We have also removed the time periods in the start and the end of the year since significant areas are masked during low solar angles. The overall results are valid in the period March-October. All together 9 years (2003-2011) from MODIS and AATSR has been used to calculate the average snow depletion curves.

The overall comparison between the total snow cover fraction with MODIS and AATSR shows remarkable similarities for the most of the year (Stdev=2.35, BIAS=0.77). The differences are largest in March and October as expected due to poorer coverage in the AATSR time series.

Figure 5.29 shows also the snow depletion curves for the individual years for MODIS (middle panel) and AATSR (bottom panel).

The difference in total snow cover fraction for Europe is also shown in Figure 5.30. The figure shows that the MODIS estimates for SCF is often higher than AATSR for the spring period, but that this trend is reversed in the summer months where AATSR typically is 1% higher. We suspect that the fluctuations early in spring and late in fall are related to the poorer temporal coverage in AATSR.

All equations used for the trend analysis are provided in Appendix K.

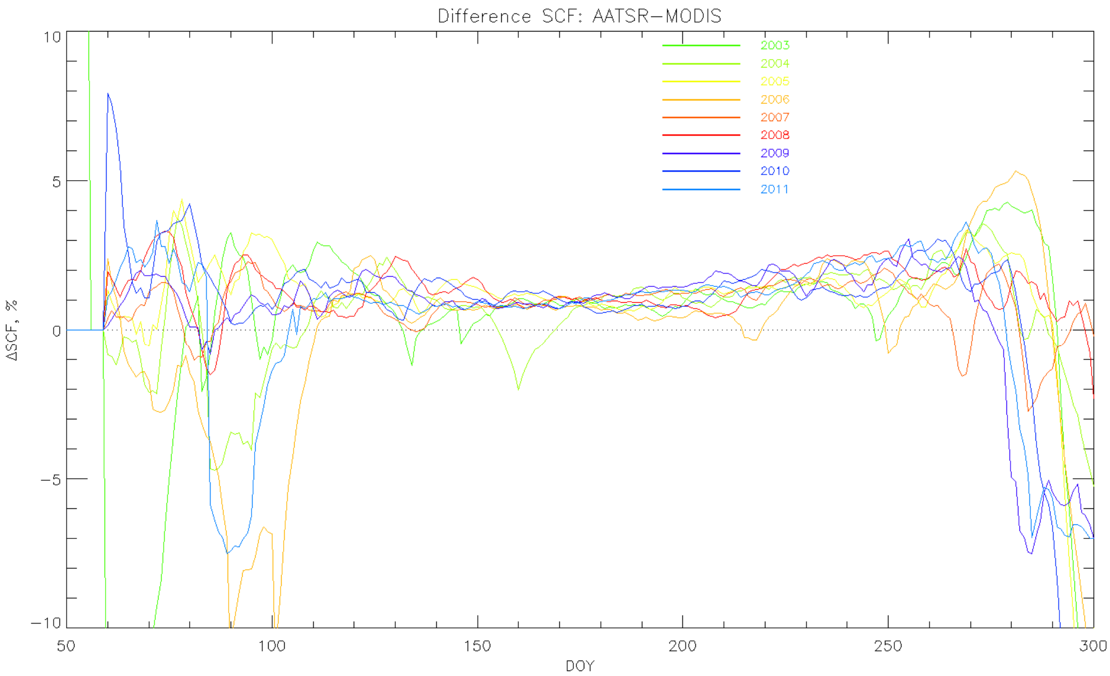


Figure 5.30: Difference in estimates of snow cover fraction for Europe based on AATSR and MODIS as a function of DOY.

6 SUMMARY AND CONCLUSION

6.1 Evaluation with in-situ measurements (MeteoSwiss, ZAMG, SYKE)

The validation of the GlobSnow v2.1 SE-product has been carried out by in-situ snow measurements in Finland and Austria. In-situ data of Switzerland were used to validate the GlobSnow v2.0 SE product. Results of this intercomparison should be seen as qualitative information, but absolute values might be different. Varying threshold combinations for defining a binary (satellite-based and in-situ) snow classification were defined.

6.1.1 Finland

Daily binary snow cover was evaluated for years 1999, 2000, 2003 and 2006 based on Finnish weather stations e-codes. Three different thresholds were used to generate binary snow maps from the GlobSnow-2 SE v2.1 products: SE0, SE15 and SE50. Thresholds SE0 and SE50 are directly comparable to e-codes, whereas the true FSC may be below or above 15% (SE15) for e-code 4 and 5.

Good overall accuracy was obtained for SE50 based on observations from all years. PODsnow and PODno-snow were 0.97, 0.94 and HR was 0.95. The observed PODsnow decreased for SE0 and SE15; 11% and 13% of snow covered cases were not detected, respectively. Comparisons of results for year 2003 showed no significant changes to previous GlobSnow product v.1.2. Statistical parameters were similar for both sensors, ATSR-2 (1999, 2000) and AATSR (2003, 2006).

6.1.2 Austria

For the intercomparison of GlobSnow-2 SE v2.0 products with in-situ measurements in Austria a total of 43 ZAMG weather stations were selected. The stations represent all main climatological regimes in Austria and vary between 245 m asl and 1794 m asl. The validation was carried out for the years 2003, 2004, 2006 and 2010 (according to the gridded snow depth validation). The binary metrics were calculated based on four threshold combinations: SE15/SD01, SE15/SD15 and SE50/SD01, SE50/SD15.

The overall accuracy in terms of Hit Rate (HR) is highest for the SE15/SD15 combination (0.9) and lowest for SE50/SD01 (0.86). Probability of detection (POD) for snow cover occurrences is very low all threshold combinations (between 0.19 for SE50/SD15 and 0.44 SE15/SD15). POD for snow-free occurrences is very high (between 0.96 and 1). False Alarm rate for snow cover occurrences varies between 0.09 (SE50/SD01) and 0.41 (SE15/SD15) and is much lower for snow-free occurrences (between 0.08 and 0.14). POD and FAR for snow-free events show little variance between the different threshold combinations, so does the overall accuracy (Hit Rate). For snow-cover occurrences there is a higher difference between the values. In summary, there exists no ideal threshold combination, however the 50% FSC, 1 cm Snow Depth combination tends to show the best agreement with in-situ snow stations in Austria.

6.1.3 Switzerland

The in-situ validation over Switzerland was carried out by comparing daily FSC (binary classified) data as provided by the SE v2.0 product derived from ATSR-2 and AATSR over the period 1995-2012 with ten high-quality in-situ validation sites representing different climatological regions, altitudes and land covers. The accuracy assessment included a total of 5847 data pairs. Four threshold combinations have been defined with varying FSC (15% and 50%) and in-situ thresholds (≥ 1cm and ≥ 15cm) to distinguish between snow and no-snow.

Overall, we observed a good agreement with a KSS varying between 0.88 (SE15/SD01) and 0.76 (SE50/SD01) for all stations over the entire period. Concerning the overall accuracy (ACC), the SE product v2.0 indicates that 95% of all snow events were correct detected by the algorithm (SE15/SD01). In general, FAR is smallest (4%) when (SE50/SD01) is chosen, representing a conservative threshold for the binary satellite-based snow cover classification.

When comparing the SE v2.0 products from both the ATSR-2 and AATSR with the in-situ data, it was identified that AATSR-derived SE corresponds more strongly with the in-situ data.

Overall, we conclude that the variation of the performance between the different in-situ sites representing varying land cover, topography and snow distribution, tends to be smallest and highest when a threshold combination of 15% FSC and an in-situ snow depth of ≥1cm is chosen.

The overall good performance of the SE product v2.0 highlights the importance of satellite-based snow cover monitoring, complementing ground-based observations and its role in the generation of potential high-quality climatological time series.

6.2 Evaluation with Model data (snow extent) (ZAMG)

Austria and Carpathian Region

In summary, the statistical outcomes of the AATSR validation against snow model data are very similar over both regions. The FSC ≥ 15% and snow depth ≥ 1cm threshold combination (SE15_SD01) is suggested as the most valuable one for both domains.

For the Austrian domain, the KSS ranges between 0.26 and 0.48 depending on the applied land cover mask. If no mask is applied, the KSS is 0.39. For the Carpathians KSS values are ranging between 0.59 and 0.74.

Concerning the overall accuracy in terms of Hit Rate (HR) over Austria, the SE product v2.1 indicates, that between 84 and 91 Percent of all snow events were correctly detected by the algorithm (SE15_SD01). Hit Rate is lower for the other threshold combinations, ranging approximately between 67 and 85 Percent. Very similar results are found for the Carpathians with an overall accuracy of around 93 Percent (SE15_SD01). It is also constant throughout the various classes.

Generally, the differences of all of the statistical values between the masked pixels (land cover masks) are only marginal for any threshold combination, for any year and for both regions. No significant statistical outliers are found in the scores when different landcover masks are applied.

Eventually a clear signal in the statistical results towards a better performance of GlobSnow-2 SE v2.1 products compared to SE v1.2 products can be found for both regions. Focusing on the threshold combinations the FSC ≥ 15% and snow depth ≥ 1 cm reveals the best performance of GlobSnow-2 SE v2.1 products compared to modelled snow depth data.

6.3 Evaluation with satellite-borne snow products (ENVEO, UBE, SYKE, NR)

6.3.1 Comparison of AATSR SCAmod v2.1 with AVHRR SE (European Alps)

Overall the match between the two SE products (AVHRR SE and GlobSnow SE v2.1) over the European Alps is satisfactorily high but always depends on landcover type and snowline altitude. While differences mainly occur at the transition between snow and snowfree areas, they are generally assumed to be caused by differing snow detection algorithms, snow under trees and different cloud masking techniques. These results (as well as the results presented in the Preliminary SE validation report DEL11, Chapter 6.4 – which are considered slightly more representative for this purpose) are promising with regard to an FCDR production incorporating both products. No particular comparison can be carried out between the Preliminary SE validation report DEL-11 and the full validation report DEL-21 because the methods do slightly vary. However, as the differences between the two GlobSnow SE versions; the one investigated in the preliminary validation report and the final FPS v2.1 are expected to be marginal for the Region of the European Alps it is assumed that – with regard to blending the products or their SCA time series – the good agreement found in Chapter 6.4 in DEL-11 remains generally unchanged. A comparison between the FPS v1.2 and v2.1 (with corrected pixel shift) shows a clear improvement with respect to the AVHRR SE product. Hence, the correction in the AATSR geo-shift also indicates the sensitivity of such a validation to a stable and very accurate geolocation and co-location of the two products compared. This also represents a very important step when proceeding towards the compilation of a consistent long-term SCA data set. However, some more efforts concerning algorithm design and instrument decision are still requested to harmonize the products and compile a consistent fused dataset. Furthermore, it is recommended to compare the SCA time series over a longer time period to confirm the good overall agreement over a longer time period.

In order to compile a SE Climate Data Record (CDR) the satellite-based data set needs to fulfil certain requirements in terms of data consistency, continuity and stability (GCOS 2008). As a preparatory study, a CDR has been compiled for the extent of the European Alps derived from historical AVHRR data archived at the University of Bern (Hüsler et al. 2012, 2014). Within this study it has been shown, that the processing steps of calibration, geolocation and snow retrieval have to be carefully investigated and extensively validated to derive a reliable SE time series, which can be used for further climatological analyses (i.e. Gutman 1994, Teillet 2000, Latifovic 2005).

To use the AVHRR sensor to extend the GlobSnow SE v2.1 product back in time for the full NH, all efforts need to be directed towards gathering the data from different sources to compile a complete AVHRR NH archive. After having the data ready, a three-step procedure is suggested: Firstly, external data sets (e.g. digital elevation model, land use/land cover information) have to be prepared to fulfil the needs of SPARCmod algorithm for an improved retrieval of snow extent. Secondly, the SPARC algorithm has to be trained based on external snow data and thirdly, the SE product has to be extensively validated, particularly in terms of temporal stability across various sensors, to guarantee a stable long-term data set useable as CDR. Furthermore, a combination of different sensors (AVHRR and ATSR-2/AATSR) or their SE products (SPARCmod or SCAmod) need a critical evaluation to consider the requirements of GCOS. Before merging two different

SE products one has to investigate – from a scientific point of view – the additional benefit of a merged product over the single products. For the actual merging process it is then suggested to include: decision on instrument (AVHRR and ATSR-2/AATSR) and algorithm (SPARCmod or SCAmod), assessment of geometrical and radiometric stability over time and extensive SE retrieval validation in terms of long-term consistency. Furthermore, in case two different instruments or/and two different algorithms are involved, the blending of the two products need to be carefully investigated regarding homogeneity.

6.3.2 Comparison of GlobSnow-2 SE v2.1 product with HR satellite data

For the evaluation of the GlobSnow-2 SE v2.1 products 70 Landsat 5 TM and ETM+ scenes, and 8 Kompsat-2 scenes were selected for different environments, in different climate regions, and at different snow conditions. The full temporal range of the GlobSnow-2 SE v2.1 product data set was used for selecting the high resolution satellite data for the evaluation with snow maps from high resolution satellite data. Several snow mapping approaches were applied on the Landsat data in order to get a representative reference data set. The algorithms of Dozier and Painter (2004), Klein et al. (1998), Salomonson and Appel (2006) – all these slightly modified – and a multi-spectral unmixing approach developed by ENVEO for high alpine non-forested areas were selected. While ENVEO's approach was only applied on 34 scenes with less forest cover the algorithm of Salomonson and Appel (2006) was applied on 69 scenes, and the other both were applied on all scenes. For the snow map generation from Kompsat-2 data a mainly manual mapping procedure was applied, using the advantage of the high spatial resolution of these scenes also for mapping snow cover in forested areas. The snow maps were generated with the high resolution, and afterwards resampled to the pixels size of the GlobSnow-2 product, in order to enable a pixel-by-pixel comparison.

The results of the intercomparison of the GlobSnow-2 SE v2.1 products with snow maps from Landsat 5 TM, 7 ETM+ and Kompsat-2 scenes indicate that the matching of the snow maps rely very much on the algorithm selected for the snow map generation from the high resolution satellite data. This has implications for the assessments of the SE v2.1 product performance. The largest apparent mismatches between v2.1 SE and the Landsat-based reference occurred over forested areas, and partly also in complex terrain, depending on the snow conditions. For forests, this is suggested to be often a result of the poor performance of Landsat-based methods (see Metsämäki et al., 2014). It is noteworthy that also earlier (local scale) validation/evaluation activities suggest that SCAmod performs well also for forests, compared to alternative methods (Metsämäki et al. 2012&2014, Preliminary SE validation report DEL11).

The mean correlation coefficient derived from all intercomparison of the GlobSnow-2 SE products with snow maps from selected Landsat imagery is 0.81 for the snow maps generated with ENVEO's approach, and in the order of 0.69 for snow maps generated by all other selected algorithms. The mean unbiased RMSD is in the order of 14 %, and mean Bias is about -3 for all except for Klein, where it's only 0.57. The mean standard deviation for the intercomparison of all data pairs is in the order of 24 %. The matching of the GlobSnow-2 SE v2.1 products with snow maps from Kompsat-2 scenes vary significantly with the location and the occurring snow conditions. The unbiased RMSD ranges between 1 % and 30 %, with Bias between -10.3 and 8.6. Absolute correlation coefficients between 0.10 and 0.77 were found for these intercomparisons. Major differences were found for forested areas. Additionally, the algorithms applied on the high resolution satellite imagery showed different performances over different surface classes.

The overall performance of the GlobSnow-2 SE v2.1 products is significantly improved compared to the previous SE version 1.2, as a direct intercomparison of evaluation results with snow maps from selected Landsat scenes showed.

6.3.3 Comparison of GlobSnow-2 SE v2.1 product with other global/hemispheric snow products

On a hemispheric and continental scale the GlobSnow-2 SE v2.1 products were intercompared with the daily global Fractional Snow Cover product MOD10_L2 from NSIDC, and with the daily Pan-European Fractional Snow Cover product from the EU FP7 project CryoLand. For these intercomparisons the years 2003, 2004 and 2010 were selected. For assessing the differences between the product spatial difference maps were generated from the daily products, and additionally statistical metrics as correlation coefficient, RMSD, Bias and Standard Deviation are applied.

The main differences between the GlobSnow-2 SE v2.1 products and the MOD10_L2 products were found for forested areas, both in plain and mountainous terrain. The differences for non-forested complex terrain and plain areas are minor. In total, the two products show mean annual correlation coefficients in the order of 0.81, mean annual unbiased RMSD of about 11 % and mean annual Bias in the order of 2.5. The mean annual standard deviations are in the order of about 28 %.

The results of the intercomparison with the CryoLand FSC product for the Pan-European area are slightly different. Although both products are generated by the same algorithm, but with different input data, and by slightly different processing lines, the products show partly large differences. The correlation coefficients for the selected years is indeed significantly lower, only in the order of 0.65, but the mean annual unbiased RMSD is in the order of 10 % and the mean annual Bias values are in the order of 1.1. The mean annual standard deviations are in the order of 23 %.

6.4 Trend analysis

The two datasets (MOD10A1 and GS2 SE v2.1) have been compared for the years 2003-2011 in the periods March-October. Based on the method we applied, we found that the two datasets capture the trends in the snow depletion curve very similarly. The overall differences between the total snow cover fractions are found to be 2.35% in standard deviation.

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8 APPENDIX

Further details to the selected reference data and extended evaluation results are provided in the Appendix, attached as separate document. Below is the table of contents of the Appendix.

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