SnowPEx –

The Satellite Snow Product Intercomparison and Evaluation Exercise

Methods and Protocols for Intercomparing and Validating Snow Extent and Snow Water Equivalent products – FINAL

Deliverable D7

Snow Extent

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SnowPEx Report

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Abstract:

This document is the final protocol for the intercomparison of global/hemispheric snow extent products, including all relevant definitions, processing steps and metrics. For the intercomparison of global/hemispheric snow extent products two approaches are described, one developed by ENVEO, and one developed by CCRS. For evaluating global/hemispheric snow extent products with in-situ snow observations the approach adopted from the ESA DUE project GlobSnow-2 and further developed by SYKE is used. Additionally, a protocol for the intercomparison of global/hemispheric snow extent products with snow maps from high resolution satellite data developed by ENVEO is presented.

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1. INTRODUCTION

1.1 Purpose

This is a protocol for assessing the performance of continental to global land surface snow extent (SE) maps spanning annual cycles. Included are definitions and a methodology for producing and reporting performance statistics. The protocol was developed based on work conducted within the European Space Agency funded Snow Products Intercomparison Exercise (SnowPEx) endorsed by the World Meteorological Organization (WMO) Global Cryosphere Watch and the Committee of Earth Observing Systems (CEOS) Working Group on Calibration and Validation Sub-group on Land Parameter Validation.

Products currently available for the intercomparison and evaluation exercises are described in Deliverable D3. The methodology relies on the availability of sufficient reference snow cover extent datasets. The available reference data packages are described in Deliverable D9 (Landsat imagery) and Deliverable D10 (in-situ measurements). Protocols for the production of reference data sets from high resolution optical sensors are described in Deliverable D8.

1.2 CEOS Satellite SE Product Validation

CEOS defines satellite product validation as 'the process of assessing, by independent means, the quality of the data products derived from satellite instrument measurements' (http://lpvs.gsfc.nasa.gov/). CEOS identifies four product validation stages described in Table 1.1. This protocol performs Stage 3 Validation for Global and Hemispheric SE products that have already completed Stage 2 validation.

Table 1.1. CEOS Satellite Product Validation Stages (CEOS, http://lpvs.gsfc.nasa.gov/)

Stage	***Requirements***
1	Product accuracy is assessed from a small (typically < 30) set of locations and time periods by comparison with in-situ or other suitable reference data.
2	Product accuracy is estimated over a significant set of locations and time periods by comparison with reference in situ or other suitable reference data. Spatial and temporal consistency of the product and consistency with similar products has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature.

Stage	***Requirements***
3	Uncertainties in the product and its associated structure are well quantified from comparison with reference in situ or other suitable reference data. Uncertainties are characterized in a statistically rigorous way over multiple locations and time periods representing global conditions. Spatial and temporal consistency of the product and with similar products has been evaluated over globally representative locations and periods. Results are published in the peer-reviewed literature
4	Validation results for stage 3 are systematically updated when new product versions are released and as the time-series expands.

1.3 Thematic Definition of Snow Extent

Snow extent is a generic term that includes both the concept of the presence or absence of snow in a mapping unit (‘binary snow extent’ or SEB) and the fractional cover of snow over a mapping unit (‘snow cover fraction’ or SCF). For convenience we provide formal definitions for SE, SCF and SEB here. More detailed explanations of each definition and their relationships to associated quantities are provided in Annex A.

Snow extent (SE) is defined as the unique area of snow covered surfaces projected on the local horizontal datum within a spatial mapping unit at a specified time. Here unique implies that the projected area from two vertically superimposed snow covered surfaces is only counted once. The units of snow extent correspond to SI units for area (m^2).

For forested areas SE products from satellite data can be differentiated between viewable snow and snow on ground:

- **Viewable snow extent** (VSE) is the area of snow projected into the field of view of a top of canopy imaging sensor (e.g. air photo, airborne scanner, satellite borne imager) that is not occluded.
- Information related to the occluded area (e.g. forest cover) and the surface under the occluded area is required to relate VSE to SE, and thus to get information on **snow on ground**.

Snow cover fraction (SCF) is the ratio of SE to the horizontal ground area of the mapping unit. Units are dimensionless with 0≤SCF≤1, but sometimes also percentage number is used (range 0-100%). SCF is sometimes reported using irregular intervals.

Binary snow extent (SEB) indicates the occurrence of snow cover (SCF>threshold τ) or snow free (SCF< threshold τ) conditions in a mapping unit. SEB is usually reported as a Boolean flag (True = 'snow covered'; False='snow free') although a third condition corresponding to no definitive status or a trace amount is sometimes reported. Here, SEB_τ is used to denote SEB corresponding to threshold τ.

1.4 Main statistical measures

In Table 1.2 and Table 1.3 the main statistical measures used to describe the agreement of products and the performance of products evaluated with reference snow maps from high resolution optical satellite data and with in-situ observations are summarized.

Table 1.2: Uncertainty statistics for SCF.

Performance	*Metric*	*Description*
Total Measurement Error	RMSE	Areas weighted root mean square difference in SCF.
Bias	Bias	Area weighted sum of differences in SCF.
Precision	Bias Corrected RMSE	Area weighted RMSE after removing bias over 3 months.
Completeness	Mapped area fraction>50%	Fraction of dates with greater than 50% mapped area within 3 months
Similarity	SCF anomaly	Area weighted daily SCF anomaly from ensemble mean aggregated over 3 months

Table 1.3: Uncertainty statistics for SEB.

Performance	*Metric*	*Description*
Total Measurement Error	Accuracy	(True Positives + True Negatives) / (True Positives + False Positives + False Negatives + True Negatives)
Total Measurement Error	f	2 * True Positives / (2 * True Positives + False Positives + False Negatives)

Performance	Metric	Description
Bias	Recall	True Positives / (True Positives + False Negatives)
Precision	Precision	True Positives / (True Positives + False Positives)

1.5 Outline

An overview on the protocols for intercomparison and validation of SE products is given in Chapter 2. Two intercomparison approaches are applied within SnowPEx: the ENVEO comparison approach (Chapter 3) and the CCRS comparison approach (Chapter 4). Details on the SYKE validation protocol using in-situ measurements as reference data are provided in Chapter 5. The protocol for validation medium resolution snow products with reference snow maps from high resolution optical satellite sensors is described in Chapter 6. Conclusions are given in Chapter 7. Annexes are provided for associated definitions (Annex A), detailed descriptions of the used ancillary data sets (Annex B), and supporting material related to the CCRS intercomparison approach (Annex C).

1.6 Parameters and Acronyms

f	f-Factor
f_m	Ratio of mapped area to total valid area
N_{equ}	Number of equivalent fully snow covered pixels
SCF_M	Mapped SCF
SCF_U	Unmapped SCF
$\widetilde{SCF_m}$	Expected value of mapped SCF (e.g. mean, median, mode)
$\widecheck{SCF_m}$	Minimum mapped SCF
$\widehat{SCF_m}$	Maximum mapped SCF
CCRS	Canadian Centre for Remote Sensing

CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
DEM	Digital Elevation Model
DUE	Data User Element
EASE	Equal-Area Scalable Earth
ECA&D	European Climate Assessment & Dataset
ECMWF	European Center for Medium Range Weather Forecast
ENVEO	Environmental Earth Observation IT GmbH
ESA	European Space Agency
ESU	Elementary Sampling Unit
ETSCF	EASE-GRID 2.0 Transformed Snow Cover Fraction
ETSEBXX	Binary snow extent retrieved from ETSCF applying a threshold XX
FCS	Fraction snow cover for a 25km EASE-GRID2 grid cell
FN	False Negatives
FP	False Positives
HR	High Resolution
ISSPI-2 WS	2nd International Satellite Snow Product Intercomparison Workshop
MAA	Mapped Area
NCDC	National Climate Data Center
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration

NSIDC	National Snow and Ice Data Center
PDF	Probability Density Function
RIHMI	Russian Research Institute for Hydro-meteorological Information
RMSE	Root Mean Square Error
SCE	Snow Cover Extent
SCF	Snow Cover Fraction
SD	Snow Depth
SE	Snow Extent
SEB	Snow Extent Binary
SMHI	Swedish Meteorological and Hydrological Institute
SRTM	Shuttle Radar Topography Mission
SYKE	Finnish Environment Institute
SWE	Snow Water Equivalent
TC TOAR	Topographically Corrected Top Of Atmosphere Reflectance
TMSCAG	Thematic Mapper Snow Cover And Grain size spectral unmixing algorithm
TN	True Negatives
TP	True Positives
VAA	VAlid Area
VSE	Viewable Snow Extent
WMO	World Meteorological Organization

2. PROTOCOLS FOR SE PRODUCTS INTERCOMPARISON AND VALIDATION

This chapter provides a protocol for validation of gridded SE products with reference measurements and the intercomparison of these products. Both validation and intercomparison are performed at comparison sites located in EASE-GRID 2.0 coordinates. Comparison sites are defined as regions over which products and reference measurements are sampled for the purpose of comparison. The comparison sites may correspond to locations of in-situ or spatial reference data where validation is being performed but they may also correspond to locations where intercomparison is being performed without any co-located reference data. Critically, the comparison sites follow an objective sampling design that accounts for: i) differences in 'valid areas' between products ii) geolocation and re-gridding uncertainty iii) the impact of land cover conditions on algorithm performance.

A major challenge of SE product intercomparison and validation is to incorporate the uncertainty of comparing point measurements used as reference data with the associated grid cell(s) of SE products having significantly lower spatial resolution. Two approaches for addressing spatial resolution differences are implemented: ENVEO and the CCRS probabilistic approach. The ENVEO approach requires a minimum mapped area threshold for each product in a comparison site and estimates SE deterministically based on the average SCF of mapped areas. The CCRS approach requires a minimum mapped threshold for product pairs being compared and estimates SE probabilistically by modelling and sampling a probability density function of SCF over the comparison site given the SCF over mapped areas and a priori assumptions about product precision. Further, approaches for validating medium resolution snow extent products with in-situ measurements and with reference snow maps generated from high resolution optical satellite data are documented.

The SnowPEx intercomparison and validation exercises of daily medium resolution snow extent products are executed according to the following protocol:

1. Collect products from product providers for a pre-defined period
2. Collect and prepare all required geo-spatial ancillary data:
    a. Digital Elevation Model
    b. Surface classification, including at least water and forest
    c. Any other ancillary data, e.g. climate zones
    d. Prepare static masks of ancillary data including water, forest, mountains used for partitioning the intercomparison and validation exercises
3. Prepare products and used geo-spatial ancillary data:

   a. Transform products and ancillary data sets to a common projection and aggregate the data to a common grid size

   b. Account for thematic differences between products

4. Prepare reference data:

   a. Generate snow maps from high resolution satellite data (Landsat)

   b. Prepare data base with in-situ snow measurements along transects and/or in-situ point observations

5. Select an intercomparison and/or validation approach, apply the method on the prepared snow extent products, and calculate the statistical measures (depending on selected intercomparison / validation approach) describing the products agreements:

   a. ENVEO comparison approach, applicable for intercomparison of products

   b. CCRS comparison approach, applicable for intercomparison of products

   c. SYKE snow extent validation approach using in-situ reference measurements

   d. Snow extent validation using reference snow maps generated from high resolution optical satellite sensors

6. Document all used data sets, processing steps and the intercomparison results

In the following sections further information to the particular steps are provided, or references to relevant documents are given.

2.1 Collect Snow Extent products

The SE products participating in the SnowPEx intercomparison and validation exercises are described in detail in Deliverable D3.

2.2 Collect geo-spatial ancillary data

The used auxiliary data layers and the preparation of static masks from these layers are described in Annex B.

2.3 Pre-Processing of Auxiliary Data, Products and Reference Data

2.3.1 Stage 1 – Resampling of Ancillary data layers

Ancillary layers are required for determining regions of valid comparisons applicable to all products and to perform stratified sampling. Ancillary data layers (forest, water and mountain mask, cf. Annex B) with hemispheric coverage are provided as input in GEOTIFF format. This is a static set of layers. Ancillary layers are prepared in the original map projections and grid size of each product, as well as in the map projection EASE-GRID 2.0 aggregated to 5 km and 25 km grid sizes. Details about the preparation of ancillary data layers are provided in Annex B.

2.3.2 Stage 2 – Accounting for Thematic Differences between Products

SE products have associated uncertainties provided by the dataset producer. In general, uncertainties include total measurement error (or accuracy) as well as precision error. However, total measurement error or accuracy must be evaluated with respect to a reference and indeed is the output of this protocol so it is unlikely that uncertainties provided by producers will include this quantity. The precision error can and should be specified by the producer as the expected range of SCF for a given SCF or SEB value mapped in their product. This is an *a priori* estimate that may be theoretically based or driven by other calibration or validation studies. Nevertheless it is critical for producers to report this information for two reasons:

1. Comparison of binary SE products with other SCF or SEB products cannot be easily performed since binary SE products usually assume a threshold SCF below which SE is labelled as 'snow free' and another threshold SCF above which SE is labelled 'snow covered' (the thresholds may but do not have to be the same). Products or reference data may disagree simply due to differences in binary SE thresholds. Two approaches are adopted in this protocol to quantify the impact of such thresholds on performance metrics: i) the ENVEO approach converts SCF products to SEB using a range of thresholds and reports agreement rates based on categorical comparisons ii) the CCRS approach converts all binary SE products and reference data into SCF values based on producer specified thresholds and then reports agreement rates based on both SCF comparisons and categorical comparisons after applying a 50% SCF threshold to all products.
2. There may be substantial uncertainty in both SCF derived from either reference or product data due to measurement error or satellite or in-situ instruments and incomplete coverage of comparison grid cells. This uncertainty should be included in comparisons so that the likelihood of observing a given residual is quantified and not just the most likely or average residual that may incorporate cancelling errors. The ENVEO approach (Chapter 3) quantifies

this uncertainty by testing different thresholds for converting both reference snow maps and SCF products to SEB. This approach is suited for addressing uncertainty for SCF products or reference data. The CCRS approach (Section 4) quantifies this uncertainty by modelling the PDF of SCF estimates over a comparison grid cell for both products and reference data, irrespective of the SE quantity used, and sampling combinations (realizations) of product and reference SCF values.

2.4 Preparation of reference data

2.4.1 Reference snow map preparation

This protocol includes comparisons of products with reference snow maps generated from high resolution optical satellite data. A detailed description of the generation of reference snow maps from Landsat data is provided in Deliverable D8.

2.4.2 In-situ Reference Data Preparation

Reference estimates of SEB can be derived from in-situ measurements. In-situ data are point-wise observations, and are used with the assumption that a single observation is representative for a larger area corresponding to the pixel size of the Snow Extent product to be validated. Although this might not be true particularly for medium or even coarse resolution products, this approach is considered reasonable enough, keeping in mind that spatially dense observations (i.e. multiple observations within a product pixel) were not available except for the very local areas from a particular field campaigns. In-situ datasets, following the specified SnowPEx format, include at least information on the locations of the in-situ site, date of the observation and the observed quantity (Snow Depth). Additionally, information on the elevation and quality may be given, depending on the dataset. If quality flag was present, only observations with the best quality were chosen. Each in-situ dataset provides the locations of the sites as WGS-84 latitude, longitude geographical coordinates. These were first converted to each product's coordinate system; after this, all spatially and temporally matching pixels were extracted from the product files and associated to the corresponding in-situ observation.

For RIHMI weather station data providing supplementary snow information to the actual snow depth (cf. Deliverable D10, Section 2.1.2), specific rules were applied to convert the Snow depth and the provided additional information (Q1, and Q2, Bulygina et al., 2015b) to final snow depth to be used for validation. These rules are given in Table 2.1.

Table 2.1:
Conversion between RIHMI snow data and output Snow Depth.

Original Snow Depth [cm]	*Q1 - additional information on snow depth*	*Q2 – quality flag from snow depth*	*Output Snow Depth [cm]*
SD	0	0	**SD**
–	1 or 2	0	**0**
–	3	0	**0.25**

2.5 Intercomparison and validation approaches

Each two different approaches for SE product intercomparison and validation were discussed at the 2nd International Satellite Snow Product Intercomparison Workshop (ISSPI-2 WS), held in September 2015 at NSIDC in Boulder, Colorado, USA. The workshop participants agreed to continue with these approaches. Adaptations of the preliminary SE intercomparison and validation protocols requested by the SE experts at the ISSPI-2 WS are considered in this final version.

Two approaches are used for intercomparisons of medium resolution products:

- ENVEO comparison approach (Chapter 3)
- CCRS comparison approach (Chapter 4)

Medium resolution SE products are validated with

- In-situ measurements (Chapter 5)
- Reference snow maps from Landsat data (Chapter 6)

Detailed documentations of the intercomparison and validation approaches applied in SnowPEx are provided in the following Chapters.

2.6 Documentation

The data sets used for the intercomparison and validation exercises, and applied pre-processing steps are documented in the following deliverables:

- Participating products: D3 – Review of algorithms and products
- Ancillary data and pre-processing of these data: D7 – Methods and Protocols for Intercomparing and validating SE products, Annex B
- Reference data:
    - D9 – Description of Landsat datasets
    - D10 – Description of in-situ data datasets
    - D8 – Guidelines for the generation of snow extent products from high resolution optical sensors
- Processing steps: this document
- Intercomparison and validation results:
    - D13 – Snow Product intercomparison and validation report
    - Publication in peer-reviewed journal

3. ENVEO COMPARISON APPROACH

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This protocol is adapted based on the comparison approach developed by ENVEO within the ESA DUE project GlobSnow2 (2011 – 2015) (Bippus et al. 2014).

The ENVEO intercomparison and validation approach compares each global/hemispheric/regional snow extent product (binary and fractional) pixel by pixel with all other available snow extent products. Figure 3.1 shows the main processing steps of this approach.

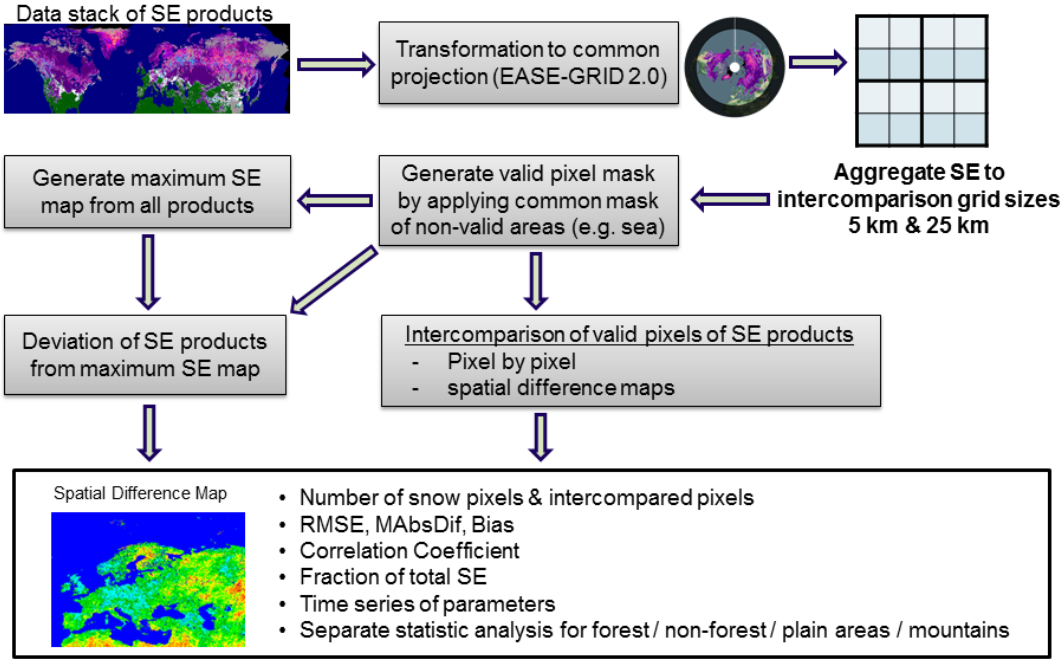

Figure 3.1: Concept for pixel-by-pixel intercomparison approach for global/hemispheric snow extent products.

The intercomparison is carried out in a common 5 km and 25 km EASE-GRID 2.0 grid map projection. All SCF and SEB products are transformed into this map projection. Metrics for providing the quality of the similarity of the products are calculated from a pixel by pixel comparison of products in EASE-GRID 2.0. Additionally, weekly and monthly minimum and maximum snow maps (ETSE_MIN_WEEKLY, ETSE_MAX_WEEKLY, ETSE_MIN_MONTHLY, ETSE_MAX_MONTHLY) are generated based on all valid pixels of the SCF and SEB products in EASE-GRID 2.0 projection. These minimum and maximum snow maps are compare with Northern Hemisphere EASE-Grid 2.0 Weekly /

Monthly Snow Cover and Sea Ice Extent Version 4 product, which is based on the NOAA/NCDC Climate Data Record (CDR) of Northern Hemisphere (NH) Snow Cover Extent (SCE) by D. Robinson (2012) and regridded to the EASE-GRID 2.0 (Brodzik, M. and R. Armstrong, 2013). The minimum and maximum extents of all products are compared with this climatological data set on a weekly and monthly basis, and additionally deviations of the products to the climatological SE are calculated.

3.1 Preparation of SEB and SCF Products

The SEB (Binary Snow Extent) products are transferred to fractional snow extent products by assuming 100 % SCF (Snow Cover Fraction) for 'snow' pixels and 0 % SCF for 'snow free' pixels.

The following preparation steps are applied on the products:

1) **Reprojection**: The snow extent products are transformed to EASE-GRID 2.0 map projection, dividing each pixel into smaller subpixels, which are then transformed to the new map projection.

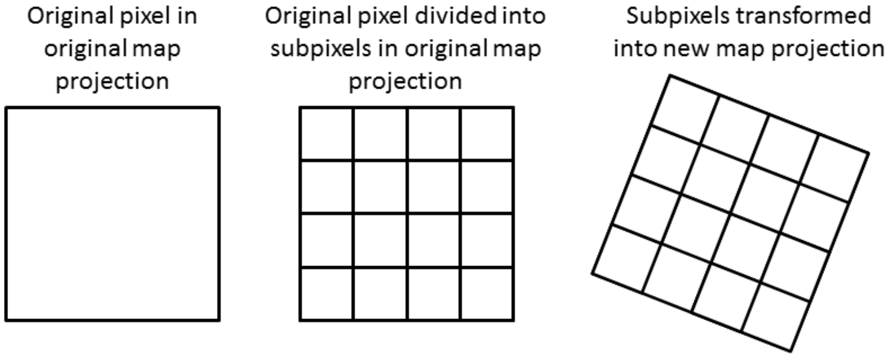

Figure 3.2: Illustration of pixel transformation to new map projection.

2) **Pixel aggregation**: After reprojecting SCF and SEB products to EASE-GRID 2.0, the subpixels of the SCF and SEB products are aggregated to 5 km and 25 km grid size. Due to aggregation, a fractional snow extent can be given for binary snow products and fractional snow products. The resulting products thus include snow cover fraction in map projection EASE-GRID 2.0, and are defined as EASE-GRID 2.0 transformed Snow Cover Fraction (ETSCF) products.

   ETSCF pixels are only considered as valid pixels if more or equal than 50 % of the pixel are classified as land cover. ETSCF pixels with more or equal than 50% water are classified as invalid pixels, and are not used for intercomparisons or validations.

For converting the ETSCF products to binary snow estimates in EASE-GRID 2.0 map projection (ETSEB), three different ETSEB estimates are produced from each ETSCF product estimate. The ETSCF threshold and nomenclature for these derived estimates are given in Table 3.1.

The thresholds 0.15 and 0.50 are widely used in the snow community to convert SCF to SEB (e.g. Elder, Rosenthal, & Davis, 1998, Painter et al., 2009, Rittger, Painter, & Dozier, 2013). The threshold 0.25 is additionally used to test if there is any effect on the performance and product agreement.

Table 3.1:
Conversion between ETSCF and SEB labels.

Quantity	**Criteria**
ETSEB15	if ETSCF≥15% then ETSEB15="snow" else ETSEB15="no snow"
ETSEB25	if ETSCF≥25% then ETSEB25=”snow” else ETSEB25=”no snow"
ETSEB50	if ETSCF≥50% then ETSEB50="snow" else ETSEB50="no snow"

Note: the CryoClim products with 5 km pixel size and the MEaSUReS products with 25 km pixel size remain unchanged for the intercomparisons at the corresponding grid sizes. Both binary products are already provided in EASE-GRID 2.0.

3) **Generation of Masks of Pixels used for intercomparison**: Statistical ETSCF intercomparison parameters are derived only for snow covered pixels (with ETSCF > 0%). In order to avoid problems due to different cloud screening, open water masks, etc. in the various products, we generated a mask of used pixels for intercomparison. We calculated two masks, the TOTAL_VALID_PIXEL_MASK and the SNOW_VALID_PIXEL_MASK.

   The *TOTAL_VALID_PIXEL_MASK* includes all ETSCF and ETSEB pixels which are snow free or snow covered in all products and is calculated as follows:

   1. First, all ETSCF and ETSEB pixels which are cloud covered, open water, polar night or invalid data in one of the products are masked out.
   2. The remaining pixels are labelled as the TOTAL_VALID_PIXEL_MASK, including snow free and snow covered pixels.

- The *SNOW_VALID_PIXEL_MASK* includes all pixels which are snow covered (ETSCF or ETSEB > 0%) in at least 1 product and is calculated as follows:
    1. From the TOTAL_VALID_PIXEL_MASK all pixels which are snow free in all products are masked out.
    2. The remaining pixels are snow covered (ETSCF or ETSEB > 0%) in at least one of the products and are called SNOW_VALID_PIXEL_MASK.
- Both masks, the TOTAL_VALID_PIXEL_MASK and the SNOW_VALID_PIXEL_MASK are calculated on a daily basis.

3.2 Metrics for Pixel-by-Pixel Intercomparisons of Snow Extent products

3.2.1 Metrics for fractional SE products intercomparison

The following statistical parameters are calculated to evaluate the agreement of the fractional snow extent products transformed to EASE-GRID 2.0 map projection (ETSCF):

- The fully snow covered area of each individual product is derived by the number of equivalent fully snow covered pixels (SCF = 100%, SEB = 1) (***N****equ_fse*), which is given according to:

$$N_{equ\_fse} = \sum_{j=0}^{y} \sum_{i=0}^{x} \frac{SE_{100}(i,j)}{100} \qquad \text{Equ. 3.1}$$

  where the SE_{100} indicates only pixels with full snow cover in SCF, and all snow pixels in SEB products.

- The total snow covered area of each individual product is derived by the number of equivalent snow covered pixels (***N****equ_se*), which is given according to

$$N_{equ\_se} = \sum_{j=0}^{y} \sum_{i=0}^{x} \frac{FSC(i,j)}{100} \qquad \text{Equ. 3.2}$$

  where the fractional snow coverage is in per cent (values between 1 to 100 %).

- For determining the Bias between two products, the pixels specified by N_{ui} are used as calculation basis:

$$BIAS = \frac{1}{N_{ui}} \sum_{j=0}^{y} \sum_{i=0}^{x} (FSC_{EXT}(i,j) - FSC_{REF}(i,j)) \qquad \text{Equ. 3.3}$$

- The root-mean-square error, RMSE, between two products is calculated using all pixels suitable for inter-comparison (Nui) according to

$$RMSE = \sqrt{\frac{1}{N_{ui}} \sum_{j=0}^{y} \sum_{i=0}^{x} (FSC_{EXT}(i,j) - FSC_{REF}(i,j))^2} \quad \text{Equ. 3.4}$$

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

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

Equ. 3.5

- The correlation coefficient calculation between two products (EXT = SCF Extent in Product 1, REF = Product 2 or Reference snow map, e.g. from Landsat) includes only the valid pixels for the inter-comparison (N_{ui}) and is given by

$$CorrCoef = \frac{\sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{EXT}(i,j) - \overline{FSC_{EXT}} \right) \left(FSC_{REF}(i,j) - \overline{FSC_{REF}} \right)}{\sqrt{\sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{EXT}(i,j) - \overline{FSC_{EXT}} \right)^2 \sum_{j=0}^{y} \sum_{i=0}^{x} \left(FSC_{REF}(i,j) - \overline{FSC_{REF}} \right)^2}} \quad \text{Equ. 3.6}$$

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

These statistical parameters are also calculated for all ETSCF products aggregated to 5 km and 25 km grid sizes, treating binary snow covered pixels as 100 % snow and snow free pixels as 0 % snow. It has to be considered that the results of these statistical measures can be biased, as binary products often overestimate the snow extent compared to fractional snow extent products.

3.2.2 Metrics for binary SE products intercomparison

Additionally, there are some further statistical parameters intended for the intercomparison of binary snow products. Similar, as the binary snow products are also included in the statistical calculations intended for fractional snow extent products, the ETSCF are converted to binary snow maps (Table 3.1).

The intercomparison of the ETSEB products per pixel can result in four cases, as also indicated in Figure 3.3:

- True Positive (TP) = correctly identified

- False Positive (FP) = incorrectly identified
- True Negative (TN) = correctly rejected
- False Negative (FN) = incorrectly rejected

PRODUCT REF (reference) in Figure 3.3 indicates the condition to be met by the test case PRODUCT EXT (extent to be evaluated). In case of intercomparison with binary snow maps from Landsat or a daily mean snow map generated from all available products, the global/hemispheric product refers to PRODUCT EXT, and the Landsat snow map or the daily mean snow map refers to PRODUCT REF.

		PRODUCT REF	
		SNOW	SNOW FREE
PRODUCT EXT	SNOW	True Positives (TP)	False Positives (FP)
	SNOW FREE	False Negatives (FN)	True Negatives (TN)

Figure 3.3: Confusion matrix for intercomparison of two binary snow extent products. Detailed descriptions are given in the text.

Based on these match cases four common statistical metrics (e.g. Fawcett, 2006) are calculated, assessing the agreements of the binary products (Table 1.3).

3.3 Intercomparisons for particular surface and climate classes

To intercompare the products for different surface classes or terrain the masks SNOW_VALID_PIXEL_MASK and TOTAL_VALID_PIXEL_MASK are each intersected with surface cover maps and topographic parameters.

Additionally to intercomparisons of the total area in the SNOW_VALID_PIXEL_MASK and TOTAL_VALID_PIXEL_MASK, we discriminate the major land surface classes relevant for snow, which is forested/ non-forested and a rough classification of mountainous versus plain regions. Combinations of these major classes result into four further classes as indicated in Figure 3.4.

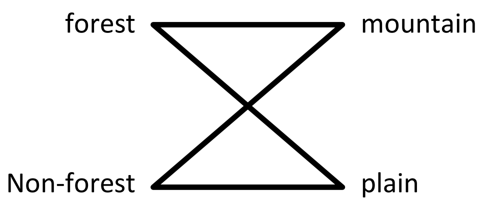

Figure 3.4: Combination options for selected surface classes considered for product intercomparison.

Intercomparisons in forested areas are separated for products providing information about snow on ground and products showing viewable snow. For open land all products are compared with each other.

Further, the snow climate classes according to Sturm et al (1995) are considered for the intercomparison of products.

3.4 Deviation from the climatological mean Snow Extent

For an independent and direct intercomparison of all products the deviation of the products from the climatological mean is calculated. This intercomparison is done on a weekly and a monthly basis using the weekly / monthly climate snow data provided by NSIDC (Brodzik and Armstrong, 2013), available from ftp://sidads.colorado.edu/pub/DATASETS/nsidc0046_weekly_snow_seaice/data/.

The weekly and monthly aggregated minimum and maximum ETSCF and ETSEB products are compared with the corresponding climatological mean SE maps from NSIDC. The same statistical measures as used for the product vs product intercomparisons performed by ENVEO (cf. Section 3.2) are calculated to describe the intercomparison results. Additionally, the deviations of the weekly and monthly minimum and maximum snow areas of the products applying the intercomparison masks (cf. Section 3.1) from the climatological snow extent data set are calculated in km² and in percentage.

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4. CCRS COMPARISON APPROACH

Richard Fernandes, CCRS

The CCRS comparison approach (summarized in Figure 4.1) essentially performs replicate comparisons of product pairs over valid regions in a stratum for a 3 month period. Each replicate results in a single estimate of the metrics specified in Section 1.4 resulting in a probability density function for each metric from which the expected value and precision of the metric is quantified. For consistency the CCRS approach uses pre-processing and thresholds for defining valid comparisons described in the ENVEO approach.

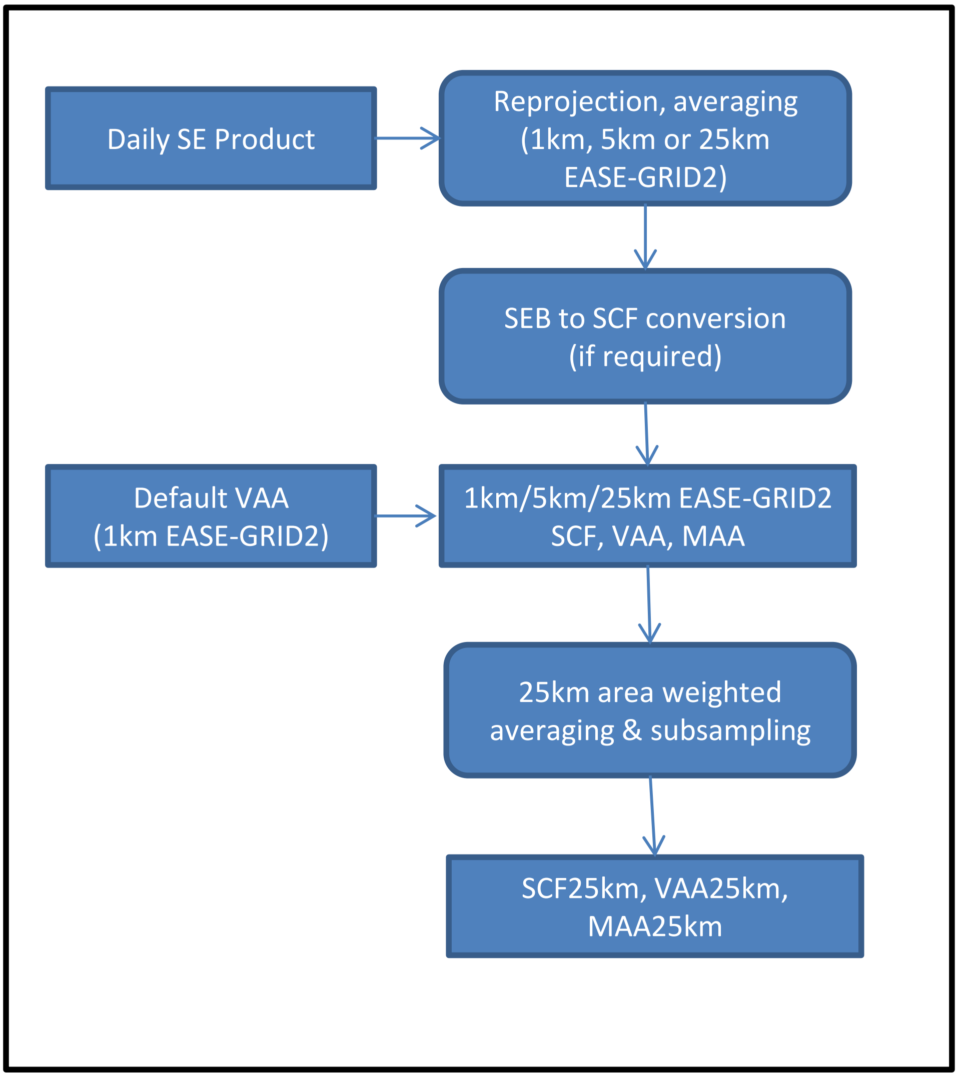

Figure 4.1: Product intercomparison pre-processing flow chart.

4.1 Preparation of SEB and SCF Products

The SEB (Binary Snow Extent) products are transferred to fractional snow extent products by assuming 100 % SCF (Snow Cover Fraction) for 'snow' pixels and 0 % SCF for 'snow free' pixels.

The following preparation steps are applied on the products:

1) **Reprojection**: The ENVEO approach is used.
2) **Pixel aggregation**: The ENVEO approach is used to produce ETSCF.
3) **Generation of Masks of Pixels used for intercomparison**: Statistical ETSCF intercomparison parameters are derived between pairs of products where, for both products, both the valid area fraction and mapped area fraction for a 25km EASE-GRID2 grid cell (VAA25km and MAA25km respectively) exceeds for 50%.

   The VAA25km is computed based on a provided daily 5km resolution EASE-GRID2 VAA fraction layer at the aggregated product grid definition (5km or 25km EASE-GRID2) as:

   $$VAA25km = \frac{1}{25}\sum_{i=1}^{25} VAA_i \qquad \text{Equ. 4.1}$$

   In the absence of a daily VAA fraction layer a default VAA25km based on the GlobCover land water mask (Annex B) is used.

   The MAA25km is computed based on a provided daily 5km resolution EASE-GRID2 MAA fraction layer at the aggregated product grid definition (5km or 25km EASE-GRID2) as:

   $$MAA25km = \frac{1}{25}\sum_{i=1}^{25} MAA_i \qquad \text{Equ. 4.2}$$

   In the absence of a daily MAA fraction layer the product SCF layer is used to estimate MAA25km as:

   $$MAA25km = \frac{1}{25}\sum_{i=1}^{25} Boolean(SCF_{<i} < 100) \qquad \text{Equ. 4.3}$$

   where $Boolean(x)$ returns 1 is the argument x is true.

4.2 Modelling the SCF Probability Density Function

For each product, the probability density function (PDF) of SCF25km, $p(SCF25km)$, is modelled as the area weighted sum of the PDF of SCF over mapped areas $p(SCF_M)$ and unmapped areas $p(SCF_U)$ within each 25km EASE-GRID2 cell:

$$p(SCF25km) = f_M p(SCF_M) + (1 - f_M)p(SCF_U) \quad \text{Equ. 4.4}$$

where

$$f_M = \frac{\mathrm{MAA25km}}{\mathrm{VAA25km}} \quad \text{Equ. 4.5}$$

The $p(SCF_M)$ is modelled as a truncated triangular distribution (Figure 4.2) with mode $\widetilde{SCF}_M = SCF25km$ (denoted here as $\mathrm{ttri(mode, left\ bound, right\ bound)}$) limited to the range $(0, 1)$:

$$p\left(SCF_M|\widetilde{SCF_M}, \widetilde{SCF_M}, \widetilde{SCF_M}\right) = ttri\left(\widetilde{SCF_M}, \widetilde{SCF_M}, \widetilde{SCF_M}\right) \quad \text{Equ. 4.6}$$

where $\widetilde{SCF_M} = \widetilde{SCF_M} - \delta^-$ and $\widetilde{SCF_M} = \widetilde{SCF}_M + \delta^+$.

The range of $p(SCF_M)$ corresponding to $[\delta^-, \delta^+]$ is modelled as the Euclidean sum of product measurement error ($\varepsilon^-{}_m$ and $\varepsilon^+{}_m$) and the natural variability in SCF_M ($\varepsilon^-{}_n$ and $\varepsilon^+{}_n$) for positive and negative branches in the PDF:

$$\delta^- = \sqrt{\varepsilon^{-2}_{\mathrm{m}} + \varepsilon^{-2}_{\mathrm{n}}} \quad \text{Equ. 4.7}$$

$$\delta^+ = \sqrt{\varepsilon^{+2}_m + \varepsilon^{+2}_n} \quad \text{Equ. 4.8}$$

The product measurement error where there are N mapped product grid cells within the 25km EASE-GRID2 comparison grid cell is currently defaulted to $0.2/\sqrt{\mathrm{N}}$.

The SCF natural variability ε_n is given as:

$$\varepsilon^-{}_n = 0.5\left\{\widetilde{SCF}_M - min(SCF_i)\right\} \quad \text{Equ. 4.9}$$

$$\varepsilon^+{}_n = 0.5\left\{max(SCF_i) - \widetilde{SCF}_M\right\} \quad \text{Equ. 4.10}$$

Where SCF_i corresponds to the SCF of the i[th] product pixel with MAA exceeding the minimum MAA threshold in the 25km EASE-GRID2 comparison grid cell. The scaling by 0.5 is used to relate a maximum deviation to the number of standard deviations under the Gaussian error combination model used.

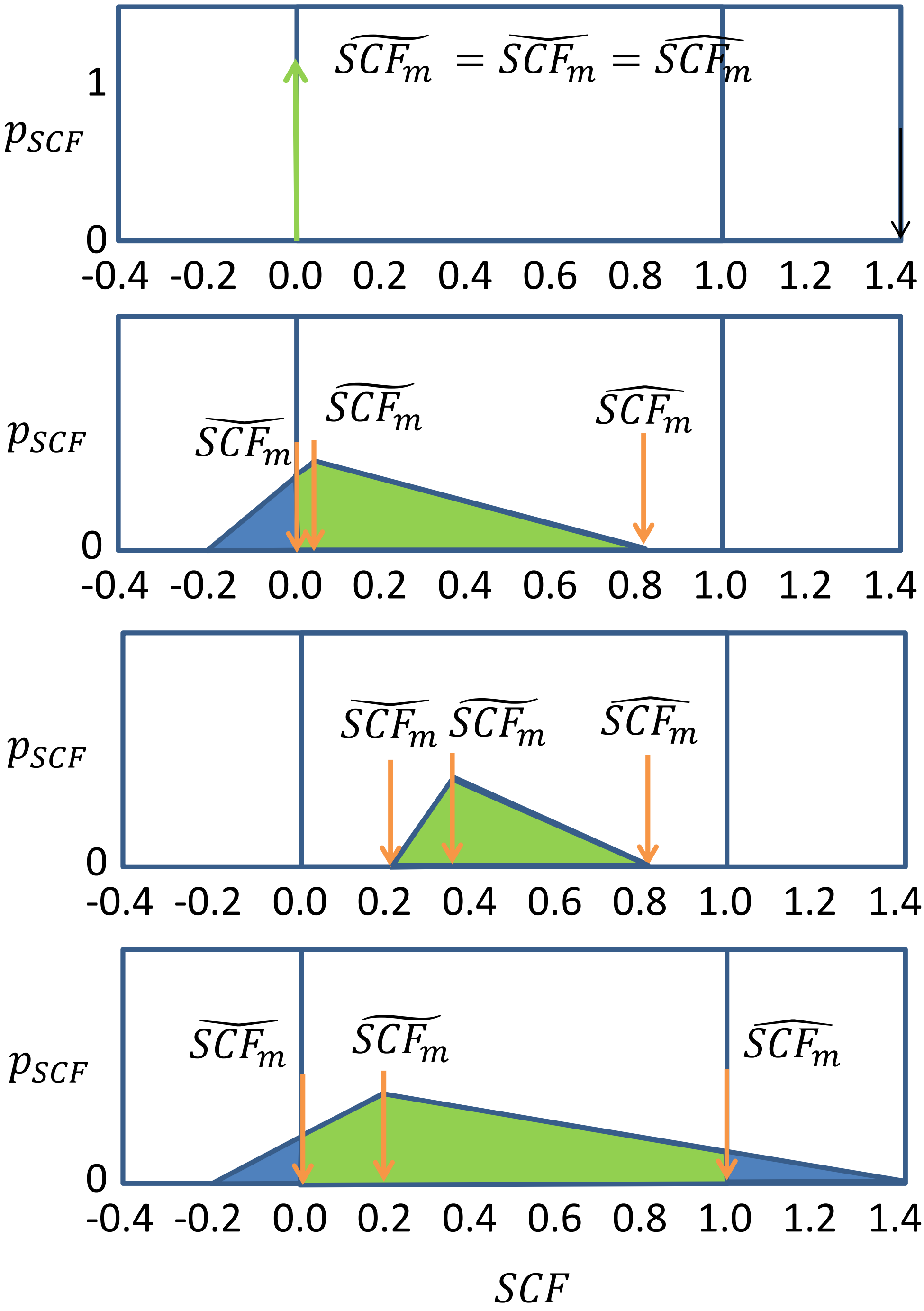

Figure 4.2: Examples of truncated triangular SCF probability distribution functions (p_{SCF}) shown in green for different values of modal ($\widetilde{SCF}$), minimum ($\widetilde{SCF}$) and maximum ($\widetilde{SCF}$) product SCF estimates indicated with orange arrows. Blue areas are corresponding non-truncated distributions.

4.3 Metrics for Pixel-by-Pixel Intercomparisons of Snow Extent products

A unique realization of SCF25km from two products over all valid comparison grid cells for the same 3 month temporal interval and spatial strata defined by the ENVEO approach (Section 3.3) is generated by randomly sampling from $p(SCF25km)$ of both products. Metrics analogous to the ENVEO metrics (Section 3.2) are computed for each realization.

4.3.1 Metrics for fractional SE products intercomparison

The following statistical parameters are calculated to evaluate the agreement of the fractional snow extent products transformed to ETSCF:

- The fully snow covered area of each product is estimated for each temporal and spatial stratum. For each day, for each product, 25km EASE-GRID2 grid cells are labelled fully snow covered ($SE_{100} = 1$) if the 95%ile confidence interval of SCF25km exceeds 0.90 across all realizations for the product and where the VAA25km and MAA25km exceeds 50% for all products. $N_{equ\_fse} = \sum_{j=0}^{y}\sum_{i=0}^{x}\frac{SE_{100}(i,j)}{100}$ Equ. 3.1 is then applied to estimate (***N_{equ_fse}***) for each product over the entire stratum. The precision of this metric is computed by repeating it for the 75%ile and 99%ile confidence intervals for $SE_{100} = 1$.

- The total snow covered area of each product is estimated for each temporal and spatial stratum. For each day, for each product the average fraction snow cover for each 25km EASE-GRID2 grid cell (FCS) is estimated as the SCF25km of 1 realization for the product and where the VAA25km and MAA25km exceeds 50% for all products. One realization of the total snow covered area (N_{equ_se}) of each product is determined by the average FCS over the stratum using $N_{equ\_se} = \sum_{j=0}^{y}\sum_{i=0}^{x}\frac{FSC(i,j)}{100}$ Equ. 3.2. The averages of 95%ile confidence interval across all realizations are used to quantify the total snow covered area of each product.

- The BIAS, RMSE, Unbiased RMSE and correlation coefficient are calculated using Equations Equ. 3.3, Equ. 3.4, Equ. 3.5 and Equ. 3.6, respectively, using FCS for each unique realization of valid pairwise comparison between two products over a stratum. The median and 95%ile confidence interval for the statistics are reported.

- The completeness of SE products is reported as the fraction of 25km EASE-GRID2 grid cells satisfying the minimum MAA threshold.

4.3.2 Metrics for binary SE products intercomparison

The intercomparison of the ETSEB products uses the same protocol as applied by the ENVEO approach but applied separately to each unique realization of valid comparisons between product pairs in a stratum. The median and 95%ile confidence interval of derived metrics are across all unique realizations are reported.

5. SYKE APPROACH FOR VALIDATION OF PRODUCTS VERSUS IN-SITU REFERENCE MEASUREMENTS

Sari Metsämäki, SYKE

5.1 Introduction

The validation protocol in SnowPEx produces standardized measures of the performance of snow products. To accomplish this, all products and in-situ data are treated as binary (snow/no-snow) information. Although a majority of the involved Snow products provided binary information, some of the products provide information on Snow Cover Fraction. However, treating all data as binary was found the only feasible way to encompass the validation. The clear reason for this is that practically all in-situ measurements provide observations on Snow Depth not on SCF, and there is no reliable way to convert SD to SCF. On the other hand, conversion from in-situ SD to binary information is an established method in the snow remote sensing and this method is practised in SnowPEx as well. Accordingly, the SE products featuring SCF are converted to binary; this is accomplished by using a threshold for SCF to determine if a product pixel is 'snow' or 'no-snow'. Originally binary products are used directly in the validation. After these conversions the in-situ observations are associated with temporally and spatially matching product pixels. The generated dataset includes thousands of cases, from which several very established binary metrics are calculated. The results are stratified according to the Sturm snow zones and additionally according to the different land-cover classes (cf. Section 3.3). Since it is expected that the performance of a snow product varies during the year, the binary metrics are produced for four three-month periods: October-December, January-March, April- June, July-September. This approach benefits the interpretation of the results and helps us to comprehend when and where each product performs the best.

5.2 Products and in-situ data used in the validation

Validation of products with pointwise in-situ observations employs products of moderate resolution i.e. the coarse resolution products (IMS24 and MEASU) are excluded. All other available products are used in the analyses. As the validation focuses on the Northern Hemispheric scale products the analyses are predominantly accomplished using spatially well-distributed in-situ datasets whilst the local ones are remained for the later use. The employed datasets in Northern Hemisphere scale are ECMWF, ECA&D, SMHI, Northern America extended and RIHMI. These are described in detail in Deliverable D10.

5.3 Conversion of in-situ measurement to binary information

For in-situ data typically including measurements on Snow Depth (SD), binary conversion relies on three different thresholds: SD=0cm, SD=2cm and SD=15cm, which are separately analysed. The in-situ observation is labelled 'snow' the threshold is exceeded, otherwise it is labelled 'no-snow'.

Table 5.1:
The conversion from SCF values to binary value with product naming convention.

Name of the resulting in-situ variable	Criteria
RefSEB0	if SD>0cm then ”snow” else ”no snow"
RefSEB2	if SD≥2cm then "snow" else "no snow"
RefSEB15	if SD≥15cm then "snow" else "no snow"

In case of SD threshold of 0cm, the SnowPEx protocol requires that labelling pixel as 'no-snow' (SD=0cm), the same value has to reported for the preceding and the following days. This would increase the reliability of the true 'no-snow' conditions.

5.4 Conversion of products to binary information

SnowPEx provides a protocol for converting SCF products to binary products. The difficulty related to this conversion originates from the basic question of what is meant with 'snow' or 'no-snow' at a pixel scale. Is a pixel considered 'snow' is it's fully snow covered or is it enough to have e.g. 5% snow coverage? There is no a generally applicable threshold for the conversion (neither is there such an information available for the originally binary products i.e. the data producer cannot give a SCF-threshold for their binary product.) The true value is highly varying even for one product, depending e.g. on the season as well as on the local land cover and snow properties. In SnowPEx, the threshold of SCF=50% was chosen to categorize a pixel as 'snow' or 'no-snow'. In addition, another threshold of SCF=25% is used to investigate the effect on different threshold on the validation results. The resulting two different binary product sets are analysed separately in the validation work. The two approaches for the conversion are presented in Table 5.2.

Table 5.2:
The conversion from SCF values to binary value with product naming convention.

Name of the resulting product	Criteria
SEB50	if SCF≥50% then "snow" else "no snow"
SEB25	if SCF≥25% then "snow" else "no snow"

5.5 Binary metrics

The in-situ validation protocol handles only *binary* (i.e. snow/no-snow) information. In the validation procedure, a contingency matrix of true positives, true negatives, false positives and false negatives are generated from in-situ/product pairs at pixel level. These are partly described already in Section 1.4. An example of a contingency matrix is given in Table 5.3. Accordingly, the evaluation of the performance of each product is expressed as a set of *binary metrics*. The ones used in SnowPEx in-situ validation are listed in Table 5.4; these are partially the same as described in Section 3.2.2 for product intercomparisons. Table 5.3 also describes the decision rules for a minimum number of observations required for producing a binary metric. The rules are used to increase the probability of results. Since thousands of comparison pairs are employed in the SnowPEx validation in general, these rules would apply only for the partitioned data which may provide a small number of cases, depending on the partition. Same applies to the temporal stratification: e.g. during summer months the number of in-situ observed snow (*Nref_snow* in the table) might be zero or close to zero which makes it unreasonable to provide value for *Recall* as this is a metric describing the products ability to identify true (according to the in-situ reference) snow cases. Accordingly, provision the *False Alarm* Rate would be unreasonable if there were very few in-situ observations on 'no-snow' compared to the total number of comparison pairs: even a few false positives would increase the False Alarm Rate close to one (100%), which necessarily would not reflect the product's performance is general. The *Hit Rate* is sensitive to the possible imbalance between number of in-situ 'snow' and 'no-snow' cases. It is included in the provided list of binary metric, but *F-score* is considered more representative and is given a higher importance when interpreting the results. As Hit Rate, F-score is a measure of accuracy, but it considers both the Recall (product's capability to find the 'snow' cases out of in-situ snow cases i.e. false snow omissions decrease the Recall) and *Precision* (a measure describing how large portion of the identified 'snow' cases really are 'snow' according to in-situ observations i.e. false snow commissions decrease the Precision). Another metrics emphasized in the presenting the results is *Critical Success Index*, which considers both false snow omissions and false snow commissions at the same time; while those are separately described by (1-Recall) and False Alarm Rate, correspondingly.

Table 5.3:
Examples of a contingency matrix with naming convention.

Product / ***in-situ***	**snow**	**no-snow**
snow	True Positive (TP)	False Negative (FN)
no-snow	False Positive (FP)	True Negative (TN)

Table 5.4:
The binary metrics applied in the in-situ validation.

Metric	**Description**	**Special considerations for Nref_snow = TP+FN; Nref_nosnow = TN+FP; Ntot = TP+TN+FN+FP;**
Recall	TP / (TP+FN)	IF Nref_snow<20 THEN Recall = 'not-defined'
Precision	TP / (TP+FP)	IF Nref_snow<20 or Nref_nosnow<20 THEN Precision= 'not-defined'
False Alarm Rate	FP / (FP+TN)	IF Nref_nosnow / Ntot <0.10 THEN False Alarm Rate = 'not-defined'
Hit Rate (Accuracy)	(TP+TN)/ (TP+TN+FP+FN)	IF Nref_snow<20 or Nref_nosnow<20 THEN Hit Rate = 'not-defined'
Critical Success Index	TP/(TP+FN+FP)	IF Nref_snow<20 or Nref_nosnow<20 THEN Critical Success Index= 'not-defined'
F-score	2*TP / (2*TP + FP + FN)	IF Nref_snow<20 or Nref_nosnow<20 THEN F-score = 'not-defined'

5.6 Sampling design for a product at an in-situ location

The validation approach relies on point-to-point comparison, so that the product value is compared with the in-situ value at the pixel determined by the coordinates of the in-situ site. As the in-situ coordinates most typically do not refer to the centre of the pixel, the neighbouring pixels have to be taken into account to ensure that the relevant product pixels are involved in the validation. A feasible way of handling this is to make a list of the four nearest neighbours and only if they represent the same value the site is accepted for the analyses. An inhomogeneous neighbourhood is rejected. This approach also diminishes the possible small inaccuracies in the geolocation of the products.

5.7 The general protocol for the compiling analyses

Most of the Snow Extent products to be validated against in-situ are of hemispheric scale. Therefore the analyses and stratifications are made in hemispheric scale, using the combined data from all available seasons and from all available in-situ data sources. In addition to the continental scale products there are three products that are available only for a smaller region. When analysing these three products, the small region to be considered is extracted from the NH-scale products and analyses are made only for this area. These three products are CRYOL (Pan-Europe), EURAC (Alps) and MODSCAG (one region in the western parts North America and another one in East Asia). The partitioning treats Sturm Snow classes as primary data; for these, results are presented separately for 'Forested' area (including plains and mountains) and 'non-forested' areas (including plains and mountains). However for particularly interesting cases, mountains and plains can be analysed separately.

It should also be noted that each product is evaluated using all in-situ observations for which the product provides snow/no-snow information. Practically this means that different number of cases is used when validating the different products. For instance, for products providing snow/no-snow information for all land pixels i.e. do not introduce 'cloud' pixels at all, a larger number of cases are evident. This was found reasonable as using only intersecting data (i.e. only those in-situ observations for which all the products provide snow/no-snow information) would reduce the data excessively. An exception to this is the areal limitation for the regional products as explained above. Also, the yearly seasons covered by different products may vary, from one season to all five seasons. Basically, the validation results are inter-compared regardless of the number of available seasons, except for season 2011-2012 which is analysed separately to avoid the possible bias caused by the unavailability of the extensive Northern America dataset for that period. The separate analysis is also justified due to the fact that season 2011-2012 is the only one for which HSAF10 and HSAF31 are available.

In addition to the general approach described above, there may be several other ways to investigate and comprehend the results. These will only be identified as the validation work progresses; then a set of further analyses e.g. for specific regions or for specific seasons may be found necessary in the light of the gained results.

6. VALIDATION OF DAILY AND MAXIMUM SE MAPS WITH SNOW MAPS FROM LANDSAT DATA

Gabriele Bippus, Elisabeth Ripper, Thomas Nagler, ENVEO IT GmbH

Snow maps from Landsat data are used as reference data for evaluating the hemispheric snow extent products. For this evaluation the SCF and SEB products remain in their original map projection and grid size. The intercomparison concept of hemispheric snow extent products with reference snow maps generated from Landsat data is shown in Figure 6.1.

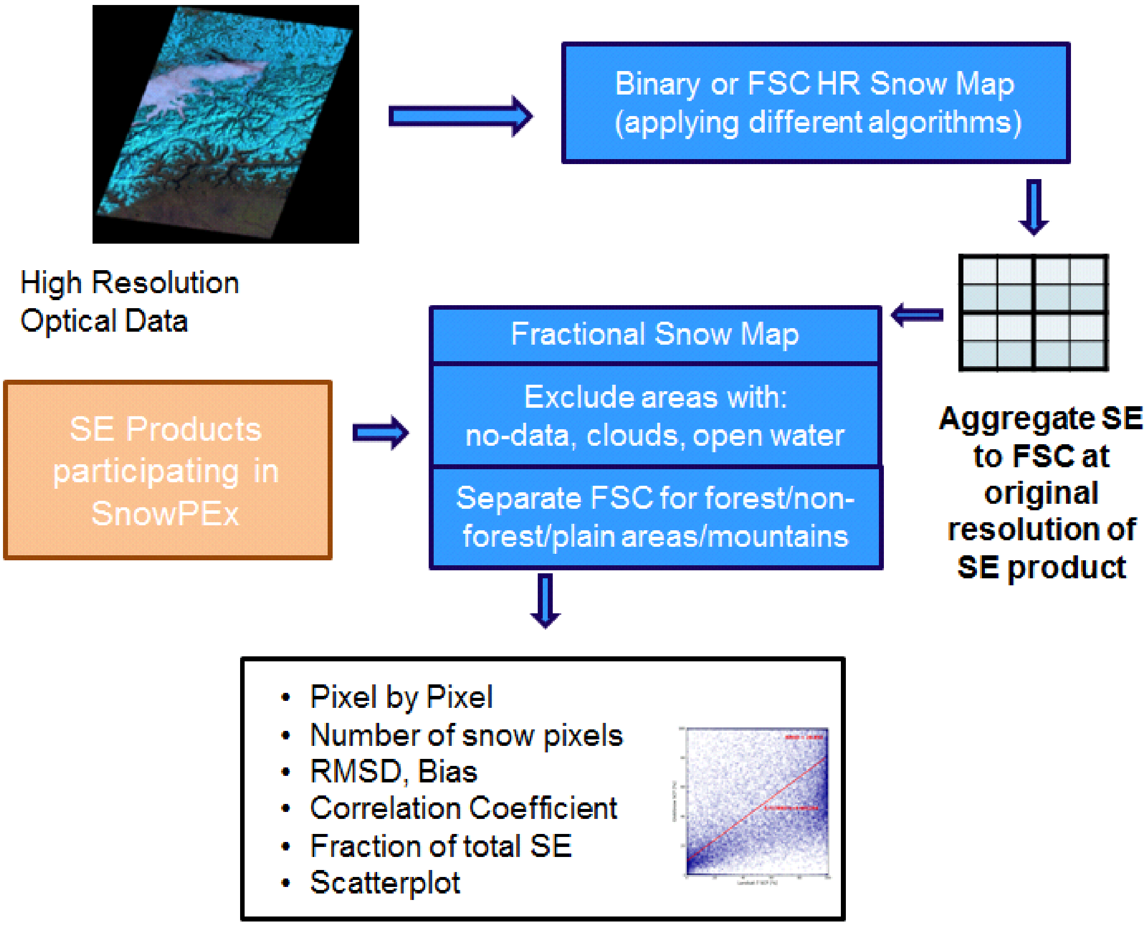

Figure 6.1: Concept for evaluating pixel by pixel global/hemispheric snow extent products with snow maps from Landsat data.

The validation procedure of hemispheric snow extent products with snow maps generated from Landsat imagery includes the following processing steps:

Step 1: Prepare snow maps from Landsat imagery as reference data. Detailed descriptions on the generation of reference snow maps from Landsat data are provided in the SnowPEx Deliverable D8.

The most important processing steps applied on the Landsat raw data are:

1. Prepare topographically corrected top of atmosphere reflectances (TC TOAR) from Landsat data in original projection and grid size.
2. Transform the TC TOAR from Landsat data to the original projection of the hemispheric snow extent products, keeping the high resolution pixel size.
3. Generate high resolution snow maps from the reprojected Landsat TC TOAR in the original projection of the hemispheric snow extent products:
    a. *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.
    b. *Fractional* snow maps from HR data are derived by 2 different approaches:
        - the approach of Salomonson and Appel (2006)
        - TMSCAG (Painter et al., 2009)

    Water bodies are excluded using the HR water mask from the SRTM DEM and the data mask from Hansen et al. (2013).

    The retrieved snow maps from Landsat data provide different thematic information on snow extent: either snow on ground, which includes a correction for canopy, or viewable snow:

    - Dozier and Painter (2004): binary snow on ground
    - Klein et al. (1998): binary snow on ground
    - Salomonson and Appel (2006): viewable fractional snow cover
    - Painter et al. (2009) – TMSCAG: viewable fractional snow cover and fractional snow on ground

Resulting snow maps from Landsat data are projected in the original projection of the hemispheric snow products, but keep the high resolution grid size.

Step 2: The snow maps derived from Landsat imagery by applying multiple algorithms are aggregated to fractional snow information at the original grid size of the global/hemispheric SE products.

The resulting snow maps from Landsat data are projected in the original projection and meet the grid size of the hemispheric snow products.

Step 3: Identify valid pixel masks used for validation of hemispheric snow products with reference snow maps from Landsat data.

Intercomparisons of medium resolution products with Landsat snow maps are only performed for the TOTAL_VALID_PIXEL_MASK and the SNOW_VALID_PIXEL_MASK.

For product validation with Landsat imagery only the total area covered by one Landsat scene is considered for the statistical analyses. Distinguishing between the different surface classes after resampling the Landsat reference snow map to the product grid size might not be representative anymore as the number of remaining pixels for a particular surface class can be small.

The preparations of a medium resolution product for the intercomparison with a Landsat snow product follow the descriptions in Section 3.1.

Step 4: Validate the hemispheric snow products with the reprojected and aggregated snow maps from Landsat imagery. The validation of hemispheric fractional and binary snow products is a pixel by pixel intercomparison where snow free values in the binary SE products are treated as 0 % snow and snow covered pixel as 100 % snow. In addition to the pixel by pixel intercomparison of the whole Landsat image, validation is done for 4 fractional snow classes:

- 0 % - 25 % SCF
- 26 % - 50 % SCF
- 51 % - 75 % SCF
- 76 % - 100 % SCF

For the evaluation of the daily global/hemispheric snow extent products with local snow maps from Landsat data the statistical parameters for fractional and binary SE products are used, depending on the global/hemispheric/regional SE product.

Additionally, the different thematic information, snow on ground or viewable snow, of the SE products and the generated reference snow maps are considered for the evaluation exercises in forested areas.

The NOAA IMS24 and MEaSUREs products are excluded from Landsat validation due to their low resolution (24 and 25 km, respectively) and the resolving limited amount of valid pixels of the aggregated Landsat image.

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7. CONCLUSIONS

A protocol for the intercomparison and validation of global and continental satellite-based snow extent (SE) products is presented. The protocol address validation and inter-comparison of snow cover fraction and binary snow extent products using a limited set of statistics corresponding to total measurement error, precision error, bias error and completeness.

Pre-processing steps applied on products and mandatory ancillary data to make different binary and fractional snow extent products comparable at all are documented in detail. All SE product intercomparisons are carried out in EASE-GRID 2.0 map projection and with 5 km and 25 km pixel size. Two approaches for the intercomparison of global and hemispheric products are presented: a deterministic approach applied by ENVEO and a probabilistic approach applied by CCRS. The deterministic approach by ENVEO is a pixel-by-pixel comparison using all valid pixels from all products for the intercomparison. Additionally, intercomparisons are performed for snow pixels only. These intercomparisons are carried out on a daily basis but are aggregated on a monthly and a 3-monthly basis for illustrating the results. Further, the weekly minimum and maximum snow extent of each of the global and hemispheric products are compared with the weekly northern hemispheric snow cover product from the NOAA/NCDC Climate Data Record (CDR) by D. Robinson (2012) provided by NSIDC (Brodzik and Armstrong, 2013). The CCRS intercomparison approach is applied on randomly selected comparison sites. The approach requires explicit knowledge of measurement error and sampling within each comparison site but can provide estimates of precision of uncertainty statistics independent of natural variability in uncertainty over sampling strata.

Further protocols for validating global, hemispheric and continental snow extent products with in-situ reference data and snow maps from high resolution optical satellite data are documented. Only snow extent products with pixel sizes up to 5 km are used for these validation exercises in order to get meaningful results. For the validation of global and hemispheric snow extent products with in-situ observations all snow information, the products and the in-situ snow depth measurements, are transformed to binary snow information. In-situ snow depth observations available from ECMWF, SMHI, RIHMI and North America and Canadian measurement networks are used as main reference data sets. Details about these in-situ data sets are described in Deliverable D10.

Validation with snow maps from high resolution optical satellite data are carried out with fractional and binary snow extent information.

High resolution snow maps generated from about 450 selected Landsat scenes by applying four different algorithms and in-situ snow depth observations available from ECMWF, RIHMI and North

America and Canadian measurement networks are used as main reference data sets. Details about the reference data sets are described in Deliverables D8, D9 and D10, respectively.

One focus of the intercomparison and validation activities is on the discrimination of product performances over different surface types and in particular snow climate zones classified by Sturm et al (1995). For the intercomparisons and validations in forested areas also the different thematic information of the multiple snow products, showing either snow on ground or viewable snow, are considered.

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