EUMETSAT Satellite Application Facility on
Support to Operational Hydrology and Water Management

Product Validation Report (PVR) for product SWE-H (H65)

Snow water equivalent by MW radiometry

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1.0	4/1/2021	Baseline version prepared for PDCR
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1 Introduction: Aim of this report

This validation report is an Operational Readiness Review (ORR) of H SAF product SWE-H (Snow Water Equivalent – Hemispherical, by microwave radiometry), which will be referred hereafter for convenience with the internal name H65.
H65 is a new EUMETSAT H SAF Snow Water Equivalent (SWE) product, developed during CDOP3, based on assimilation of ground-based Snow Depth (SD) observations and space borne radiometer (SSMI/S) derived SWE estimates.
The actual used operational product SWE-E (with internal H SAF name H13) has provided the SWE for the Pan-European domain (longitude 25°W to 45°E, latitude 25°N to 75°N, with horizontal res. 0.25°). The flat areas are provided by Finnish Meteorological Institute (FMI), whereas the mountainous areas by the Turkish State Meteorological Service (TSMS). The FMI part is a data fusion of ground-based SD observations and space-borne passive microwave derived SWE estimates. The TSMS uses passive microwave observations only.
The new SWE product H65 is comparable to the H13, but with major improvements concerning the region covered and SWE error estimate for flat areas. The SWE is now provided over the Northern Hemisphere instead of Pan-European domain only. In addition, there are some minor algorithm improvements involved. The H65 product is also a merge of FMI and TSMS parts. For details, please see the corresponding H65 ATBD document.
Instead of latitude – longitude grid, the H65 product is provided in the Equal Area Scalable Earth (EASE) grid version 2.0 (https://nsidc.org/data/ease) for Northern Hemisphere (Lambert's equal-area, azimuthal) with EPSG code 6931. The size of the grid is 720 x 720 pixels and the nominal spatial resolution of the H65 product (~ 25 km) is comparable to that of H13 (0.25°). The advantage of the EASE 2.0 grid is that the projection geoid is WGS84 and as the projection name suggests, all the pixels have equal area (625 km2). For SWE, this is especially handy because one can sum up the SWE pixel by pixel and get the liquid water volume for a larger area of interest.

2 Validation methodology

The quantitative validation of SWE given in the H65 product has been performed for 3 months in the past snow season (2021), i.e. January 1, 2021 till March 31, 2021.
The validation is performed using measurements (SD and SWE) obtained from the selected ground observation network of four participating countries in the H SAF validation cluster, by the H SAF validation team of: Finland (FMI), Turkey (Cankiri Karatekin University, HidroSAF METU), Germany (BafG) and Poland (IMGW).
Each Validation Team contributes to long statistic validation by providing the seasonal statistical scores. The results are shown separately for flat and mountainous areas (if applicable), since the product requirements have different thresholds in the two areas. Where not applicable (that is if no distinction is made) the stricter rules of the mountainous areas are considered.
Additional details over Finland and Turkey are provided, with 2 extensive case studies over one Snow Station and a hydrological basin.
As H65 is similar to product H13, with the extended coverage to Northern Hemisphere, the standard validation procedure and the same station network of the yearly Operational Review (OR) of H13 is performed. This methodology is described in ATBD, PUM and PVR of product H13: EUMETSAT H SAF H13 ATBD, https://hsaf.meteoam.it/Products/Detail?prod=H13.

To assess the degree of compliance of the product with product requirements (cf. Table 1), the contributing members of the Validation Group provided the statistical results, following the standard validation methodology.

Area	Threshold	Target	Optimal
flat (RMSE)	40 mm	20 mm	10 mm
mountain (RMSE)	45 mm	25 mm	15 mm

Table 1 Product requirements for product SWE-H (H65)

3 Results

3.1. Validation for mountainous areas in Turkey

<u>Methodology</u>

The validation of SWE from microwave imagery from SSMI/S (merged H65 product) is performed by using SD measurements obtained from the ground observation network of TSMS. The locations of all available AWOS (automated weather observing system), SPA (snowpack analyser), and synoptic stations of TSMS are presented in Figure 1

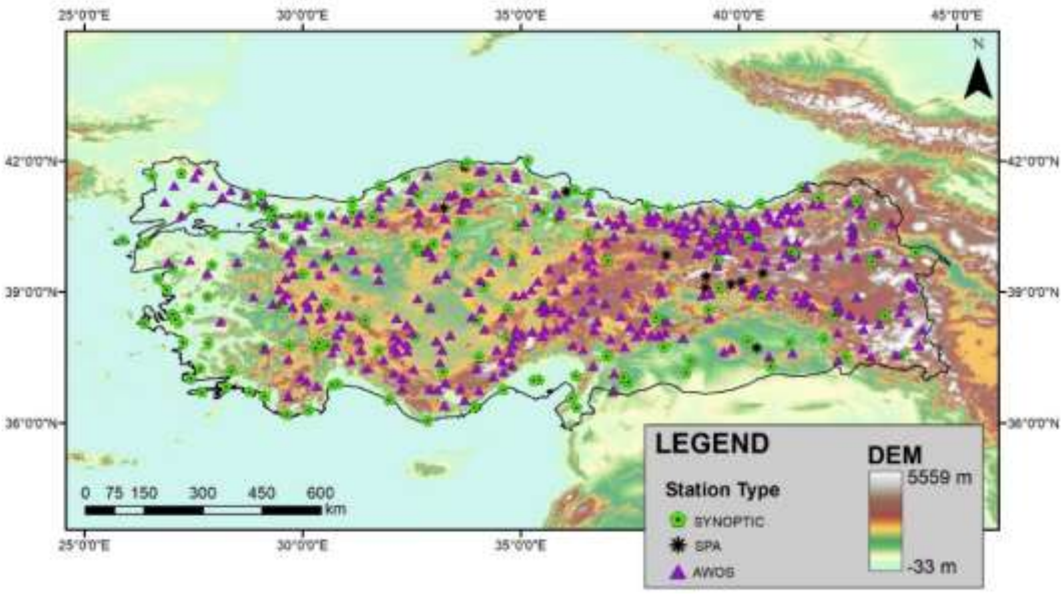

Figure 1 AWOS, SPA and Synoptic stations of TSMS reporting snow depths.

The in-situ data falling in the mountain mask are included in the validation analysis. The validation dataset covers the period of January 2021 - March 2021 and 1184 measurements collected from 68 stations (AWOS: 62, SPA: 6) have been utilized in the validation study for the mountainous areas (cf. Figure 2). The H65 Validation routine developed in the MATLAB environment is used in the validation study. The average SD value for the above-mentioned validation interval is calculated as 21.46 cm.

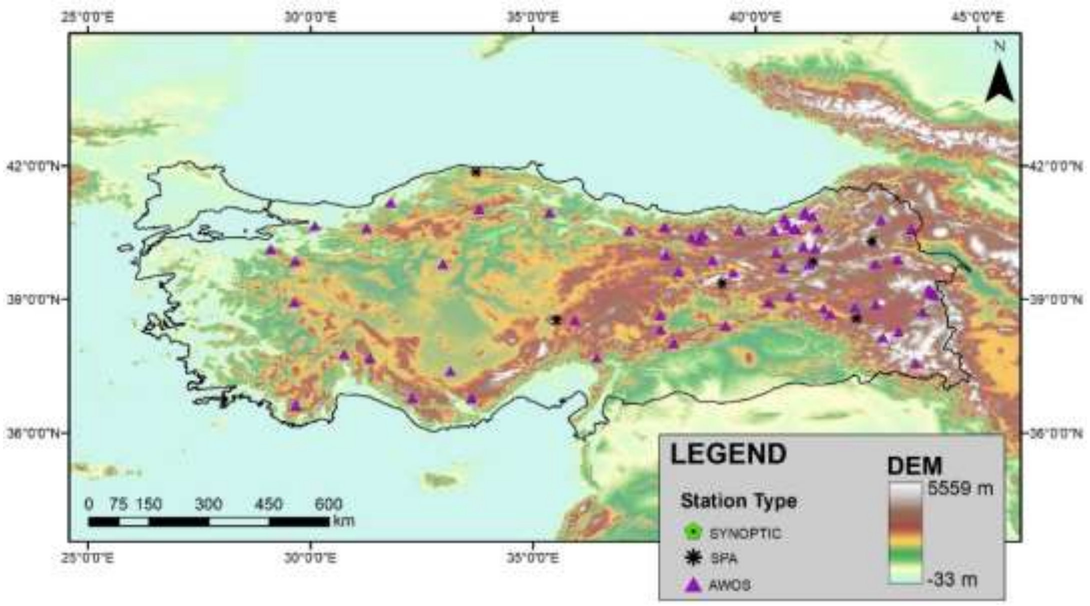

Figure 2 AWOS and SPA stations used in the validation.

In-situ measurements are compared individually with the corresponding 25 x 25 km2 SSMI/S footprint. For each measurement location the elevation of the weather station is compared against the SSMI/S pixel median elevation where the measurement falls inside it. If the elevation difference between the measurement location and the pixel's median elevation value is greater than 400 meters, that weather station is excluded from the validation analysis. Since the SWE product is developed for dry snow conditions, the validation period is selected as January to March. The results are presented in Table 2 for the 2021 water year. The comparison between the retrieved and observed SWE values is presented in Figure 3.

Range (mm)	**Meas. SWE (mm)**	**Calc. SWE (mm)**	**Stand. Dev.**	**Data Count**	**Mean Error**
0-25	0.30	32.64	1.32	636	-32.34
25-50	41.15	43.85	6.09	20	-2.70
50-75	65.37	60.34	7.02	59	5.03
75-100	88.36	74.79	6.65	177	13.57
100-125	111.98	97.57	6.62	188	14.41
125-150	133.38	108.36	5.55	99	25.02
150-175	153.00	101.03	0.00	1	51.97
175-200	185.25	195.74	7.54	4	-10.49

Table 2 Results for validation period Jan 2021 - Mar 2021

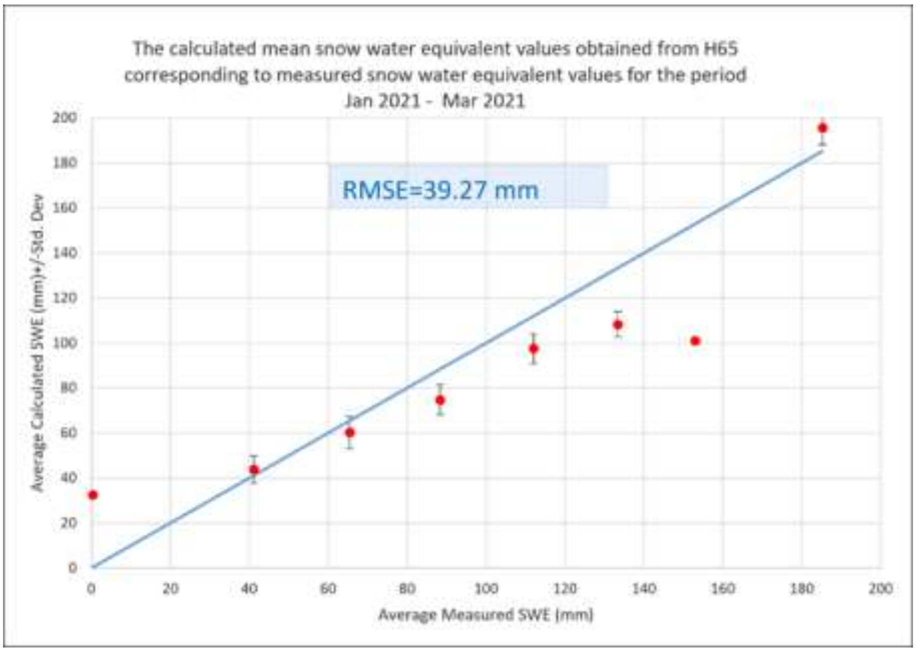

Figure 3 Calculated mean snow water equivalent obtained from H65 corresponding to measured snow water equivalent values for the period Jan 2021 - Mar 2021.

The penetration characteristics of the SSMI/S instrument for shallow and deep snow lead under and over estimation in the SWE retrieval. In Figure 3, underestimation of SWE is seen when ground truth SWE is larger than 150 mm. This is a typical behaviour of the algorithm since with large values of SWE, the signal of the radiometer is saturated. The maximum SD observed in 2021 was 88.76 cm, the mean of the observed SD over 68 stations was 21.46 cm.

The overall RMSE for January 2021 - March 2021 is 39.27 mm: RMSE is calculated as 39.92 mm, 39.33 mm and 38.02 mm for January, February, and March, respectively. The results indicate that the threshold for user requirement of 45 mm for the mountainous areas is fully satisfied according to overall and monthly RMSE values.

3.1.1. Case Study: time series of a SPA snow-station in Erzurum area

As a case study during this validation, the temporal evolution of snow cover between Jan-Mar 2021 is evaluated by comparing daily in-situ SWE measurements at the location of a selected SPA station (i.e., SPA station 17777 of TSMS, cf. Figure 4) against SWE values from the associated pixel of H65 product (cf. Figure 5).

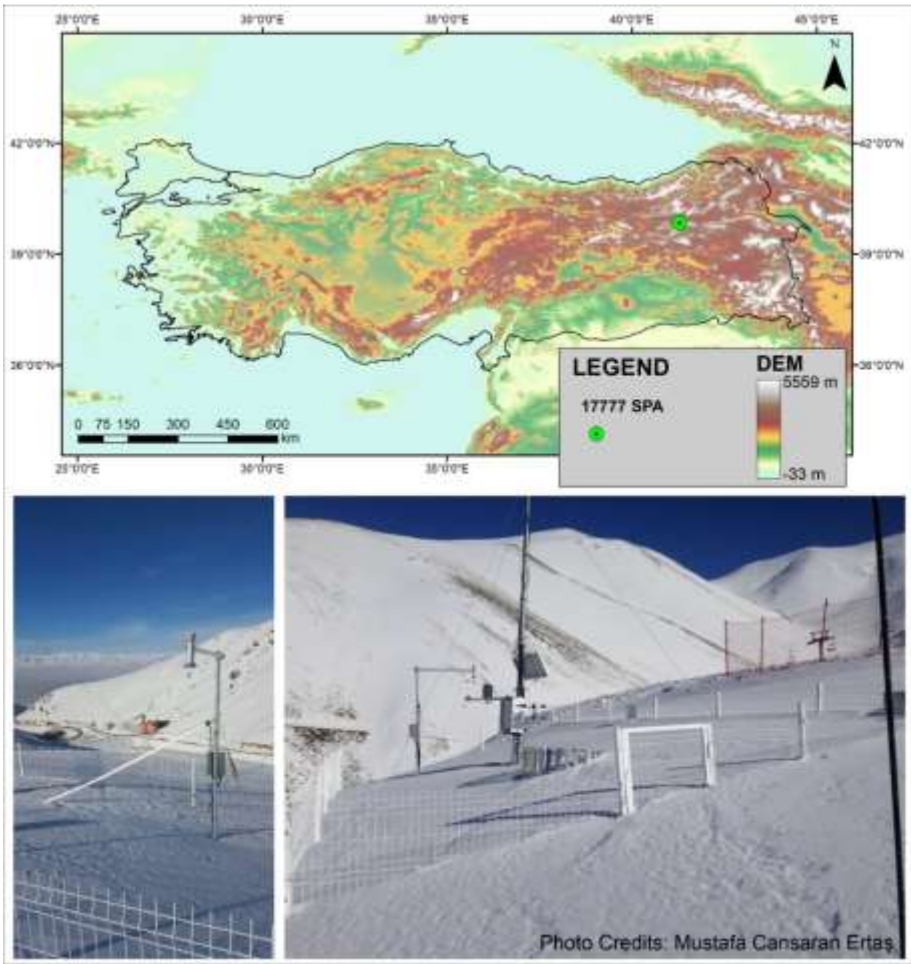

Figure 4 The location and snapshots of SPA station 17777 at Palandöken Ski Center, Erzurum (altitude 2615 m).

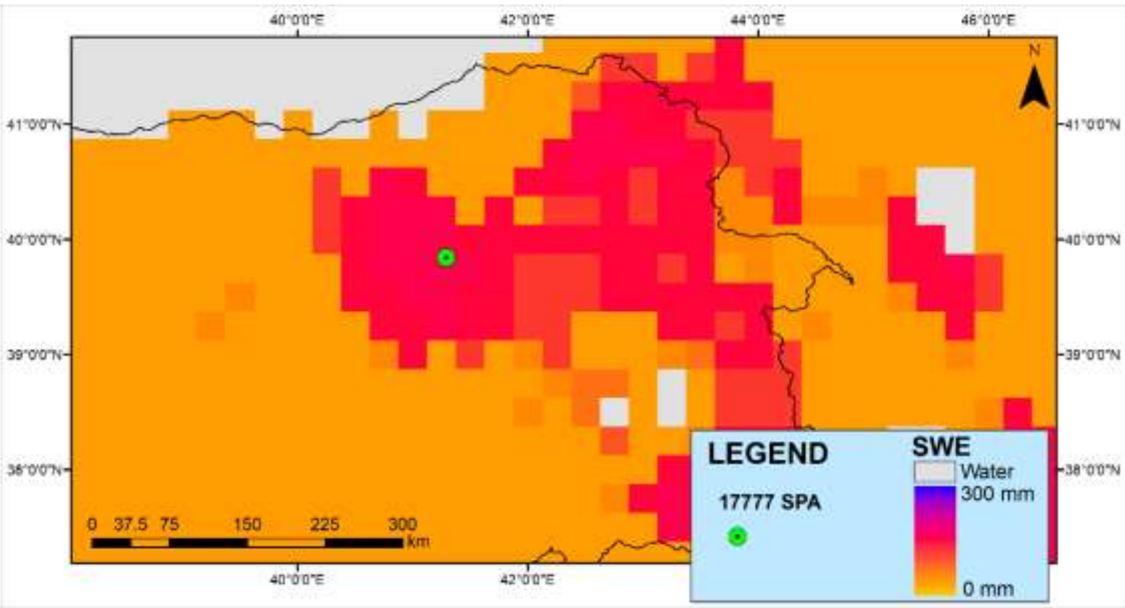

Figure 5 SPA station 17777 and the corresponding H65 on Jan 1st, 2021.

The SWE observations from the SPA station (i.e., 17777) are compared with the H65 SWE values (cf. Figure 7). The H65 SWE underestimation for March and April is clearly seen in the figure.

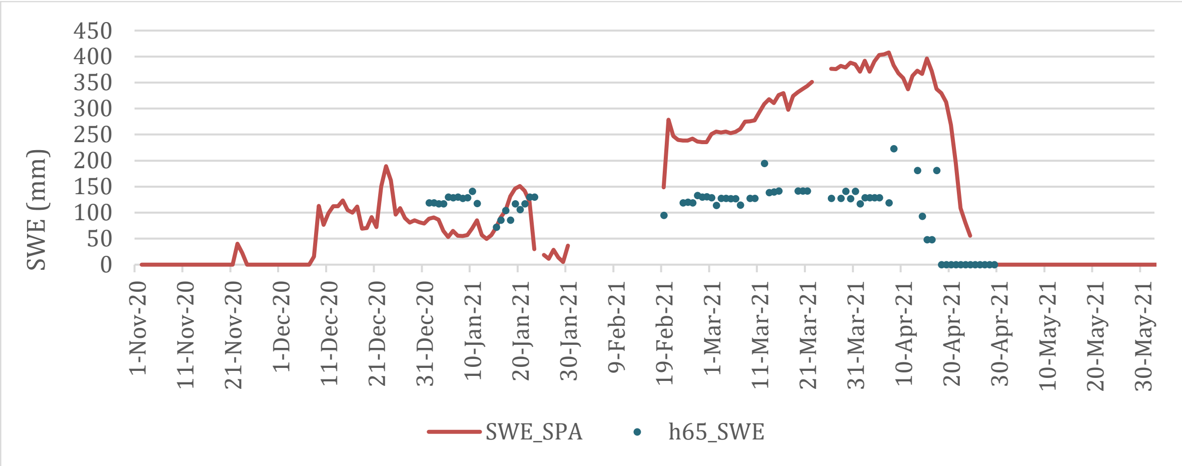

Figure 6 SWE measurements from SPA station 17777 versus H65 SWE values

3.2. Validation for flat areas in Finland

EUMETSAT H SAF H65 SWE product on flat areas is based on the assimilation of ground-based SD observations and space borne radiometer (SSMI/S) derived SWE estimates. Since SD data are used as input to the algorithm, it means that an independent data set describing SWE is required.

In this validation effort, Finnish Environment Institute's (SYKE) snow course measurements have been used. SYKE estimates SWE with both SD and snow weight measurements. These actions are conducted on a course (typically length of 2-4 km) and including multiple types of land use. Resulting SWE is average of these measurements and thus a good representative of a radiometer resolution (~ 25 km) pixel. There are altogether 150 active snow courses (cf. Figure 7) and measurements are performed once or twice in a month.

Figure 7 Snow course locations in Finland

H SAF H65 SWE was validated for period from Jan 1, 2021 to May 31, 2021. Scatterplot of SYKE snow course SWE versus H65 SWE estimate is presented in Figure 8.

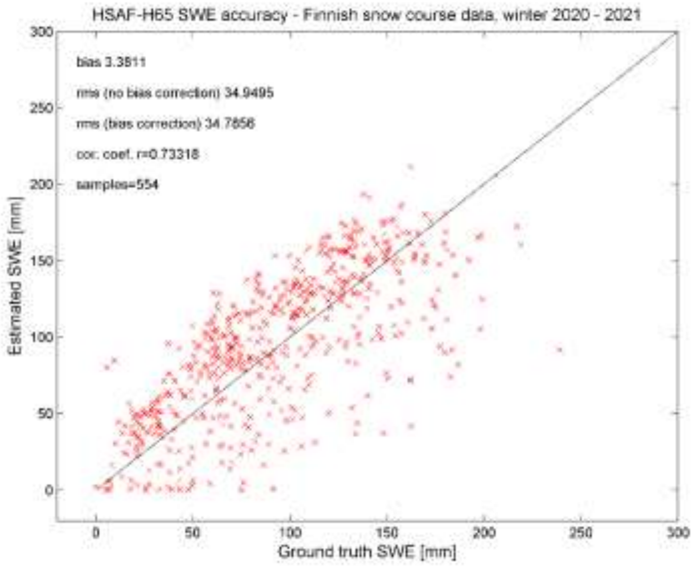

Figure 8 Scatterplot of SYKE snow course SWE vs. H65 SWE estimate.

The obtained statistical figures were bias of 3.4 mm, RMSE without bias correction 34.9 mm, RMS with bias correction 34.8mm, and correlation coefficient 0.73.

The results in Figure 2 show, that the H65 SWE agrees well with ground truth measurements. It must be noted, that the SYKE snow courses are independent of the SD observations used as an input to the FMI part of the product. SWE values over 150 mm tend to be somewhat underestimated. This saturation is due to the thick snowpack when the brightness temperature begins to be dominated by the component of snow.

In Figure 9, the same results in Figure 2's scatterplot are presented in an alternative fashion with average values and error limits.

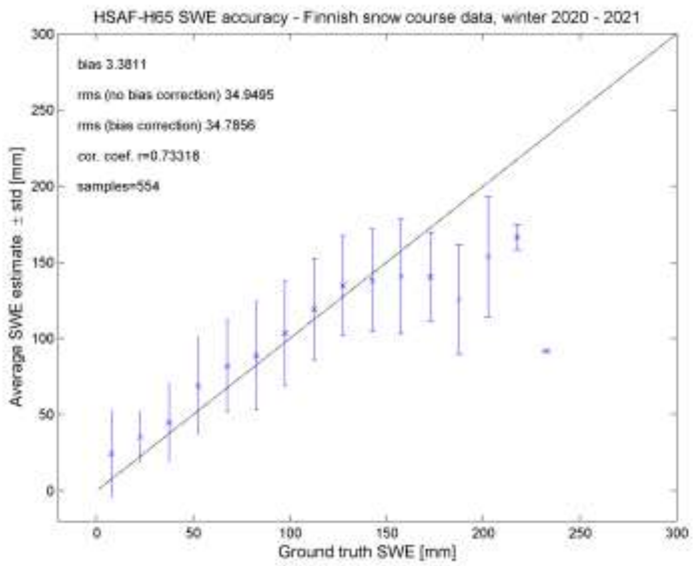

Figure 9 Scatterplot of SYKE snow course SWE vs. H65 SWE estimate

Looking Figure 3, one can see a clear underestimation of SWE when ground truth SWE is larger than 150 mm. This is typical behavior of the algorithm since with large values of SWE radiometer SWE estimates saturate.

In sum, **RMS value 34.9 mm** was obtained. This is in between the target and the threshold value.

3.2.1 Case Study: Product performance in Kemijoki River drainage basin in spring 2021

The H65 is provided as a geocoded (EPSG:6931) NetCDF4 file. Reading the data to a GIS software such as QGIS is thus straightforward. In Figure 10, a sample of H65 SWE on Apr 4, 2021, is plotted in the QGIS software together with coastlines and state borders and the Kemijoki basin. The Kemijoki basin was chosen because of its location in Northern Finland and its importance for hydropower company Kemijoki oy.

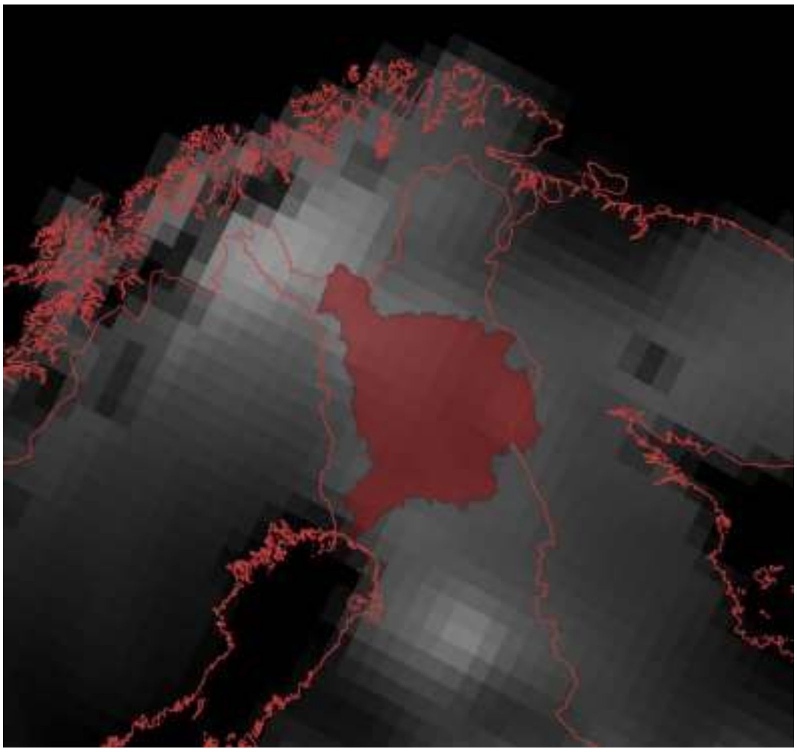

Figure 10 The H65 SWE of Apr 4, 2021, plotted in QGIS software with coastlines and state borders and the Kemijoki River basin is indicated with red color fill.

For hydrology, the peak value and timing of SWE is very important. With GIS software, it is possible to calculate statistics over a polygon (in this case the river catchment). The mean SWE and the standard deviation were calculated for the whole Kemijoki catchment from Feb 15 to Apr 4. The results are presented in Figure 11. In addition, the statistics calculation showed that the Kemijoki catchment covers 84 pixels in the H65 product.

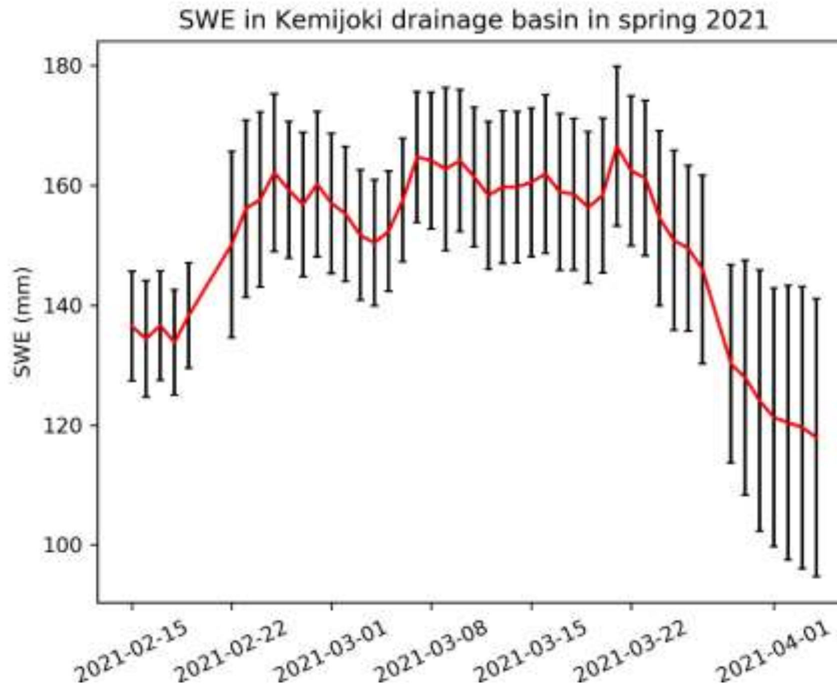

Figure 11 The development of the average SWE in Kemijoki drainage basin during spring 2021. The red line indicates the mean, and the error bars represent the deviation of SWE over the area.

The results show that the mean SWE increases from February to March. There is a slight decrease of SWE in early March, but after that the SWE is stable. The maximum value (166.5 mm) is reached on March 21 and after that the SWE value begins to decrease as springtime is at hand. The growing deviation also indicates this.

The area covers 84 pixels with area of 625 km^2 or $6.25*10^8$ m^2. This gives in average $84*6.25*10^8$ $m^2*0.1665$ m $=8.74*10^9$ m^3 of water available to the spring river discharge.

In the context of the EUMETSAT H SAF project, the obtained SWE values can be used as an input to a hydrological model. FMI operates an in house developed hydrological model called HOPS (https://hops.fmi.fi). The HOPS model can assimilate SWE data in addition to various other meteorological and hydrological parameters within the Kemijoki catchment area.

This case study shows that the new SWE product H65 in the EUMETSAT H SAF product portfolio has a potential to be an important data source for hydrological applications. First, the area is extended to the Northern Hemisphere as compared to the H13 product, including other improvements. Second, the validation results show that the product is within the defined user requirements. Third, even though the product projection might appear exotic, it has clear advantages for the hydrological end users being an equal area projection. Fourth, the product format (i.e., NetCDF4) makes it easy to import the data to a GIS software.

3.3. Validation in Germany

The H65 product is validated for 20 mm < SWE(H65) < 100 mm, within the period January 2021-February 2021, the obtained statistical scores are presented in Table 3.

Statistics	Scores
Number of cases	**1838**
Standard Deviation	22.7
Correlation Coefficient	0.05
Root Mean Square Error (mm)	**33.5**
Root Mean Square Error (%)	0.84

Table 3 Statistical scores for validation period January 2021 – February 2021 for Germany

Scores for continuous statistics suggest rather good correspondence of SWE values derived from h65 product and ground measurement, evaluated with SD of more than 20 cm. The RMSE value of 33.5 mm lies below the threshold, and the statistics are rather good, with 1957 observations analysed.

3.4. Validation in Poland

Statistical scores of H65 product validation for SD > 2 mm, in the snow period from January 2021 to February 2021 are presented in Table 4.

Statistics	Scores
Number of cases	**1328**
Standard Deviation	33.8
Correlation Coefficient	0.27
Root Mean Square Error (mm)	**34.4**
Root Mean Square Error (%)	1.0

Table 4 Statistical scores for the validation period January 2021– February 2021 for Poland

Scores for continuous statistics suggest good correspondence of SWE values derived from H65 product and ground measurements. In those cases, the overall RMSE of 34.4 mm is below the threshold, albeit far from target levels, as in the other countries; the statistics are good, with 1328 observations analysed.

4 Conclusions: Product requirement compliance

As shown in Table 5, the statistical scores obtained by the validation of H65 satisfy the Product Requirements, with RMSE between threshold and target values in all areas. Since the SWE product is developed for dry snow conditions, validation period was limited in the 3 core winter months of 2021 (i.e., January, February, and March).

In this validation, RMSE value of 39.3 mm was obtained for the mountainous areas of Turkey and RMSE of 34.3 mm for the mostly flat areas of Finland, Germany and Poland; both RMSE values are between the threshold and the target. In all countries, the scores are very similar and therefore product performances are consistent, yet the best performances are obtained in the flat areas, as expected.

The reported Turkish and Finnish case studies show the good temporal correspondence of product in a single Snow Station (eastern Turkey) and also in the mean over river basin (northern Finland). Underestimation arises when SWE values are larger than 150 mm, as was the case with product H13.

Table 5: Compliance analysis for product SWE-H (H65)

Between target and optimal	Between threshold and target	Threshold exceeded by < 50 %	Threshold exceeded by ≥ 50 %

Product requirements for H65				RMSE (mm)				
	threshold	target	optimal	**AVERAGE**	Poland	Finland	Turkey	Germany
N. samples					1328	554	1184	1838
Mountainous Area	45 mm	25 mm	15 mm	**39.3 mm**			39.3 mm	
Flat Area	40 mm	20 mm	10 mm	**34.3 mm**	34.4 mm	34.9 mm		33.5 mm

5 References

- EUMETSAT H SAF H13 ATBD, https://hsaf.meteoam.it/Products/Detail?prod=H13
- EUMETSAT H SAF H65 ATBD
- SYKE Open data river catchments, https://ckan.ymparisto.fi/dataset/valuma-aluejako
- FMI HOPS model (https://hops.fmi.fi)
- QGIS, A Free and Open Source Geographic Information System, **Errore. Riferimento a collegamento ipertestuale non valido.**

Annex 2: Acronyms

ATBD	Algorithms Theoretical Baseline Document
AU	Anadolu University (in Turkey)
BfG	Bundesanstalt für Gewässerkunde (in Germany)
CAF	Central Application Facility (of EUMETSAT)
CESBIO	Centre d'Etudes Spatiales de la BIOsphere (of CNRS, in France)
CMSAF	SAF on Climate Monitoring
CNMCA	Centro Nazionale di Meteorologia e Climatologia Aeronautica (in Italy)
CNR	Consiglio Nazionale delle Ricerche (of Italy)
CNRS	Centre Nationale de la Recherche Scientifique (of France)
DEM	Digital Elevation Model
DMSP	Defence Meteorological Satellite Program
DPC	Dipartimento Protezione Civile (of Italy)
DWD	Deutscher Wetterdienst
ECMWF	European Centre for Medium-range Weather Forecasts
EOS	Earth Observing System (Terra, Aqua, Aura)
EUM	Short for EUMETSAT
EUMETCast	EUMETSAT's Broadcast System for Environmental Data
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FMI	Finnish Meteorological Institute
FTP	File Transfer Protocol
GEO	Geostationary Earth Orbit
GRAS-SAF	SAF on GRAS Meteorology
GTOPO	Global digital elevation model (U.S. Geological Survey)
H SAF	SAF on Support to Operational Hydrology and Water Management
HUT	Helsinki University of Technology (same as TKK)
IFOV	Instantaneous Field Of View
IMWM	Institute of Meteorology and Water Management (in Poland)
IPF	Institut für Photogrammetrie und Fernerkundung (of TU-Wien, in Austria)
IR	Infra Red
IRM	Institut Royal Météorologique (of Belgium) (alternative of RMI)
ISAC	Istituto di Scienze dell'Atmosfera e del Clima (of CNR, Italy)
ITU	İstanbul Technical University (in Turkey)
LATMOS	Laboratoire Atmosphères, Milieux, Observations Spatiales (of CNRS, in France)
LEO	Low Earth Orbit
LSA SAF	SAF on Land Surface Analysis
Météo France	National Meteorological Service of France
METU	Middle East Technical University (in Turkey)
MW	MicroWave
NASA	National Aeronautical and Space Administration (in USA)
NMA	National Meteorological Administration (of Romania)
NOAA	National Oceanic and Atmospheric Administration (Agency and satellite)
NWC	Nowcasting
NWC SAF	SAF in support to Nowcasting & Very Short Range Forecasting
NWP	Numerical Weather Prediction
NWP SAF	SAF on Numerical Weather Prediction

AC SAF	SAF on Ozone and Atmospheric Chemistry Monitoring
OMSZ	Hungarian Meteorological Service
OSI-SAF	SAF on Ocean and Sea Ice
PUM	Product User Manual
PVR	Product Validation Report
RMI	Royal Meteorological Institute (of Belgium) (alternative of IRM)
RMSE	Root Mean Square Error
SAF	Satellite Application Facility
SCA	Snow Covered Area
SD	Snow Depth
SHMÚ	Slovak Hydro-Meteorological Institute
SSM/I	Special Sensor Microwave / Imager (on DMSP up to F-15)
SSMIS	Special Sensor Microwave Imager/Sounder (on DMSP starting with S-16)
STD	Standard Deviation
SVRR	System Validation Results Review
SWE	Snow Water Equivalent
TSMS	Turkish State Meteorological Service
TU-Wien	Technische Universität Wien (in Austria)
UniFe	University of Ferrara (in Italy)
VIS	Visible
ZAMG	Zentralanstalt für Meteorologie und Geodynamik (of Austria)