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Validation of EUMETSAT H-SAF space-born snow water equivalent product (H13) for the 2020-2021 snow year over Turkey

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ABSTRACT

Timely and consistent information on the seasonal snow cover is critical for various scientific studies and operational applications, especially for hydrological purposes. Snow water equivalent (SWE) is a significant seasonal snow parameter, which serves as a key input for many hydrological and climatological models. H13 is a SWE product supplied within the frame of EUMETSAT's H-SAF project based on the processing of passive microwave radiometer data. The basic aim of this study is to perform a validation of H13 over Turkey for the 2020-2021 snow season by using in-situ snow depth measurements. The validation covers the period between January and March 2021, and it includes 1282 ground-based observations. According to the results, the annual RMSE of the H13 SWE product is obtained as 40.00 mm, which lies within the acceptable limits of the required product compliance. The minimum and maximum snow depth measurements within the validation period are 2.80 cm and 95.34 cm, respectively. The results obtained in this validation study clearly indicate the usability of the H13 SWE product in hydrological and climatic studies.

Key Words: Snow water equivalent, EUMETSAT, H-SAF, microwave radiometer, SSM/IS, remote sensing of snow

EUMETSAT H-SAF H13 uzay tabanlı kar suyu eşdeğeri ürününün 2020-2021 kar yılı için yersel kar derinliği ölçümleriyle Türkiye üzerinde doğrulanması

ÖZ

Mevsimsel kar örtüsü hakkında zamanında ve tutarlı bilgi elde edilmesi, çeşitli bilimsel çalışmalar, operasyonel uygulamalar ve özellikle de hidrolojik amaçlar için kritik öneme sahiptir. Kar suyu eşdeğeri (KSE), birçok hidrolojik ve iklimsel model için önemli bir girdi işlevi gören mevsimsel bir kar parametresidir. H13, EUMETSAT'ın H-SAF projesi çerçevesince pasif mikrodalga radyometre verilerinin işlenmesiyle üretilen bir KSE ürünüdür. Bu çalışmanın temel amacı, yersel kar derinliği ölçümlerini kullanarak 2020-2021 kar sezonu için Türkiye üzerinde H13 ürününün doğrulamasının gerçekleştirilmesidir. Doğrulama, Ocak - Mart 2021 arasındaki dönemi kapsamakta ve 1282 yer tabanlı gözlem içermektedir. Doğrulama sonuçlarına göre, H13 KSE ürününün yıllık RMSE'si 40,00 mm olarak hesaplanmıştır ve gerekli ürün uyumluluğunun kabul edilebilir sınırları içindedir. Doğrulama dönemindeki minimum ve maksimum kar derinliği ölçümleri sırasıyla 2,80 cm ve 95,34 cm'dir. Bu doğrulama çalışmasında elde edilen sonuçlar, H13 KSE ürününün hidrolojik ve iklimsel çalışmalarda kullanılabilirliğini açıkça göstermektedir.

Anahtar Kelimeler: Kar suyu eşdeğeri, EUMETSAT, H-SAF, mikrodalga radyometresi, SSM/IS, karın uzaktan algılanması

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1. Introduction

Climatic drivers have significant role on the environmental processes such as meteorology, hydrology and water cycle (Dawson et al., 2014; Allan et al., 2020; Lee et al., 2020), and they also have important implications in forestry-related applications (Nuri and Mutlu, 2009; Eken and Oner, 2017; Corbaci et al., 2019; Bilgili et al., 2020). As one of the main climatic drivers, snow cover is an important physical element of the cryosphere, which plays a crucial role on the Earth's radiation budget (Dietz et al., 2012), as well as on many environmental processes directly related to hydrology, ecology and meteorology at both regional and global scales (Tekeli et al., 2005; Akyürek et al., 2010; Kuter et al., 2022). Consistent monitoring of snow by Earth-observing satellites has a long history dating back to 1960s (Hall and Martinec, 1985). Remote sensing serves as an effective tool for the retrieval of two main snow parameters, which are the snow extent (SE) and the snow water equivalent (SWE). SWE refers to the amount of liquid water contained in the snowpack, and it is realized by using active/passive microwave techniques (Brown and Robinson, 2005). SE indicates the areal coverage of snow, and it is further divided into two subcategories as binary snow cover (i.e., snow/no snow) and sub-pixel snow cover (i.e., fractional snow cover – FSC, i.e., percentage area fraction of snow in a pixel's footprint), which are derived from multispectral optical remote sensing data (Metsämäki et al., 2015).

As a significant seasonal snow property, SWE estimates are strictly needed in hydrological and climatological applications, like river discharge and flood forecasting during spring snowmelt, climate model evaluation, hydropower production, and prediction on freshwater availability (Pulliainen and Hallikainen, 2001; Venäläinen et al., 2021). Even though SWE estimation is possible through snowfall measurements (Broxton et al., 2016) or surface snow depth (SD) interpolation (Dyer and Mote, 2006), extrapolation of these in-situ measurements over large areas, especially in northern latitudes with boreal forest cover and complex topography, has a certain limitation in catching the spatial variability in the snowpack with high accuracy (Viviroli et al., 2011; López-Moreno et al., 2013).

On the other hand, SWE retrieval from space-born passive microwave radiometer data with global coverage has been available since the late 70s (Pulliainen and Hallikainen, 2001) based on the difference in measured brightness temperatures at a frequency insensitive to dry snow, around 19 GHz, and at a frequency sensitive to dry snow, around 37 GHz (Venäläinen et al., 2021). H13-SN-OBS-4 (H13-PUM, 2018), which will be referred as H13 hereafter, is a SWE product based on passive microwave data, and it is provided within the Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF) program (https://hsaf.meteoam.it/) of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT, https://www.eumetsat.int/).

The validation of satellite-derived snow products is of vital importance *i*) to properly assess and quantify their reliability, *ii*) to identify possible errors, and finally, *iii*) to provide input for further calibrations and improvements on the associated retrieval algorithms (Piazzi et al., 2019). As stated in Hall et al. (2019), validation of a snow product is highly valuable when well-distributed and adequate ground station data is available. Thus, this study aims to validate the H13 SWE product over Turkey by using in-situ SD data for the 2020-2021 snow year, and to present the results. In addition to the in-situ SD data, SWE measurements obtained from a snowpack analyzer (SPA) station are also used in the validation. In Turkey, the installation of SPA stations, at which automatic SWE measurements can be done, were started in 2015, and a related validation study was performed by Şorman and Ertaş (2019). The study, which covered the 2017 snow season (i.e., Oct 2016 – May 2017), evaluated the performance of automated SD and SWE measurements from 11 SPA stations over Turkey and compared them against manual in-situ measurements at one specific SPA location (i.e., Palandöken, Erzurum), and satellite-based observations as well. The findings of Şorman and Ertaş (2019) indicated that the agreement in SWE between SPA and satellite-derived observations lied within the range of 30-314 mm, and this difference was mainly attributed to the changes in the topographic conditions. They also emphasized the strict necessity for the regular maintenance of the SPA stations that are exposed to harsh and long snowy conditions.

The remainder of this study is composed of the following sections: Section 2 gives brief information about the main data sources employed in the study (i.e., H13, in-situ measurements, etc.), as well as the methodology implemented during the validation. The results are presented in Section 3. Finally, conclusions are outlined in Section 4.

2. Materials and Methods

2.1 H-SAF H13 snow water equivalent product

H13 daily operational SWE product of EUMETSAT H-SAF is fundamentally based on Special Sensor Microwave/Imager (SSM/I) (Emery and Camps, 2017) and Special Sensor Microwave Imager Sounder (SSM/IS) (SSM/IS, 2007) onboard to the Defense Meteorological Satellite Program (DMSP) satellites(https://www.ospo.noaa.gov/Operations/DMSP/index.html).

The spatial coverage of H13 spans the Pan-European domain confined in longitude 25°W to 45°E and latitude 25°N to 75°N (cf. Figure 1) with a spatial resolution of 0.25° (~ 25 km). The SWE retrieval algorithm employed in H13 is basically composed of two parts: *i*) the part for the flat and forested regions is achieved through a data assimilation of the ground-based SD observations and the passive microwave-derived SWE estimates by the Finnish Meteorological Institute (FMI), whereas *ii*) the part for the mountainous areas (cf. Figure 1b) is generated by the Turkish State Meteorological Service (TSMS) using the passive microwave observations only (H13-PUM, 2018). Then, these two parts are merged at FMI to obtain the final product. The details of the retrieval algorithm, which is outlined in H13-PUM (2018), can be found in Pulliainen et al. (1993), Pulliainen et al. (1999), and Kruopis et al. (1999). The retrieval algorithm for the mountainous parts is discussed in detail by Sorman and Beser (2013). During the validation efforts for the 2020-2021 snow year over Turkey, H13 data from 1 Jan 2021 to 31 Mar 2021 is considered.

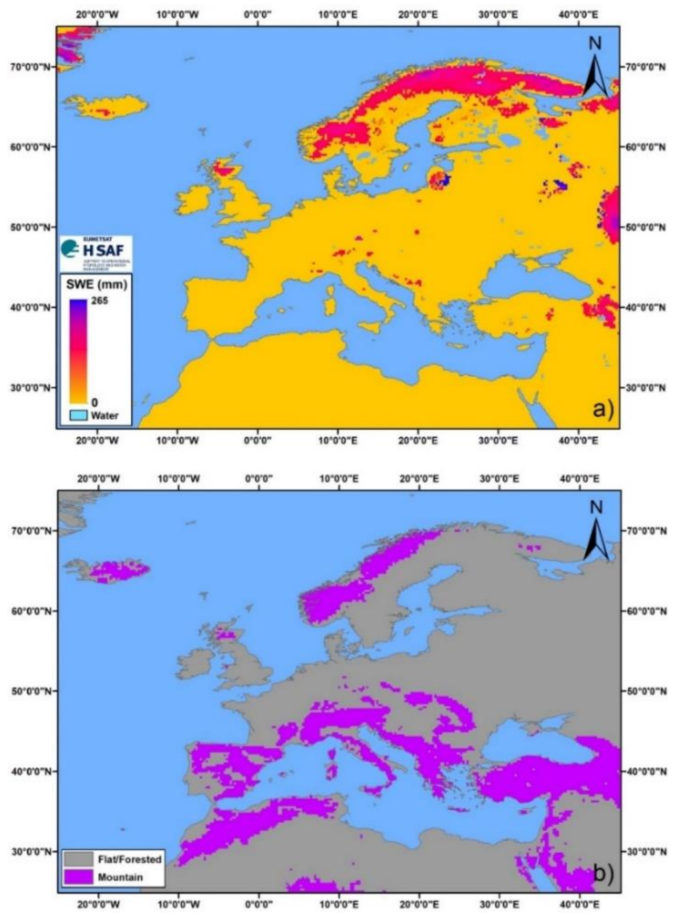

Fig. 1. a) H13 product for the 28th of January 2021, and b) the H13 mountain mask.

2.2 In-Situ snow depth data

The validation of H13 SWE product is performed by using SD measurements obtained from the ground observation network of TSMS composed of automated weather observing system (AWOS), SPA, and synoptic stations. A group of meteorological sensors are used in an AWOS to measure weather parameters (Sulistya et al., 2019), and snow depth is generally retrieved by ultrasonic sensors (i.e., ultrasonic pulse between the sensor and the snow surface) (Ryan et al., 2008). On the other hand, a typical SPA system is designed to determine the characteristics of snow cover (i.e., snow density, SWE and the contents of ice and liquid water) based on the measurements of the complex impedance along flat ribbon sensors, together with an ultrasonic snow depth sensor as well (Fiel et al., 2009).

Due to some technical considerations (e.g., insufficient maintenance, sensor failure, grass interference, etc.), not all stations are operationally usable in our validation study. Thus, detailed quality check and filtering operations (including crosschecking a specific station's readings by using the readings of a nearby station) are performed on the stations and the associated SD data to remove low quality/missing data before the validation. After these necessary quality check and filtering operations, 1282 in-situ SD measurements collected from 68 stations (i.e., AWOS: 62 (333 in total), SPA: 6 (16 in total)) between 1 January 2021 and 31 March 2021 are used in the validation study. The locations of the AWOS and SPA stations employed in the validation are shown in Figure 2.

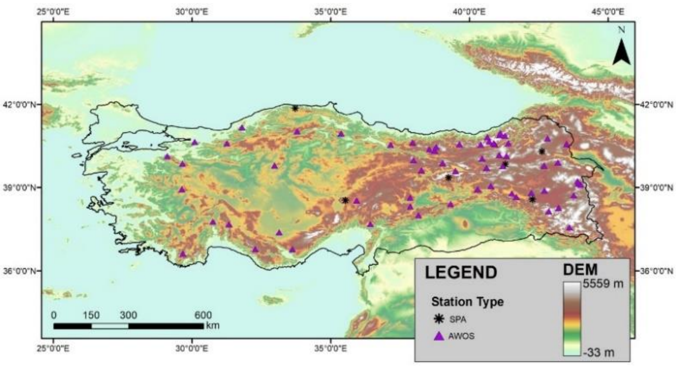

Fig. 2. The locations of AWOS and SPA stations of TSMS used in the validation.

2.3 A brief note on the validation methodology

The validation procedure described in this sub-section is based on H13-PVR (2012). In-situ SD measurements are compared individually with the corresponding 0.25° × 0.25° (i.e., ~ 0.25 km × 0.25 km) H13 footprint. For each measurement location, the elevation of the ground measurement station is compared against the median elevation of the corresponding H13 pixel, in which the measurement falls inside. If the elevation difference between the ground station and the pixel's median elevation value is greater than 400 meters, that station is excluded from the validation. Additionally, if there exist more than one ground station inside the footprint of an H13 pixel, then the average value of these stations is considered. Since the SWE product is developed for dry snow conditions, the validation period is selected as January to March. When converting the in-situ SD measurements to SWE, monthly average density values are taken (i.e., 0.25 g/cm^3 to 0.30 g/cm^3). The validation results are reported on both monthly and annual basis in terms of *root-mean-squared error* (RMSE), as given in the following expression:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(\mathrm{SWE}_{\mathrm{obs}} - \mathrm{SWE}_{\mathrm{est}}\right)^2}{N}}, \qquad (1)$$

where $\mathrm{SWE}_{\mathrm{obs}}$ is the observed SWE value obtained at the in-situ SD measurement location, whereas $\mathrm{SWE}_{\mathrm{est}}$ denotes the SWE value estimated in the corresponding pixel of the H13 product, and N is the total number of observations.

3. Validation Results

3.1 Validation with ground observations

The H13 validation is performed by using a routine developed in the MATLAB environment. The total number of in-situ SD observations involved in the validation is 1282, collected from 68 ground stations. The average SD value for the above-mentioned validation period is calculated as 23.51 cm, whereas the monthly averages read 22.12 cm, 24.25 cm, and 21.31 cm for January, February, and March, respectively. The minimum and maximum SD values recorded within the validation period are 2.80 cm and 95.34 cm, respectively.

The results are presented in Table 1 for the 2020-2021 snow year, and the comparison between the retrieved and observed SWE values is represented in Figure 3. Due to the high level of scattering, the mean of estimated and observed SWE values within each predefined SWE interval (cf. Table 1) is preferred and represented in Figure 3.

Table 1. The validation results for 1 January 2021 – 31 March 2021

Range (mm)	Obs. SWE (mm)	Est. SWE (mm)	Std. Dev. (mm)	Mean Error (mm)	Data Count
0-25	0.27	33.41	1.42	-33.13	656
25-50	42.50	53.89	4.98	-11.39	36
50-75	64.89	58.75	7.75	6.14	66
75-100	89.65	82.18	6.19	7.47	184
100-125	112.56	100.68	7.16	11.88	221
125-150	133.96	110.50	6.08	26.75	105
150-175	154.10	135.12	3.21	31.16	10
175-200	186.00	165.59	8.98	20.41	4

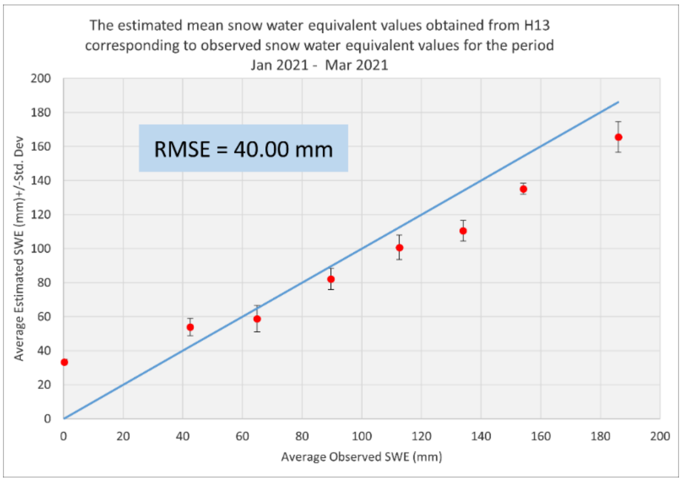

Fig. 3. The estimated mean SWE obtained from H13 (*y*-axis) with respect to the observed SWE values (*x*-axis) for the period 1 January – 31 March 2021.

The overall RMSE for 1 January – 31 March 2021 is 40.00 mm. The monthly-based RMSE values are calculated as 40.54 mm, 39.31 mm, and 38.77 mm for January, February, and March, respectively. The overall and monthly RMSE values indicate that the threshold for user requirement of 45 mm for the mountainous areas is fully satisfied, as stated in H13-PVR (2012).

3.2 A case study: Time series of a SPA station in Erzurum vs. H13 product

As a case study during this validation, the temporal evolution of snow cover between January and March 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 H13 product (cf. Figure 5).

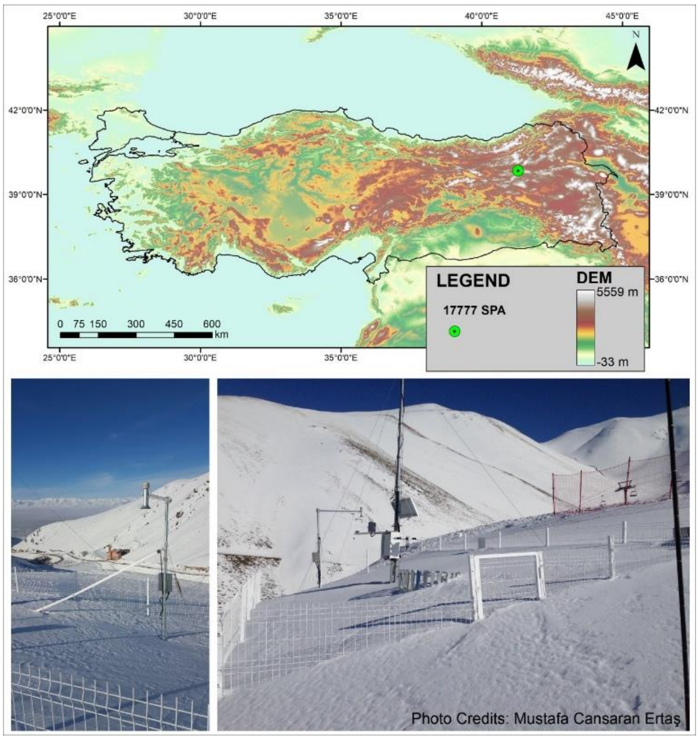

Fig. 4. The location and snapshots of the SPA station17777 (Altitude: 2615 m) at Palandöken Ski Center, Erzurum.

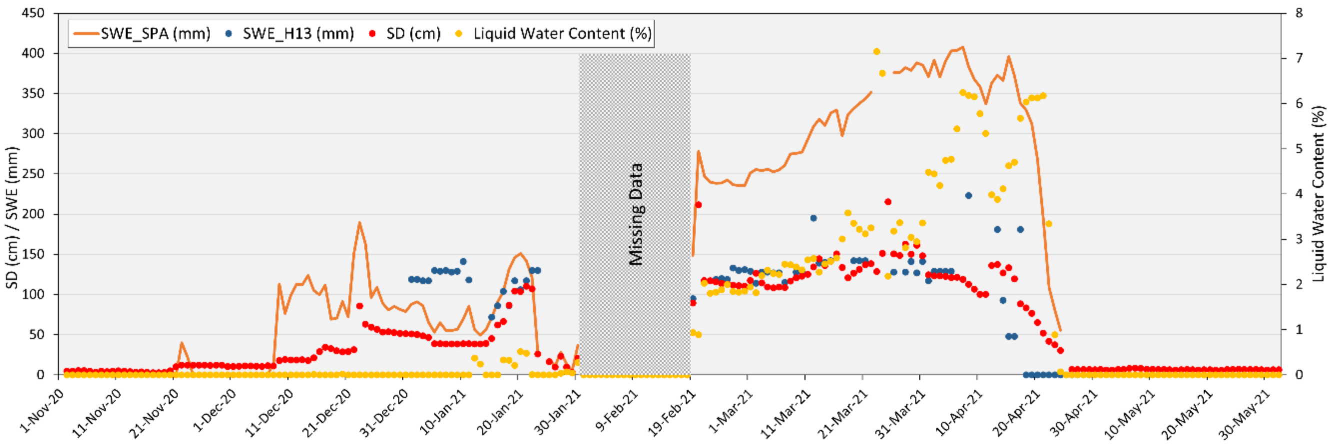

Fig. 5. SWE measurements of the SPA station 17777 versus H13 SWE values.

4. Discussion and Conclusions

The underestimation of SWE is observed when ground truth SWE is larger than 150 mm as observed in Figure 3. This is a typical behavior of the retrieval algorithm since with large values of SWE, the signal of the microwave radiometer is saturated, which has also been reported in similar studies (Pulliainen, 2006; Dong et al., 2007). The H13 SWE underestimation for March and April 2021 is also clearly seen in Figure 5. Between 1st and 19th of February, the SPA station 17777 did not work. The maximum SD at the station was measured as 215. 5 cm at the end of March 2021. Between 15 and 23 January, the agreement between the SPA SWE and H13 SWE values are good. During this period, the snow is dry and snow depth increases from 40 cm to 106 cm. The snow emission model used in the retrieval algorithm considers one-layer snowpack. Therefore, for SD values larger than 100 cm, the H13 product underestimates the SWE. The increase in the snow wetness after March 21 further contributes to this underestimation. The liquid water content of the snow retrieved from the SPA station shows that the snow is wet in April (i.e., the liquid water content of the snowpack > 3%).

It should also be noted that the ground measurements are not evenly distributed within the horizontal resolution; therefore, the whole area of individual H13 footprint is not examined. The coarse spatial resolution and the penetration characteristics of the SSM/I and SSM/IS instruments for shallow and deep snow lead under and over estimations in the SWE retrieval. On the other hand, the average RMSE value of 40.00 mm clearly indicates that the required product compliance of H13 is achieved within the validation period.

Since satellite-based data provide indirect measurements of snow-related parameters, the accuracy of snow products obtained through remote sensing needs to be quantitatively evaluated. For this reason, it is very important to comprehensively analyze the reliability of satellite snow products, to identify possible errors, and to provide the necessary input data for the studies for improving the algorithms used.

Availability of information on the quality of data obtained by remote sensing is of high importance as one of the key criteria in the selection of the most appropriate data set to be used effectively according to the final purpose. The results obtained in this validation study encourage the effective use of freely available daily H13 SWE product with high spatial coverage for hydrological and climatic applications.

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