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Piotr Struzik[*]

Institute of Meteorology and Water Management-NRI, Satellite Remote Sensing Centre,
14 P. Borowego Street, Krakow 30-215, Poland

Abstract. Snow observations from space play an important role in hydrological and climatological studies. They are especially important in remote areas with low (or none) population and sparse conventional observations at the ground. At the mid latitudes, they are needed especially for assimilation of spatially distributed data concerning snow water equivalent or snow depth derived from microwave satellite data to snowmelt models. This paper presents discussion on several problems with satellite derived snow observations focusing on the JAXA GCOM-W1 snow depth product. This product was analyzed for the period of October 1, 2012, to April 30, 2013, for an area of Poland and verified against ground observations. Benefits and disadvantages of these products were discussed in comparison to other satellite microwave products concerning snow properties. Problems with proper validation against "ground truth" were also highlighted. The possible alternative use of AMSR2 microwave data was also presented. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JRS.8.084686]

1 Introduction

The Japan Aerospace Exploration Agency (JAXA) launched a new global change observation mission-1st water (GCOM-W1) satellite on May 17, 2012, equipped with an advanced microwave scanning radiometer (AMSR2) instrument, making possible the continuation of AMSR/ADEOS-II and AMSR-E/Aqua satellite observations.[1] Among several applications of those instruments are snow observations. JAXA delivers snow depth product (SND) based on GCOM-W1 data since October 2012. Snow monitoring from space is necessary for long-term climate studies, especially in remote areas with a low density of ground observations. At mid latitudes, snowmelt processes have a large impact on the discharge into river basins. Snowmelt occurs in diurnal, intraseasonal, seasonal, and long-term cycles, also depending on latitude and altitude. This process has both positive impacts, e.g., electricity production, and negative impacts, e.g., snowmelt floods. Snow melting is an important source of water, contributing to such processes as water supply, erosion, and flooding, accounting for up to 50%–80% of the annual runoff in many catchments at the mid latitudes.[2]

Snowmelt models, initially designed for the use of ground observations, are good examples of applications which successfully assimilate both point ground observations and distributed information retrieved from satellite data. Examples of frequently used models are: Utah energy balance snow accumulation and melt model (UEB), snowmelt runoff model (SRM), energy-balance snow model (SNOBAL), and many others. Satellite products concerning snow cover, which can be used as input data, are snow extent, snow depth, snow water equivalent (SWE), and snow status (dry/wet). Other parameters also retrieved with the use of satellite data are successfully implemented such as solar radiation, long wave radiation, albedo, surface temperature, and

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*Address all correspondence to: Piotr Struzik, E-mail: piotr.struzik@imgw.pl

vegetation type. There are many papers reporting the positive results of satellite data use as inputs to snowmelt for runoff models.[3–5]

There are many factors limiting the accuracy and usefulness of snow observations. The ground network is still not dense enough, especially in areas with a scarce human population (polar areas and high mountains). Detection of snow properties from space by microwave instruments is not a trivial procedure and still has limited accuracy due to the pixel size (6–40 km depending on channel) and the features of microwave radiation emission and scattering. The sources of the main problems are land use properties (forest), water in melting snow, shallow snow cover, rain above snow, grain size model, variability of snow cover inside pixel (mountainous area), and many others.

Poland is a very interesting area for satellite snow cover product validation due to variable snow cover during winter, a relatively long snow season, and repeated snow fall/snow melt periods during winter. Rapidly melting snow is a frequent source of floods, especially in lowland areas. Such a situation is repeated several times during the period from January–April. Good knowledge of the actual snow amount available for melting is crucial for proper hydrological modeling. Due to those reasons, the possible use of the new GCOM-W1 product for monitoring snow cover evolution was analyzed, focusing on the area of Poland.

2 Analyzed Datasets

The most interesting products to be obtained from the monitoring of snow cover evolution are products representing snow extent, SWE, and/or snow depth. Analysis of the snow cover extent from satellite products has been done in many papers.[1,6–9] Such an analysis for the area of Poland, which has a typical Central European climate, is also available.[10–12] More interesting for snow monitoring is the use of microwave instruments due to their insensitivity to cloudiness, which can significantly limit VIS/IR observations of snow.

GCOM-W1 SND (snow depth) is a new product, available from autumn 2012. Among level 3 products, both SND and brightness temperatures of each channel are available from the JAXA server, covering the whole globe with 0.1 deg and 0.25 deg resolutions in two projections: equidistant and polar stereographic (N and S). JAXA decided to distribute the snow depth product instead of the SWE, previously available from AMSR-E/Aqua (clarified by a larger amount of such measurements important for validation). This decision allowed for the exclusion of the snow grain/density estimation required for conversion from SND to SWE, which is an important source of errors.

The initial method applied to AMSR-E data uses the following relations:[13]

$$SD = Rc * (Tb19 - Tb37) \quad SWE = Rc' * (Tb19 - Tb37),$$

where SD-snow depth coefficients: $Rc = 1.6$ cm/K and $Rc' = 4.8$ mm/K were static in both space and time, assuming a fixed snow density and grain radius. Brightness temperatures Tb19 (18.6 GHz) and Tb37 (36.5 GHz) were named according to AMSR-E convention.[13] Modification for the forest cover was added later with several tests for snow possibility, shallow snow, and melting snow presence.

The forest (SDf) and nonforest (SDo) components of the snow depth are computed as follows:

$$SDf[cm] = polfact\,36 * (Tb18V - Tb36V)/(1 - fd * 0.6)$$

$$SDo[cm] = [polfact\,36 * (Tb10V - Tb36V)] + [polfact\,18 * (Tb10v - Tb18V)]$$

with $polfact\,36 = 1/\log 10(pol\,36)$ and $polfact\,18 = 1/\log 10(pol\,18)$, $pol\,36 = Tb36V - Tb36H$, $pol\,18 = Tb18V - Tb18H$, $fd = $ forest density (g cm-3). Brightness temperatures: Tb10V (10.65 GHz, vertical polarization), Tb18V (18.6 GHz, vertical polarization), and Tb37V (36.5 GHz, vertical polarization), named here according to AMSR-2 JAXA convention.[14] To convert SD to SWE, a density map in the EASE-grid projection was produced by mapping the mean January through March density measurements from the datasets of Brown and Braaten[15,] and Krenke[16] to the Sturm et al.[17] seasonal snow classification map. The same method was applied to AMSR2/GCOM-W1 data to produce snow depth retrievals.[14,18–20]

Observations performed regularly at the Polish Synop stations, covering the period from October 1, 2012, to April 30, 2013, were used for the evaluation of GCOM-W1 SND product usefulness. Stations located close to the Baltic seashore were excluded from comparison to avoid problems with relatively large AMSR2 pixels covering partial sea and land areas at the seashore. Finally, approximately 60 stations remained for validation studies (depending on the day). The GCOM-W1 SND product was also compared to other SWE products, Globsnow SWE[21] and EUMETSAT H-SAF H-13 SWE.[22]

3 Results

At first, eyeball verification of snow properties retrieved from microwave satellite data was done. Examples of Globsnow SWE, H-SAF H-13 SWE, and GCOM-W1 SND (ascending and descending pass) are presented in Fig. 1. The main outcome from a visual analysis performed for the whole winter of 2012/2013 is:

- GCOM-W1 has a better spatial representation of snow cover, compared to GlobSnow SWE and H-SAF H-13 SWE. The last two products have artificial structures and extremely high values during the snowmelt period in the springtime.[23]
- the descending pass (0:30–1:30 UTC) is better than the ascending pass (12:00–13:00 UTC)–higher temperatures and more frequent wet snow in the daytime contribute to this difference,
- problems at the melting periods–water presence significantly decrease SND values,
- the lack of shallow snow cover detection–minimal depth is 5 cm.
- differences in geographical navigation between ascending and descending passes of level 3 products.

Analysis of correlation between the snow depth measured at the ground and retrieved from GCOM-W1 data was performed. Due to a high variability between individual Synop stations,
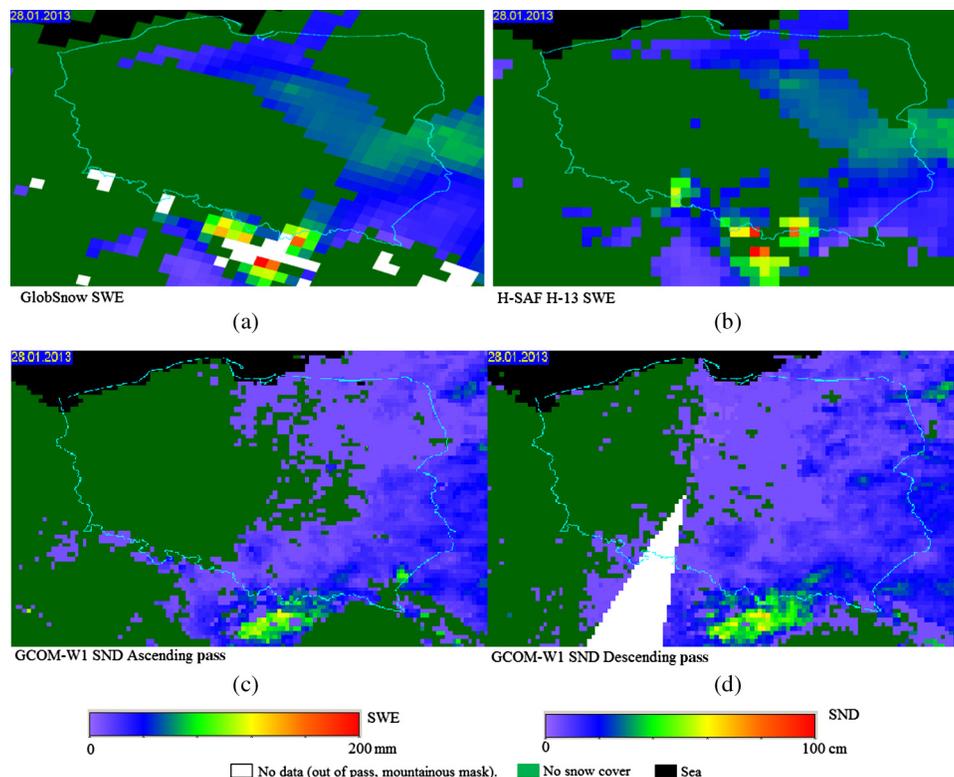

Fig. 1 Comparison of satellite products concerning SWE and snow depth—example on January 28, 2013. (a) GlobSnow SWE, (b) H-SAF H13 SWE, (c) GCOM-W1 SND ascending pass, and (d) GCOM-W1 SND descending pass.
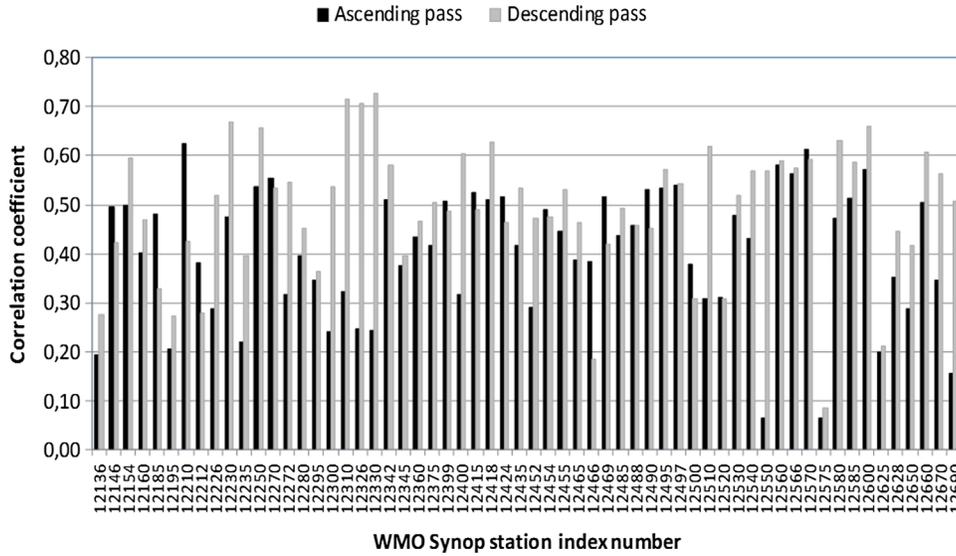
Fig. 2 Comparison of snow depth measured at the ground and retrieved from GCOM-W1 data—correlation coefficient calculated for individual Synop station.

this analysis was done separately for each station. For final presentation of results, three stations (12336 Powidz, 12385 Siedlce, and 12595 Zamość) were excluded due to a long series of snow depth SSS with a code −1000, which could be either a lack of snow or a lack of observation.

The JAXA GCOM-W1 snow depth product compared to individual Synop stations shoed better agreement between satellite and ground observations at the night (the descending pass). The average correlation coefficient for ascending passes is 0.35 and for descending passes is 0.49, but at several points, it reaches a value of 0.6–0.73 (Fig. 2).

Generally, correlation is much better than for the other two SWE satellite products that were mentioned. The problem with places with low correlation may be also connected to different factors that are not representative measurements for larger areas, such as location of Synop station (to close to the cities), high vegetation (forest), and complicated orography.

The root-mean-squared errors (RMSE) were also calculated for each station (Fig. 3). A RMSE value equal to 5–13 cm can be observed for most of the stations. The mountainous stations have a much larger difference—their RMSE is in range of 80–150 cm. Some exceptions from this behavior were noticed for a few stations.
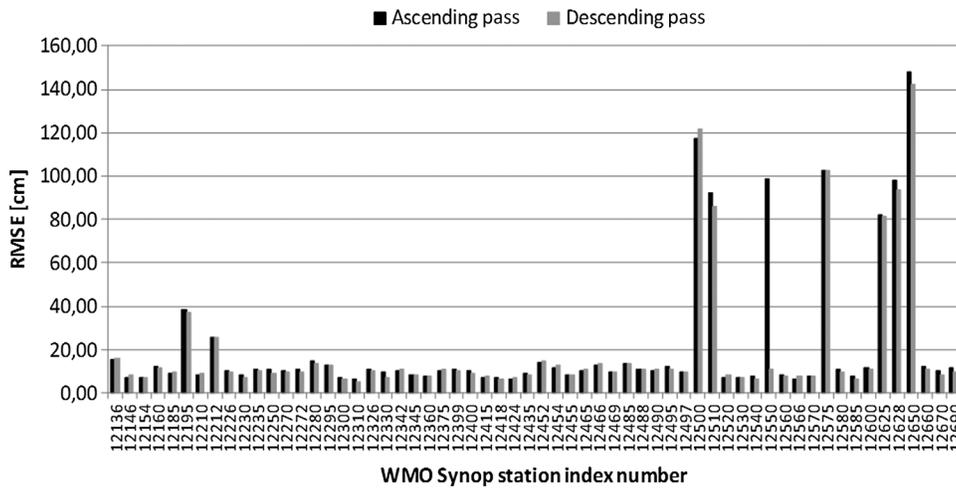

Fig. 3 Comparison of snow depth measured at the ground and retrieved from GCOM-W1 data—RMSE [cm] for individual Synop stations.
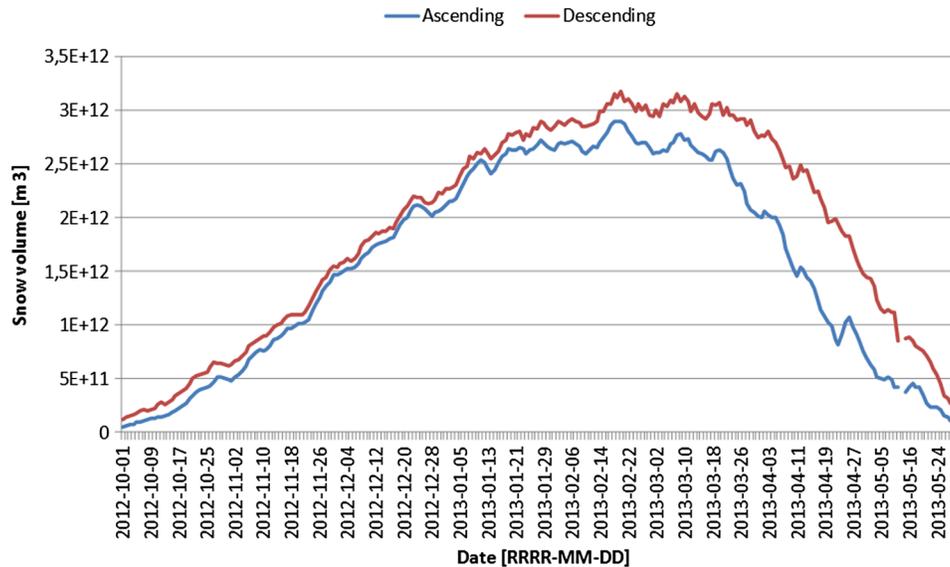
Fig. 4 Snow volume calculated from GCOM-W1 snow depth product, for the part of Northern Hemisphere (20 deg–85 deg N, 0 deg–360 deg E).

The difference between ascending and descending passes is one of the factors limiting the use of the SND product. This problem appeared at the beginning, after launch of the Aqua satellite with the AMSR-E instrument. Previous satellites with microwave sensors, (e.g., SSM/I–Special Sensor Microwave Imager), have ascending and descending passes in the morning and evening time when the snow cover has similar temperatures. Aqua and now GCOM-W1 have an ascending pass during the early afternoon hours and a descending pass at night. This leads to different temperatures following the diurnal cycle. These interesting features of the SND product were analyzed for larger areas, not only for Poland. The volume of snow cover was calculated using daily SND products for the majority of the Northern Hemisphere: 20 deg–85 deg N, 0 deg–360 deg E (Fig. 4). During snow accumulation, differences between the volume determined from ascending and descending passes are relatively small. During depletion of snow cover, differences are significantly larger, up to 100% during intensive snow melting periods.

Examples of those differences are presented in Fig. 5 for a selected spring day (31 March 2013) for the area of Europe and Asia (20–85 N, 0–180 E). Significant differences do not only concern shallow snow cover (blue-violet colors), but also snow with depths close to 1 m (orange to red colors). The same behavior was found in the Southern Hemisphere during winter 2013. In South America, more snow is detected by descending passes than ascending ones, similarly to the Northern Hemisphere. Such a situation leads to the exclusion of potential reasons of this difference because of sun position, slope aspect, or the presence of not melted snow in shadowed areas. Only temperature and/or more probably the presence of liquid water could be the reason for such dramatic differences. At clear sky conditions, snow cover may contain liquid water at the surface, even at air temperatures below 0°C. Water droplets due to much lower emissivity lead to a significant reduction of the brightness temperature in comparison to ice crystals.

Among the GCOM-W1 satellite products, available from JAXA, brightness temperatures from all channels of the AMSR2 instrument are also calibrated and navigated. They are interesting sources of information for individual experiments. An interesting feature concerns melting snow detection. The temperature difference between channels of the same frequency, but with vertical and horizontal polarizations, is usually used for rainfall detection and rainfall intensity estimation. Melting snow is also a source of significant difference for those two temperatures. It is especially well expressed at low-frequency channels (10 and 18 GHz), but also exists at the higher frequencies. Channel 18 GHz is a good compromise between spatial resolution and sensitivity to snow melting conditions.

Figure 6 presents the snow depth measured at the Koło Synop station (WMO station index 12345) and the related Tb18V-Tb18H difference. Intensive snow melting conditions are marked
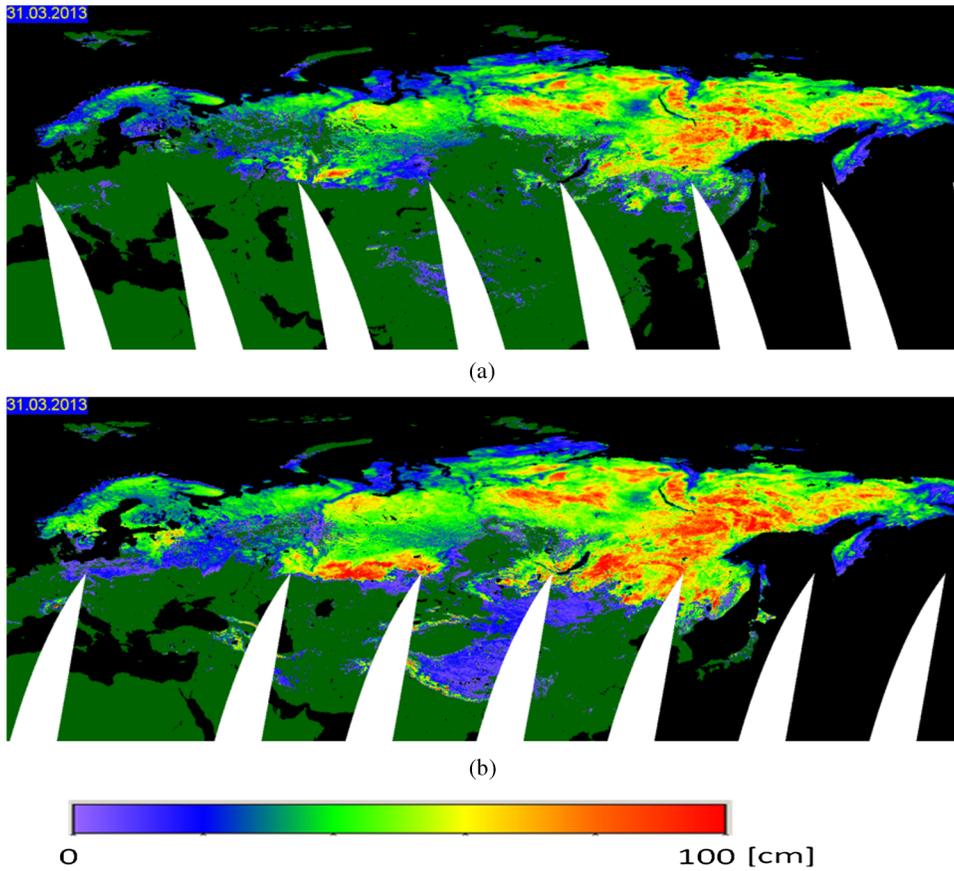
Fig. 5 Comparison of GCOM-W1 snow depth for the area of Euro-Asia on the same day: (a) ascending passes above and (b) descending passes below.

by red boxes. They correlate well with the peaks of the Tb18V–Tb18H difference. The spatial distribution of this parameter over the area of Poland is presented in Fig. 7. High values of Tb18V–Tb18H are well correlated with areas of intensive snow melting, resulting in flooding in East and Central Poland. Usually, higher values are observed during the ascending pass (daytime), and then during the descending pass (night), due to more intensive melting at higher temperatures.
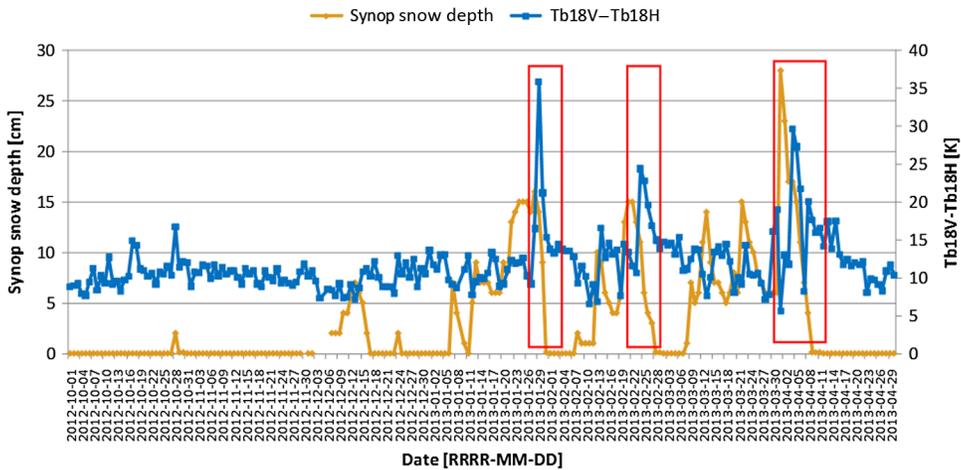

Fig. 6 Melting snow detection (red boxes indicate snow melt periods)—depletion of snow cover connected with significant peaks of Tb18V–Tb18H temperature difference. Presented example concerns Koło Synop station (WMO index number 12345).
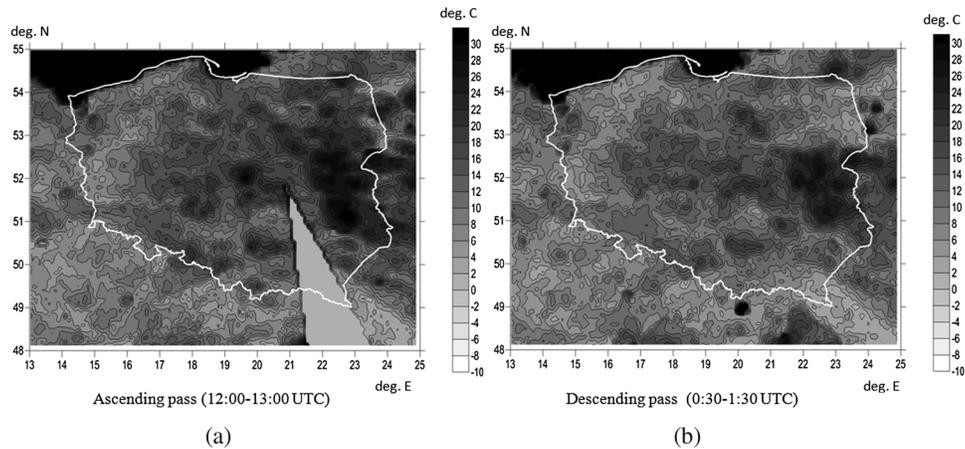
Fig. 7 Spatial distribution of Tb18V–Tb18H difference for the area of Poland on April 10, 2013. High values in the eastern and central part of Poland are well related to intensive snow melting connected with flood in this region, (a) ascending pass and (b) descending pass.

Interpretation of such signatures must be carefully done, because similar signatures are caused by presence of: rainfall, wet snow and wet soil at the surface layer. From the second hand, all mentioned phenomena are a source of runoff from the catchments, especially in coincidence. Use of this feature for better estimation of the water amount stored in melting snow, combining observations Tb18V-Tb36V and Tb18V-Tb18H, is suggested for consideration. Of course, more calibration studies are required to obtain a useful product for operational hydrology.

4 Conclusions

There is still lack of satellite product which can satisfy hydrological expectations concerning snow water monitoring in the temperate zone (e.g., Central Europe). Snow water equivalent is a crucial parameter for proper runoff modeling and warning of snow melt conditions. Interesting results were found in the GCOM-W1 snow depth product validated for the area of Poland. Unfortunately, JAXA decided to generate he snow depth product instead of the snow water equivalent, justifying it as a batter use of such observations, and, as a consequence, making it less attractive to the hydrological community. Snow properties' estimation by passive microwave instruments is most difficult for melting snow conditions, which are of high importance for hydrologists. Differences between the snow depth at night and daytime, especially during periods of snow depletion, are observed. More investigations on that problem are still required. The shallow snow cover is also a challenge for satellite passive microwave observations. A large problem exists with representative ground measurements for validation of an microwaves observation with a pixel size of 10–30 km. Ground stations are frequently located in or close to the cities, where snow cover melts more quickly.

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Piotr Struzik works at the Satellite Remote Sensing Centre of the Polish Institute of Meteorology and Water Management-NRI. He received his PhD degree in environmental engineering in 1997. He is an author of more than 70 papers on remote sensing applications. His research concern is on various RS applications, mainly oriented to meteorology and hydrology.