Calibration/validation of satellite derived snow products with *in situ* data over the mountainous eastern part of Turkey

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Abstract This paper presents the critical issues for the comparison of the parameters that optical remote sensing can deliver (snow-covered area and albedo as MODIS products) with snow survey and lately established automated weather observation stations (AWOS). The use of Earth Observation (EO) satellite images and products in hydrological applications for mountainous terrain, where the scarcity of ground data is the main problem, is discussed. The snowmelt runoff hydrograph shape is affected by the elevation bias of the MODIS snow-mapping algorithms, and underestimates the area at lower altitudes and overestimates the area in the higher elevation regions. It is an aim to overcome this difficultly in further studies by determining the fractional snow-covered area using multi-sensor data (SEVIRI, NOAA, MODIS as optical, and AMSR-E, SSM/I as microwave), which will be the basic task for future studies in Satellite Application Facilities on Hydrology (H-SAF) project, which is financially supported by EUMETSAT. Turkey is a part of the H-SAF project, both in cal/val of satellite-derived snow products with ground observations and cal/val studies with hydrological modelling in the mountainous terrain of Europe. In this paper, the early findings of the H-SAF project regarding the products for mountainous regions are evaluated.

Key words albedo; ground observations; H-SAF; snow covered area; snow mapping

INTRODUCTION

Hydrological processes and climate in mountainous areas are highly affected by the seasonal snow cover. Essential characteristics, both for hydrology and climatology, include snow cover, snow depth (SD) and snow water equivalent (SWE). The maximum SWE prior to the onset of spring snowmelt is typically the most important snow characteristic for operational runoff and river discharge forecasts. The concentration of discharge mainly from snowmelt during the spring and early summer months, causes not only extensive flooding, inundating large areas, but also the loss of much needed water required for irrigation and power generation purposes during the summer season. Accordingly, modelling of snow-covered area in the mountainous regions of Eastern Turkey, being one of the major headwaters of the Euphrates–Tigris basin, has significant importance in forecasting snowmelt discharge, especially for energy production, flood control, irrigation and reservoir operation optimization.

However, the accuracy of SD and SWE information is currently limited as the level of SD and SWE can only be assessed by interpolating observations, typically sparse, both spatially and temporally, from gauging networks and snow courses. The observations are more difficult for mountainous regions compared to flat areas. Besides knowing the importance of snow as water resources for Turkey, there is not yet a well established operational snow monitoring system in the country. Therefore comparison of satellite derived snow maps and snow course ground measurements are vital for improvement of the existing mapping algorithms.

Distributed snow models require the following spatially-distributed parameters: snow-covered area, grain size, albedo, snow water equivalent, snow temperature profile and meteorological conditions, including radiation. This paper presents the critical issues for the comparison of the parameters that optical remote sensing can deliver (snow-covered area and albedo as MODIS products) with snow course and lately established automated weather observation stations (AWOS). It also presents the structure of the EUMETSAT Satellite Application Facilities in support of the operational hydrology project, which aims to develop automated snow product generation algorithms from Earth Observing (EO) satellite images.

METHODOLOGY AND DATA

Earth Observation (EO) satellites have been used in retrieving information related to snow. Monitoring the snow covered area and snow related parameters through the satellite images need a good temporal resolution. Although the spatial resolution provided by these kind of satellites lead to over/underestimation of the snow parameters, the daily availability, easy access and the low cost make these satellite data a fundamental source of information for operational monitoring of snow covered area, snow depth and snow water equivalent. Advanced Very High Resolution Radiometer (AVHRR) and MODerate-resolution Imaging Spectroradiometer (MODIS) sensors are the well known sources for snow mapping. Relative to similar sensors, such as the AVHRR that has been operational for many years on the NOAA Polar Operational Environmental Satellite System (POESS), the MODIS sensor offers some significant advantages. The MODIS instrument is a multispectral instrument with 36 bands and nominal spatial resolution of 250 m in two bands, 500 m in five bands, and 1 km in 29 bands. An algorithm has been developed to map snow cover at 500 m spatial resolution using MODIS observations by Hall *et al*. (2002). The 500 m spatial resolution results from using MODIS bands with demonstrated capability for detecting snow and separating snow from clouds. In the context of this study, the MODIS provides observations at a nominal spatial resolution of 500-m, *versus* the 1.1-km spatial resolution of the AVHRR, and the continuously available (spatially and temporally), spectral band observations that span the visible and short-wave infrared wavelengths are useful for distinguishing the extent of snow cover.

The AVHRR bands 3 (3.55–3.93 μm) and 4 (10.30–11.30 μm) are effectively the snow/cloud discrimination channels, while band 1 (0.58–0.68 μm) facilitates the definition of the snow pack boundary due to the high contrast between snow-covered and snow free surfaces in this waveband. Clouds consisting of ice particles and large water droplets show considerable absorption in the 3.55–3.93 μm wavelengths (band 3) and, with ice clouds in particular, low thermal emission. Clouds containing smaller ice and water particles introduce higher intensity values into channel 3 and show some overlap with the spectral response of snow. Taking advantage of the fact that snow reflectance is high in the visible (0.5–0.7 μm) wavelengths and has low reflectance in the shortwave infrared (1–4 μm) wavelengths to enable distinguishing snow from clouds and other non-snow-covered conditions, Hall et al. (2002) and Klein *et al.* (1998) have used the normalized difference snow index (NDSI) to develop an automated approach to providing daily, global observations of snow cover. The NDSI is defined as the difference of reflectance observed in a visible band, such as MODIS band 4 (0.555 μm) and a short-wave infrared band such as MODIS band 6 (1.640 μm) divided by the sum of the two reflectance values.

Description of study area

Several studies have been performed in the study area called Karasu basin, which is located in eastern Turkey and the headwater of the Euphrates River (Fig. 1). The basin has a drainage area of 10 216 km^2 controlled by the stream gauging station with an elevation ranging from 1125 m to 3487 m. The topographic map of the basin (DEM) and the area around the basin is shown in Fig. 2. The snow course measurements made by the Government Agencies are also presented in Fig. 2(a), the location of the AWOS stations established by the project team (authors) in the basin is shown in Fig. 2(b). All of the data collected during the project period were used to validate spatial and temporal variability of MODIS and AVHRR snow products.

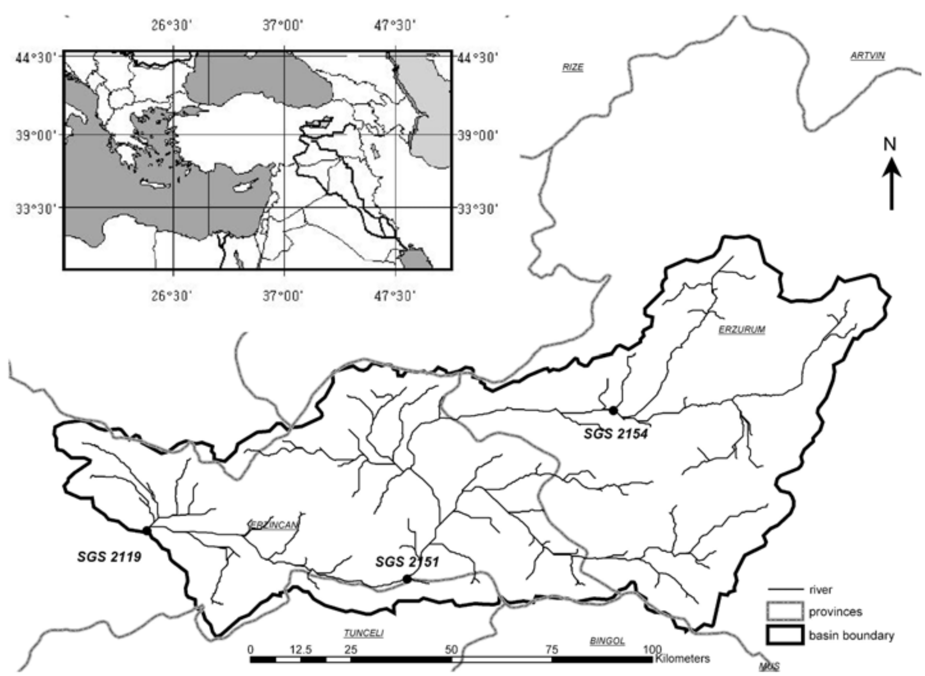

Fig. 1 Location of Karasu Basin (upper Euphrates River) in Turkey and the location of stream gauges in the basin.

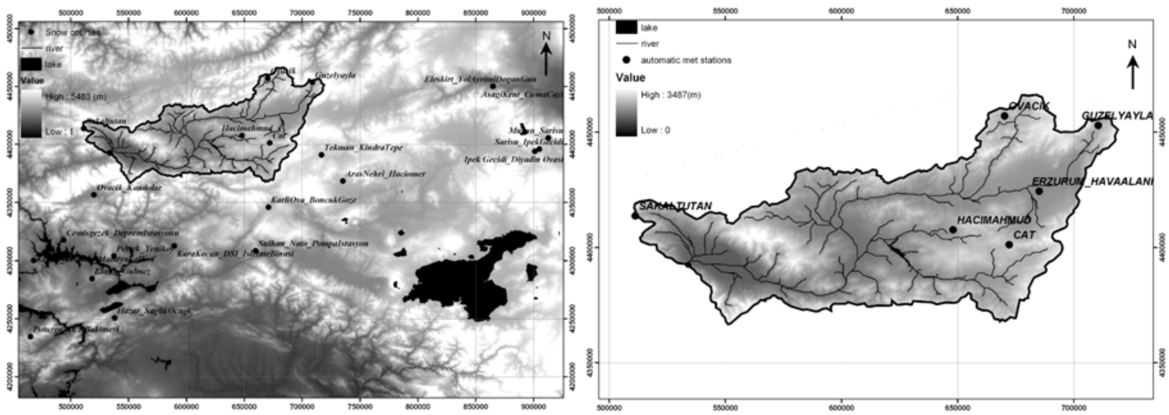

Fig. 2 (a) Location of the snow courses on DEM of Turkey. (b) Location of automatic stations on DEM of Karasu Basin.

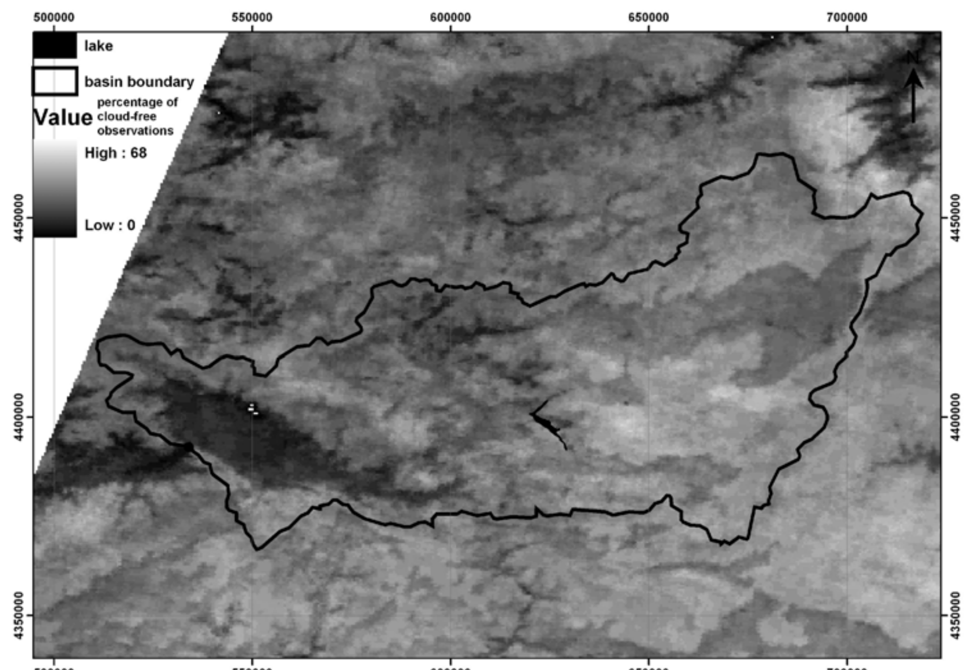

Fig. 3 Percentage of cloud-free observations mapped as snow on a per grid cell basis by MODIS over the winter 2002–2003.

ANALYSIS

The observations of two data sets from the ground data were compared with all MODIS pixels (500 × 500 m each) falling within a radius of 1500 m of the individual site location by Tekeli *et al.* (2005). The 50% or more of all cloud-free cells within this radius were classified as snow-covered pixels by MODIS satellite. Cloud cover frequency during winter months in Turkey was noticed to be high during data analysis; therefore the images acquired a couple of days (1 or 2 days) before and after the ground measured data were also preprocessed if the cell was noticed as cloud obscured on the same date as ground truth. The percentage of cloud-free observations mapped as snow on a per grid cell basis by MODIS over the winter 2002–2003 was obtained in order to see the effect of cloud cover in snow mapping by using optic bands of the EO satellites (Fig. 3).

Akyurek & Sorman (2002) derived the daily snow cover depletion data from NOAA–AVHRR images for the ablation period in 1998. In this study, the effects of topographic parameters (elevation, aspect, and slope) and meteorological variables (prevailing wind direction, temperature) in deriving the snow depletion curves, being one of the main inputs into hydrological models for computing snowmelt runoff, were analysed. For semi cloudy/cloudy days, especially if the effects of these parameters are considered in determining the snow covered areas, the snowmelt runoff predicted from the models can be improved. Also in that study the effect of solar illumination and shadowing on snowmelt was analysed and an additional effect of prevailing wind direction on sweeping and deposition of snow rather than melting on northeast slopes were observed.

Tekeli *et al.* (2006) computed MODIS daily snow albedo values based on the prototype algorithm given in Klein *et al*. (2000) and Klein & Stroeve (2002). The prototype is similar to the algorithm used to produce the current beta test product (Klein, 2003). Based on the data gathered from the AWSs and the 19 portable albedometer observations, comparisons of MODIS daily snow albedo with these ground observations were performed. Since the snow albedo is dependent on various factors, such as SWE, grain size and surface impurities of the snow pack, which itself is a heterogeneous medium, point values were compared with MODIS pixel values rather than performing any kind of averaging methodology with neighbour pixels.

DISCUSSION

Based on the studies performed in the study area, the comparison of satellite-derived snow products with *in situ* data over the mountainous eastern part of Turkey can be discussed in the following three sections.

Comparison of snow maps with ground observations

For the validation of the MODIS products, comparisons were made at automated stations and snow courses. Some errors are expected due to land cover types, topographical variability, climatological reasons and the inherent problems faced in the cloud mask used in snow mapping algorithms. The snow cover map obtained for the snow course dates through MODIS images were compared for winter 2002–2003 for validation purposes with respect to elevation zones (>1900 m). On the other hand, Table 1 shows that the percentages increase from 62.24 to 81.63 as one or two days ahead or after images of the date with ground data were searched. This can be a partial solution to the cloud obscure problems associated with the use of optic sensors. Otherwise multi-sensor multi-temporal snow-covered area algorithms and microwave

Table 1 Summary of analyses of MODIS images for winter 2002–2003.

MODIS date	Sample site status: Snow	Undetermined clouds	Matched (%)
Day of ground observation	61	37	62
One day shift from day of ground observation	70	28	71
Two day shift from day of ground observation	80	18	81

images such as AMSR-E and SSM/I would be alternatives for eliminating the cloud obscuring problems.

When the contingency table is prepared and analysed, it is noted that the omission errors (there is snow but missed by the MODIS product) are mostly captured but not commissions errors (no snow on the ground and MODIS product is noticing snow). This observation is true when the cells are fully snow covered (not patchy) and time of observation will also match, otherwise the time shift may cause the optical data to underestimate snow cover during the melting stage of the early spring months. The SCA algorithm used for MODIS also affects the under and overestimation of snow cover area. Since it does not take into account the topography of the scene, from slopes away from the sun, the reflected radiation received at the satellite will be lower than from horizontal areas and slopes facing towards the sun. This effect is most visible in winter. With low sun there will also be larger shadows in mountainous areas. This may result in estimation of no snow in shadowed areas, even if the real snow cover is 100%. The edges of the snow covered areas and land surfaces may be mapped as cloud with the current version of the algorithm. The patchiness and shallow snow depth may be the other major reason of lower accuracies in the comparison. As a result it is concluded that MODIS snow map algorithm correctly captures the snow presence on the ground surface if the image is free from clouds or clear-sky conditions exist.

Comparison of MODIS daily snow albedo

In general, the MODIS daily snow albedo was found consistent both in magnitude and temporally with on-site measurements made in Karasu basin. Generally, MODIS overestimated snow albedo by 10% over field observations during the study period. The time difference between MODIS and *in situ* data acquisition, and the reducing effect of air temperature on snow albedo, are considered to be the main reasons for the overestimation. At higher elevations, better agreement was found between MODIS snow albedo and ground observations. This might be because, at the higher elevations, air temperature is lower and, therefore, there may be no localized melting effects on the snow pack to reduce the snow albedo. In addition, more continuous snow cover (relatively less patchy snow) at higher altitudes may be another effect that favoured the better agreement. Overall, the temporal trends obtained from MODIS during the ablation period were in agreement with ground based observations obtained from both Guzelyayla and Ovacık AWSs. The findings in Tekeli *et al.* (2006) indicate that the MODIS daily snow albedo algorithm gives reasonable results for the area under study.

Discussion on hydrological model application

The impact of the snow products derived from satellite images can be observed either by comparing with the ground observations or using them in a hydrological model to estimate runoff. Tekeli *et al.* (2005) used MODIS 8-day snow cover products to minimize the cloud cover and to maximize the cover extent. So MODIS 8-day products (MOD10 A1) were used to derive the snow depletion curves for the topographic elevation zones for model simulation runs. The reason for using MODIS 8-day snow cover maps for this study was the fact that there were no ground observations that might have increased the accuracy of the daily images. The snowmelt runoff hydrograph shape is affected by the elevation bias of the MODIS snow-mapping algorithms, underestimating the area at lower altitudes and over estimate the area at higher-elevation regions.

Use of either daily or 8-day maps may lead to a further study, which would be the sensitivity analysis of MODIS maps on model runoff simulation studies. Also it would give a good idea about the timing and number of images to be used in an optimum manner. Akyurek & Sorman (2002) estimated the snow-covered area by semi-supervised classification of NOAA-AVHRR data in order to obtain the snow depletion curves as an input parameter for a snow runoff model. They also discussed the effect of aspect and slope on the snow depletion curves for different elevation zones. It is well known that solar illumination and shadowing have a great effect on snowmelt, creating a north–south direction difference. They observed that at elevations of 1900–2300 m, snow on the northwest slopes melted earlier, compared to southeast slopes, due to the steep slopes and prevailing wind direction. This result shows that besides the elevation and land use, which are stated as the main factors that may influence the MODIS classification accuracy, aspect, slope and prevailing wind direction and speed may also have an indirect effect on the classification accuracy. From the previous studies it is clear that snow depletion curves from snow-covered area can be obtained from both MODIS and AVHRR snow products (Fig. 4(a) and (b)).

EUMETSAT H-SAF PROJECT

Current use of satellite data in hydrology is limited to research applications, often to test or validate model performances. Examples of data that have been looked at with interest are: snow cover and water equivalent—direct observation (cover) or model-aided estimates (water equivalent) from VIS/IR and MW imagery from low-orbiting meteorological satellites (coarse resolution), or R&D or commercially-oriented satellites equipped with high-resolution imagers in the optical range or by active MW (SAR).

It may be observed that a large amount of information is based on data available from the backbone satellite-based Global Observing System (GOS) for operational meteorology (Meteosat, NOAA, etc.) and from other meteorological systems not part of GOS, but also operationally available (e.g. DMSP). However, a number of applications, generally those at small-catchment scale, are based on data from satellites of either an R&D nature (e.g. carrying SAR) or organized on a commercial basis (e.g. Landsat, SPOT, etc.) (EUMETSAT, 2005).

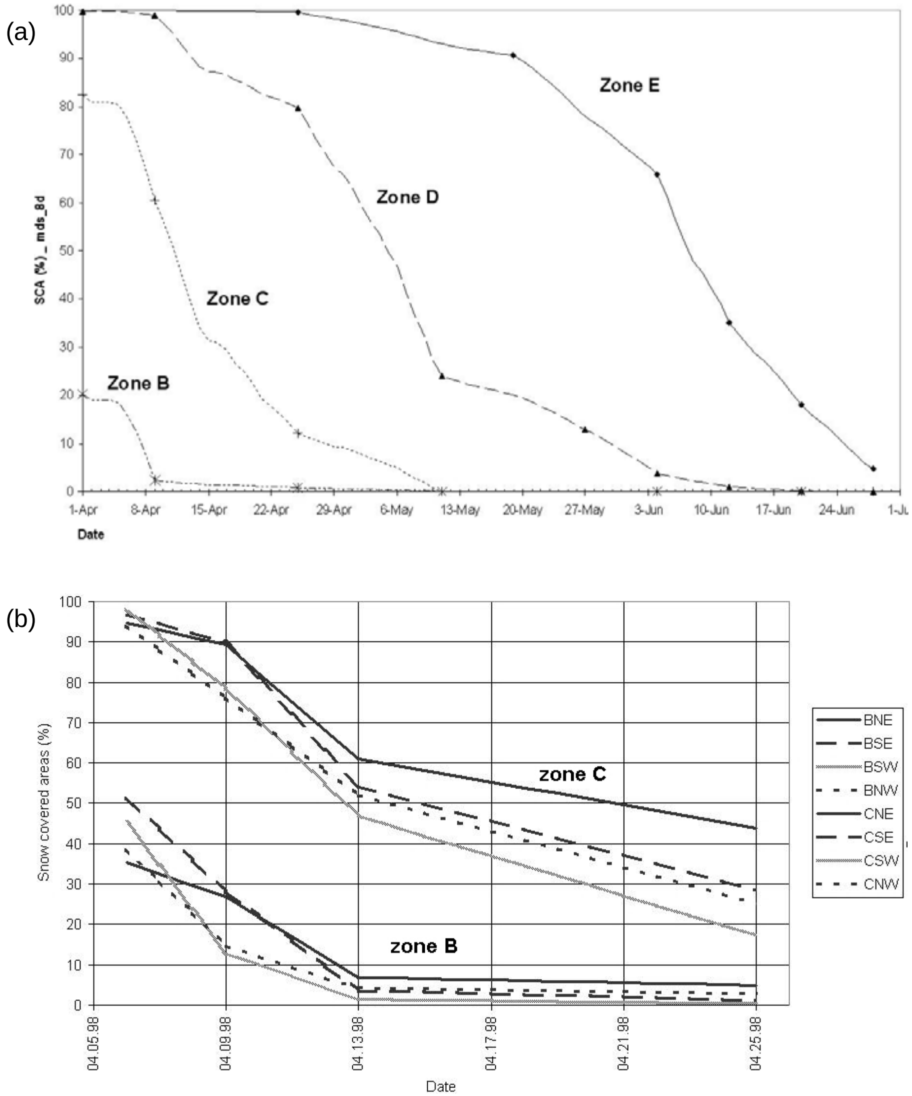

Fig. 4 Snow depletion curves obtained from MODIS (a) and AVHRR (b) snow products.

Moving from these considerations, it is believed possible to change these applications from the current experimental/scientific level to a pre-operational and possibly operational level. In fact, scanning through the alternative ground-based observing techniques, it has been easy to recognize the in-principle superior performances of space-based platforms in terms of horizontal and time sampling, and regularity of service. It has been recognized that current and soon-to-come satellites can already provide interesting data, and more will provide more in the near future. In addition, as compared to the relatively steady state-of-the-art of ground-based measuring systems, satellites have the greatest growth potential in the long term, since the physical principles available for remote sensing and the technological state-of-the-art are far from being fully exploited. The European Organization for the Exploitation of

Table 2 Satellite snow products and satellite data sources planned to be used in H-SAF.

Product	Anticipated operational product quality				Satellites / Sensors	
	Resolution	Accuracy	Cycle	Delay	Development	Operational
Snow recognition	5 km (MW) 2 km (VIS-SWIR-TIR)	95% probability of correct classification	6 hour depending on latitude	2 hour	NOAA (AVHRR) + MetOp (AVHRR, ASCAT) + Meteosat (SEVIRI) + EOS-Terra/Aqua (MODIS) + DMSP (SSM/I, SSMIS)	MetOp (AVHRR, ASCAT) + Meteosat (SEVIRI) + NPOESS (VIIRS,CMIS) + MW radiometers of the GPM constellation
Effective coverage	10 km (MW) 5 km (VIS-SWIR-TIR)	15% Depending on basin size	6 hour depending on latitude	2 hour		
Snow status wet or dry	5 km	80% probability of correct classification	6 hour depending on latitude	2 hour		
Snow water equivalent	10 km	~ 20 mm	6 hour depending on latitude	2 hour		

Meteorological Satellites (EUMETSAT) proposed a new satellite application facility in support of operational hydrology and water management (H-SAF). The satellite snow products and satellite data sources planned to be used in H-SAF are presented in Table 2.

Defining mountainous areas

Since Turkey takes part in developing the algorithms for snow products retrieval from satellite images for mountainous areas, the mountainous areas were obtained as a mask. In finding the mountain mask, GTOPO30 DEM, obtained from Eurostat/-GISCO, was used as altitude data and the slope map was derived from it. The area of interest is Europe between 25º N to 75ºN and 10ºW to 45ºE. The mesh grid with 0.0833 degrees interval is generated for the whole area. Since The H-SAF snow products will be generated at 5 and 10 km spatial resolution, a 0.0833º (~9 km) interval is considered to be a suitable interval due to storage and processing limitations. The mean, standard deviation, range, minimum and maximum elevation for each grid was calculated. The roughness of the terrain is also a critical factor in many respects. Therefore the mean, standard deviation, range, minimum and maximum slope for each grid were calculated. The mountain mask is given in Fig. 5.

Snow recognition

In 2002, the first Meteosat Second Generation satellite (MSG-1) was launched by the EUMETSAT. This satellite, now known as Meteosat-8, carries the Spinning Enhanced Visible and Infrared Imager (SEVIRI), which is the first geostationary instrument that measures at all bandwidths that are of use for snow mapping. Meteosat-8 is currently situated at 3.4º western longitude at an altitude of 36 000 km. SEVIRI continuously monitors the entire Earth disk at a frequency of 15 minutes and has 12 spectral channels. The Meteosat-8 data that was used in this study are in Level 1.5 Native

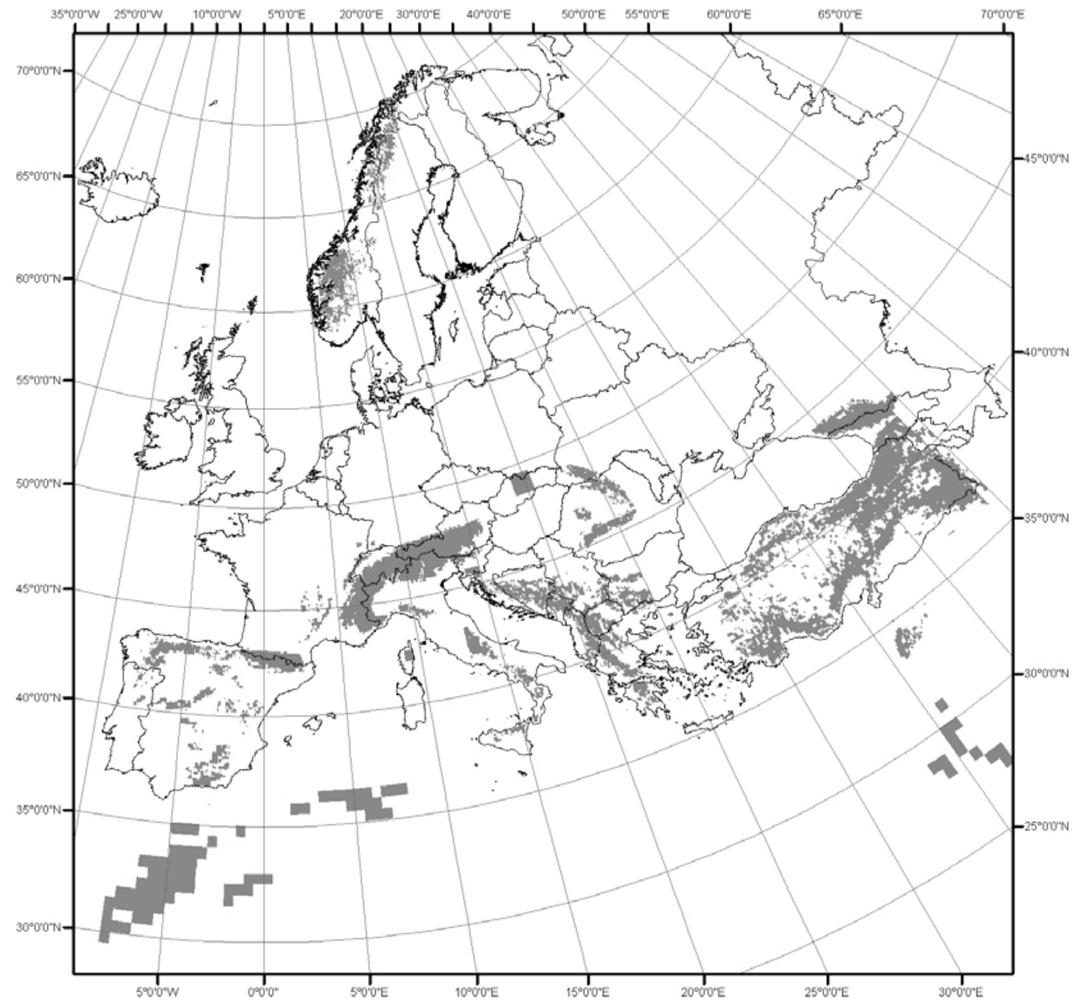

Fig. 5 Mountain mask represented (Mean Altitude ≥2000 m or Mean Altitude ≥700 m and STD Slope ≥2).

Format. These consist of raw satellite counts, which need to be calibrated and converted into reflectances (r) and brightness temperatures (BT). The raw satellite data for 2006 were obtained from the Turkish State Meteorological Service. For extraction, calibration and geo-location of the data, the algorithms in the SEVIRI Preprocessing toolbox were used. In the 13 March 2006 image, the starting scan time of 08:00 h is presented as a sample calibrated image in RGB composite (Fig. 6(a)). In this composite, the bare ground is separated from snow and cloud in 0.64 μm, many clouds are separated from snow in 1.6 μm channel and the difference in BT3.9 and BT10.8 help to distinguish cirrus clouds. During daytime, channel IR3.9 receives energy both from emitted thermal radiation and from reflected solar radiation, therefore the reflectance for BT3.9 is also corrected considering the thermal component of the radiance in this channel. The snow covered area can be detected with this composite**.** The algorithms are being developed to retrieve snow products from the satellite

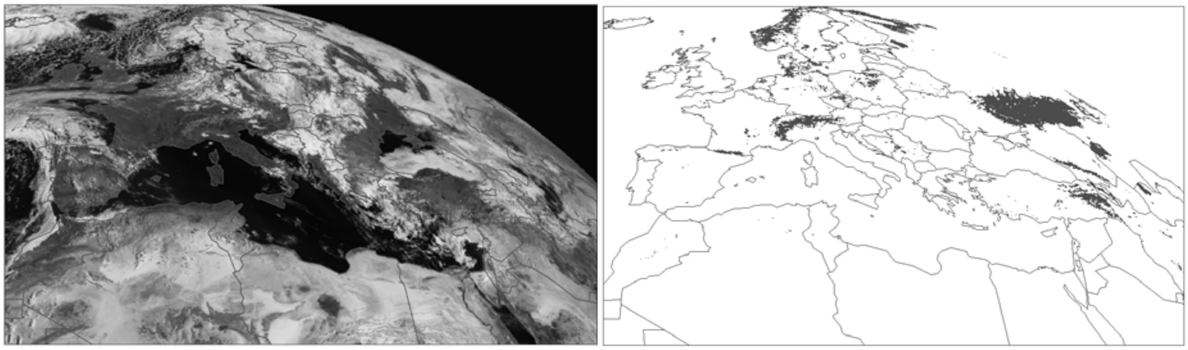

Fig. 6 RGB composite of: (a) Meteosat SEVIRI (4 April 2006) image (0.64 μm (R), 1.6 μm (G), (3.9 μm–10.8 μm) (B)), and (b) Snow cover from MSG-SEVIRI 13 March 2006.

sensors given in Table 2. The first result of the snow recognition product is presented in Fig. 6(b). The other results will be presented during water year 2007.

CONCLUSION

The studies demonstrate that a large amount of information is based on data available from the backbone satellite-based Global Observing System (GOS) for operational hydrology. Both geostationary and polar orbiting satellites provide information that can be used in hydrological modelling and water resources management. As Salomonson & Apple (2006) stated, the algorithms used in producing satellite derived snow products provide useful results in general, but improvements for specific areas are needed, as attempted in this study. In addition, a spectral, end member approach that explicitly takes into account land cover and snow characteristics in a specific region, could be developed and applied. The algorithms previously used to produce snow products should be improved by the authors of this paper by considering the atmospheric effects, the bidirectional properties of snow and topography.

It is hoped that these kinds of studies would be beneficial for the countries where crucial water resources, especially from snowmelt, must be shared and used efficiently with others. They will also help people in the private sector and Governmental Organizations taking part in operational hydrological problems.

REFERENCES

Akyurek, Z. & Sorman, A. U. (2002) Monitoring snow covered areas using NOAA-AVHRR data in the eastern part of Turkey. *Hydrol. Sci. J.* **47**(2), 243–252.

EUMETSAT (2005) Report on Proposal of the development of a Satellite Application Facility on Support to Operational Hydrology and Water Management. SAF/HSAF/PP/1.0. www.eumetsat.int

Hall, D. K., Riggs, G. A., Salomonson, V. V., DiGirolamo, N. E. & Bayr, K. J. (2002) MODIS snow cover products. *Remote Sens. Environ.* **83**, 181–194.

Klein, A. G., Hall, D. K. & Nolin, A. W. (2000) Development of a prototype snow albedo algorithm for MODIS. In: *Proc: 57th Annual Eastern Snow Conf.* (Syracuse, New York, USA, 17–19 May), 143–157.

Klein, A. G. & Stroeve, J. (2002) Development and validation of a snow albedo algorithm for the MODIS instrument. *Annals Glaciol.* **34**, 45–52.

Klein, A. G. (2003) Determination of broad band albedos of partially snow covered sites for validation of MODIS snow albedo retrievals. In: *Proc. 60th Eastern Snow Conf.* (Sherbrooke, Canada, 4–6 June), 23–35.

Klein, A. G., Hall, D. K. & Riggs, G. A. (1998) Improving snow cover mapping in forests through use of a canopy reflectance model. *Hydrol. Processes* **12**, 1723–1744.

Salomonson, V. V. & Appel, I. (2006) Development of the Aqua MODIS NDSI farctional snow cover algorithm and validation results. *IEEE Trans. Geosci. and Remote Sens*. **44**(7), 1747–1756.

Tekeli, E., Şensoy, A., Şorman, A. A., Akyurek, Z. & Şorman, A. U. (2006) Accuracy assessment of MODIS daily snow albedo retrievals with in situ measurements in Karasu basin. *Turkey Hydrol. Processes* **20**(4), 705–721.

Tekeli, E., Akyurek, Z., Şorman, A. A., Şensoy, A. & Şorman, A. Ü. (2005) Using MODIS snow cover maps in modelling snowmelt runoff process in the eastern part of Turkey. *Remote Sens. Environ.* **97**, 216–230.