Satellite Application Facility for Hydrology
Final Report on the Visiting Scientist activities:

Evaluating and improving the developed algorithms for effective snow cover mapping on mountainous terrain for hydrological applications

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Summary

Snow covered area depletion curves represent a key input for snow runoff melting models like the snowmelt runoff model (SRM). SRM is a degree-day-based model for daily runoff simulations and forecasts in mountainous areas in which snowmelt is the major runoff contributor. Satellite images and aerial photographs are valuable sources for retrieving snow covered areas on non-cloudy days. The accuracy of the snow cover mapping studies in the optical wavebands mostly depends on the algorithm's ability to detect clouds. On very cloudy days it is not possible to make accurate snow cover mapping using only optical sensors. Microwave sensors can be used to obtain snow information on cloudy days. The snow-water equivalent (SWE) of a dry snow pack can be estimated with passive-microwave sensors such as Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Scanning Radiometer for EOS (AMSR-E). Development of snow cover products based on multi-sensor data sources is needed for continuous regional and global snow cover mapping for climate, hydrological and weather applications. The proposed algorithms for snow recognition and effective snow cover products do not take the optic and microwave data into account at the same time. However the optical data do not provide information on cloudy days. In order to evaluate snow cover maps obtained by MSG-SEVIRI, NOAA/AVHRR, Terra-Aqua-EOS/MODIS, the blending methodology of snow products obtained from MODIS and AMSR-E, will be implemented and tested for mountainous areas.

A preliminary blended snow product has been developed jointly by the U.S. Air Force Weather Agency (AFWA) and NASA / Goddard Space Flight Center. The AFWA – NASA or ANSA blended snow product is an all-weather product that utilizes both visible and near-IR (MODIS) and microwave (AMSR-E) data. In this study the validation of the ANSA blended snow cover product, having 25 and 5 km spatial resolution, respectively, was performed for the eastern part of Turkey for five months in the winter of 2007-2008. This is the first time that the blended snow cover product has been evaluated in a mountainous area, where the elevation ranges between 850 and 3000 m. Daily snow data collected at 36 meteorological stations were used in the analysis. The utility of ANSA products in mountainous areas of Slovakia covered with forest was also analyzed. The ANSA blended snow products improve the mapping of snow cover extent relative to using either MODIS or AMSR-E products, alone, for the 2007-08 winter in the eastern part of Turkey. However in Slovakia ANSA products do not improve the mapping of snow cover extent. 5 km resolution ANSA prototype ANSA maps from February and March 2008 were used to derive snow cover depletion curves for the upper Euphrates basin located in the eastern part of Turkey. The results are compared with the curves obtained from MODIS daily snow products, and found to provide an improvement over using MODIS daily maps alone. This is because of cloud obscuration on the MODIS maps.

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Content

Chapter 1

The Use of Optical and Microwave Data in Snow Cover Retrieval

Monitoring the snow parameters (e.g. snow cover area, snow water equivalent) is a challenging work for the meteorologists and climatologists, who are studying climatic and atmospheric variability on a global scale. Because of its natural physical properties, snow highly affects the evolution of weather from daily bases to climate on a longer time scale. Due to its high albedo, snow also plays an important role in the earth's energy balance, affecting weather and climate. Thus, the accurate observation of the spatial and temporal variability of snow covered area is an important tool for monitoring of the global changes. From the hydrological point of view, snow acts as a high-volume water storage controlling water reservoirs, affecting the evaporation process, and is a source of sometimes uncontrolled discharge when starting to melt. Snow melting constitutes a potential risk of flooding in certain areas, but it is also an excellent source of energy for power plants

Remote sensing constitutes a unique technique to obtain spatially and temporally well-distributed information on snow parameters to complement ground-based observation networks. Snow can be mapped through optic wavebands (e.g. MODIS) with high accuracy under cloud-free conditions. Various studies were done on the validation of MODIS snow cover products under a variety of snow and land cover conditions. Hall and Riggs (2007) state that, most studies show an overall accuracy of ~94% compared with ground measurements. The lower accuracies were obtained in the fall and spring and under thin-snow conditions and in dense forests. They also indicate; the significant source of error in the MODIS snow products is due to the cloud-masking algorithm used in the snow algorithm. Parajka and Blöschl (2008) presented an evaluation of simple mapping methods that reduce cloud coverage by using information from neighboring non-cloud covered pixels in time and space and by combining MODIS data from the Terra and Aqua satellites. Ault et al. (2006) performed the validation of the MODIS snow product (MOD10_L2) and cloud mask (MOD35) in the Lower Great Lake regions. They found that when cloud cover does not obscure the ground, the MOD10_L2 snow product provides an accurate and reliable record of snow and ice extent. On the other hand, when cloud cover is prevalent in an image, the MOD10_L2 snow product can sometimes misinterpret the cloud cover as either ice or snow. In Tekeli et al. (2005), comparison of MODIS snow maps with in situ measurements over the snow season show good agreement with overall accuracies ranging between 62% and 82% considering the shift in the days of comparison. In that study the main reasons to have disagreement between MODIS and in situ data were referred as the high cloud cover frequency in the area and the current version of the MODIS cloud mask that appears to frequently map edges of snow-covered areas and land surfaces. Cloud cover is a challenging problem in retrieving snow cover information from the satellite images acquired in optical portion of the spectrum. Microwave wavebands can help to map snow through clouds and darkness at a lower spatial resolution. AMSR-E increases the accuracy of snow cover retrieval from passive microwave sensors especially near the snowline. Despite the near all-weather capability, the current microwave sensors provide measurements, at much coarser resolution (25 km) than the visible satellite sensors (1km).

Another disadvantage of passive microwave imagery is its limited capability to penetrate wet snow cover.

Development of snow cover products based on multi-sensor data sources have been performed recently, because of the need for continuous regional and global snow cover mapping for climate, hydrological and weather applications. Romanov et al. (2000) proposed a system using a combination of observations in the visible, mid-infrared, and infrared made by the Imager instrument aboard Geostationary Operational Environmental Satellites (GOES) and microwave observations of the Special Sensor Microwave Imager (SSM/I) aboard the polar-orbiting Defense Meteorological Satellite Program platform. The devised technique was applied to satellite data for mapping snow cover for the North American continent during the winter season of 1998/99. In their study snow identification with the combination of GOES and SSM/I observations was found to be more efficient than the one based solely on satellite microwave data. Kongoli et al. (2006) blended Advanced Microwave Sounding Unit (AMSU) and Interactive Multi-Sensor Snow and Ice Mapping System (IMS) data to map snow cover and extent.

A preliminary blended-snow product has been developed jointly by the U.S. Air Force Weather Agency (AFWA) and the Hydrospheric and Biospheric Sciences Laboratory (HBSL) at NASA / Goddard Space Flight Center. A description of the preliminary product, called the AFWA – NASA or ANSA blended snow-cover product is given in Foster et al. (2008a). The prototype product utilizes the Moderate-Resolution Imaging Spectroradiometer (MODIS) standard daily global (5-km resolution) snow-cover product (Hall and Riggs, 2007) and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) standard daily global (25 km resolution) snow-water equivalent (SWE) product (Kelly et al., 2003) to map snow cover and SWE. Preliminary evaluation of the ANSA blended snow product was performed in several studies. Hall et al. (2007) performed the validation of the blended snow cover product over the Lower Great Lakes region. They indicated the use of the new product improve the mapping of snow cover compared to using either the MODIS or AMSR-E product, alone. Casey et al. (2008) evaluated the new product in Finland for the 2006-2007 snow season using 9 ground observations.

"Satellite Application Facility" on Support to Operational Hydrology and Water Management (H-SAF) is established with an aim of generating satellite-derived products specifically designed as to comply with requirements for operational hydrology and water management. The main objectives of H-SAF are to provide new satellite-derived products from existing and future satellites with sufficient temporal and spatial resolution to satisfy the needs of operational hydrology and to perform independent validation of the usefulness of the products on hydrological applications. So far the snow recognition (SN_OBS1), and snow cover (SN_OBS3) products retrieved from satellite data for the mountainous areas within the HSAF domain were put in the processing chain. The snow water equivalent (SN_OBS4) product will be available in the mid of 2009. During the improvement and tuning of the snow retrieval algorithms, the intensive validation studies will be implemented. The combination of snow cover products obtained from optic and microwave data can provide continuous regional and global snow cover maps.

In this study, we evaluate the utility of a blended snow product, namely ANSA in snowmelt modeling. First the algorithms and the blending procedure were analyzed. The blended snow product in two different spatial resolutions (25 km and 5 km) was generated over the eastern part of Turkey for the 2007-2008 snow season. The 25 km ANSA product was used in validating the blended snow product for Slovakia for January 2008. This is the first time of validating the blended snow cover product in a mountainous area, where the elevation ranges between 850 m to 3000m in Turkey. In terms of snow cover mapping we discuss the contribution of blended snow product compared to MODIS and AMSR-E product alone. 5 km resolution ANSA prototype ANSA maps from February, March and April 2008 were used to derive snow cover depletion curves for the upper Euphrates basin located in the eastern part of Turkey. The results were compared with the curves obtained from MODIS daily snow products, and found to provide an improvement over using MODIS daily maps alone. SCA depletion curves obtained from ANSA and MODIS snow products were used in the snowmelt runoff simulations. In this study the preliminary results obtained from hydrological impact analyses of satellite snow products are presented.

Chapter 2

Blended Snow Cover Product: AFWA – NASA (ANSA)

2.1. MODIS data:

MODIS data have been used since early 2000 to produce validated daily, global snow maps in an automated environment. These maps, available at a variety of spatial resolutions – 500 m, 0.05 deg. and 0.25 deg. – provide snow extent and fractional snow cover (FSC) as well as snow albedo (Hall et al., 2007; Riggs et al., 2005; Klein and Stroeve, 2002). Inputs to the products include the MODIS cloud mask (Ackerman et al., 1998), land/water mask, geolocation product (Wolfe et al., 2002), radiance products and surface-reflectance product (for snow albedo) and land cover. The resulting snow product is using the MOD10C1 snow product (Figure 2.1). In developing the MOD10C1 product, snow cover extent is mapped by processing the MOD10A1 and MYD10A1 products for a day into the CMG. Snow cover extent is expressed as a percentage of coverage of the input data at 500 m resolution in a cell of the CMG. These snow products are archived and distributed through the National Snow and Ice Data Center.

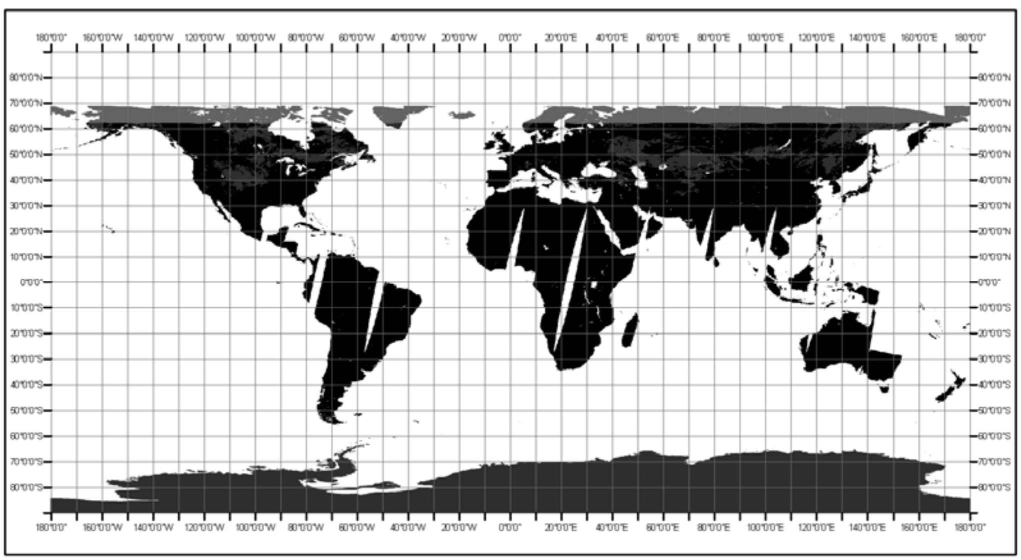


Figure 2.1. MOD10C1 product for January 19, 2008.

2.2 AMSR-E data:

A validated global daily SWE product is currently unavailable, however, passive microwave-derived methods to estimate regional to global snow depth or SWE have been developed that use frequent and wide-swath-coverage observations from satellite passive-microwave instruments. The AMSR-E sensor, on board Aqua, is the most recent addition to the passive microwave suite of instruments. The AMSR-E snow products (Kelly et al., 2003) are archived and distributed through the National Snow and Ice Data Center. Passive-microwave satellite footprints are currently ~25 km. There is a large body of literature describing the ability of passive-microwave instruments to estimate snow extent, SWE and melt onset (e.g. Chang et al., 1987). There are also studies describing systematic errors and uncertainties in SWE retrievals using passive-microwave data (Kelly et al., 2003; Foster et al., 2005).

Microwave data can be used to get information on snow for cloudy days. The SWE of dry snow pack can be estimated with passive-microwave sensors such as SSM/I (Chang et al., 2005) and AMSR-E (Kelly et al., 2003) (Figure 2.2). Kelly et al. (2003) developed a methodology to estimate snow grain size and density as they evolve through the season using SSM/I and simple statistical growth models. The approach uses the scattering signal determined by the difference in brightness temperature between 10 and 36 GHz at vertical and horizontal polarizations (Tb10V-Tb36V and Tb10H-Tb36H). A variable parameter (*a*) is calculated from the polarization difference at 36 GHz brightness temperatures which is used to multiply the brightness temperature differences (Tb10V-Tb36V and Tb10H-Tb36H). The overall approach is split into two parts with one part retrieving snow depth for the fraction of a footprint that is forest covered and the other retrieving the fraction that is forest-free. The AMSR-E data products are in HDF-EOS format, they are generated at different spatial (500 m to 25 km) and temporal (multiple swaths or daily) resolution.

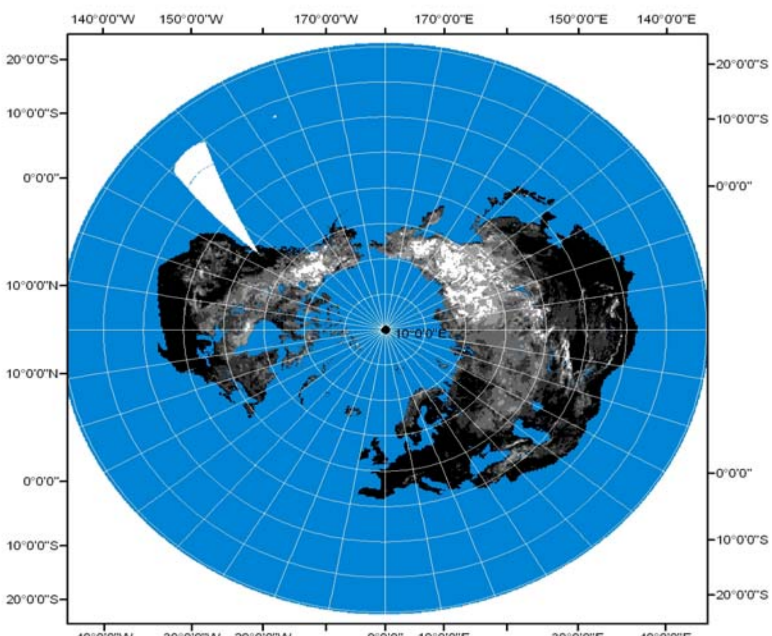


Figure 2.2. AMSR-E snow water equivalent product for January 19, 2008.

2.3. Blending Procedure

ANSA-blended snow product is an all-weather product with snow mapped by both visible and near-IR (MODIS) and microwave (AMSR-E) data. ANSA data will be available for use in a near-real time basis as a single global daily, 25-km resolution, user friendly product (Casey et al., 2008). The thematic values of ANSA and ANSA aggregated product are given in Figure 2.3 and 2.4 respectively. During the blending procedure the MOD10C1 product is re-sampled to 25km with nearest neighborhood re-sampling method and then the blending is performed with the AMSR-E product.

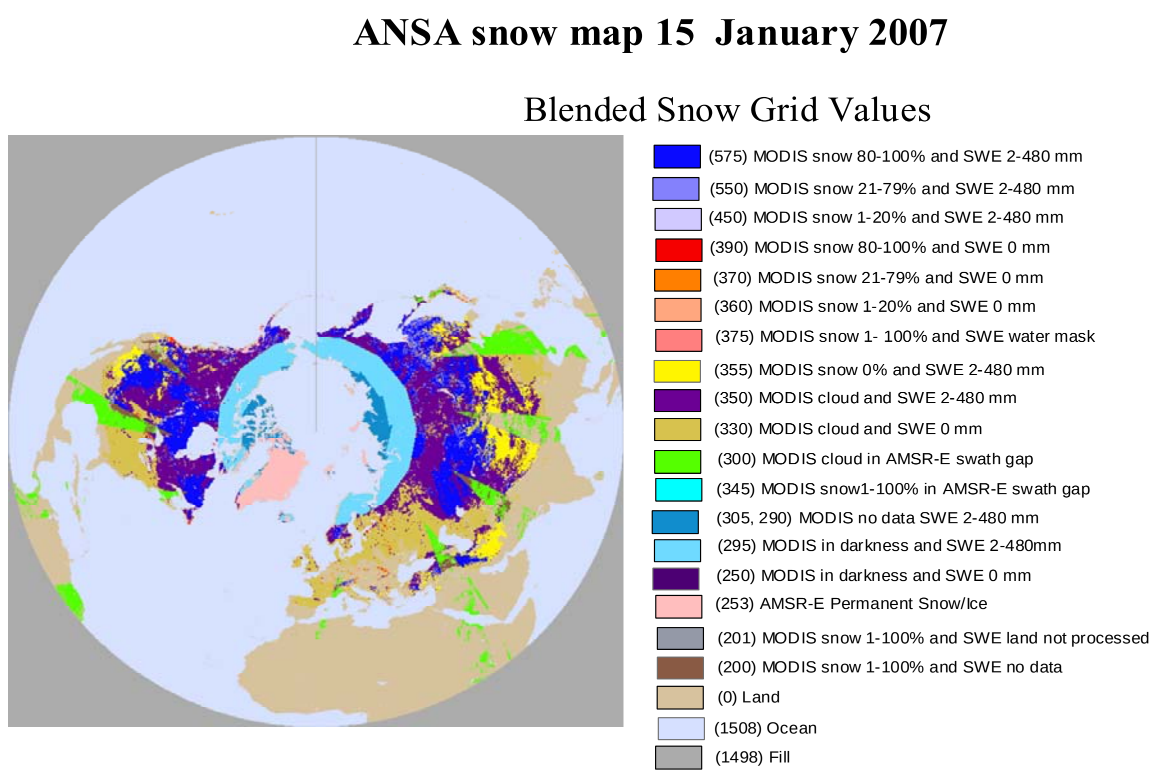


Figure 2.3. ANSA snow map 15 January 2007.

ANSA snow map 15 January 2007

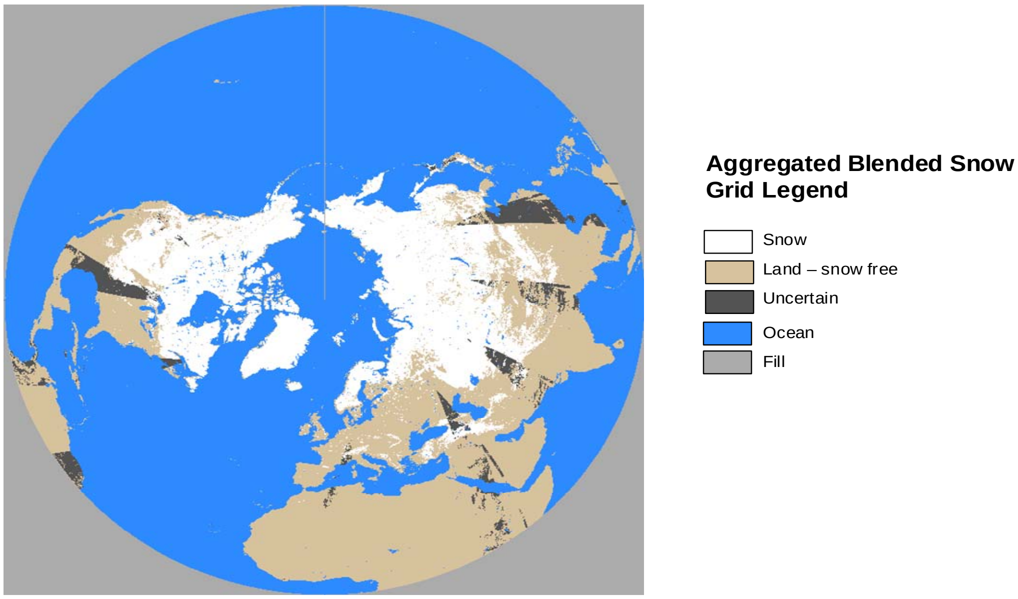


Figure 2.4. ANSA aggregated blended snow map 15 January 2007.

Chapter 3

Validation Analyses of Blended Snow Cover Product

The validation analyses were done for two study areas within the HSAF domain. The first analysis was performed for the eastern part of Turkey and the second one was performed for Slovakia.

3.1. Validation for Turkey

Hydrological processes and climate in the 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 snow-covered area in the mountainous regions of Eastern Turkey, as 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.

In this study 30 climate stations and 6 automated weather stations (AWOS) are used in the validation of ANSA products for eastern part of Turkey (Table 3.1). The validation was performed for the months November, December, January, February and March for the 2007-08 snow year. In Figure 3.1 the elevation variation in Turkey is given and in Figure 3.2 the locations of the stations used in the validation study are depicted. The name and the altitudes of the stations are also given in Table 3.1. The precipitation and the temperature values for climate stations for the listed months were obtained and the total precipitation values for 10 stations are given in Figure 3.3.

The ANSA products were obtained for the snow year 2007-2008 and samples of MOD10C1, AMSR-E and ANSA products are given for January 19, 2008 in Figure 3.4. A systematic positional shift was observed between ANSA products and the boundary coverage of Turkey, which was obtained from 500 000 scaled topographic maps. Therefore all the products were geocoded with the help of the same coverage in order to have an RMS error lower than one pixel. Then the thematic values corresponding to the filed observations were extracted from the products on daily basis.

Table 3.1. The name and the altitude of the stations located in Turkey

Station Name	**Elevation (m)**	**Type**
Guzelyayla	2070	AWOS
Ovacik	1980	AWOS
Ilica	2094	AWOS
Çat	2220	AWOS
Dumlu	2666	AWOS
Palandoken	2937	AWOS
ERZURUM	1758	B.Climate
AGRI	1632	B.Climate
IGDIR	858	B.Climate
TUNCELI	981	B.Climate
MALATYA	948	B.Climate
BINGOL	1177	B.Climate
MUS	1323	B.Climate
TATVAN	1665	B.Climate
ERZINCAN	1218	B.Climate
KARS	1775	B.Climate
ELAZIG	990	B.Climate
ISPIR	1222	B.Climate
OLTU	1322	B.Climate
TORTUM	1572	B.Climate
HORASAN	1540	B.Climate
SARIKAMIS	2102	B.Climate
TERCAN	1425	B.Climate
DIVRIGI	1120	B.Climate
MAZGIRT	1400	B.Climate
HINIS	1715	B.Climate
ARAPKIR	1200	B.Climate
AGIN	900	B.Climate
CEMISGEZEK	953	B.Climate
KARAKOCAN	1090	B.Climate
SOLHAN	1366	B.Climate
VARTO	1650	B.Climate
MALAZGIRT	1565	B.Climate
KEBAN	808	B.Climate
PALU	1000	B.Climate
GENC	1250	B.Climate

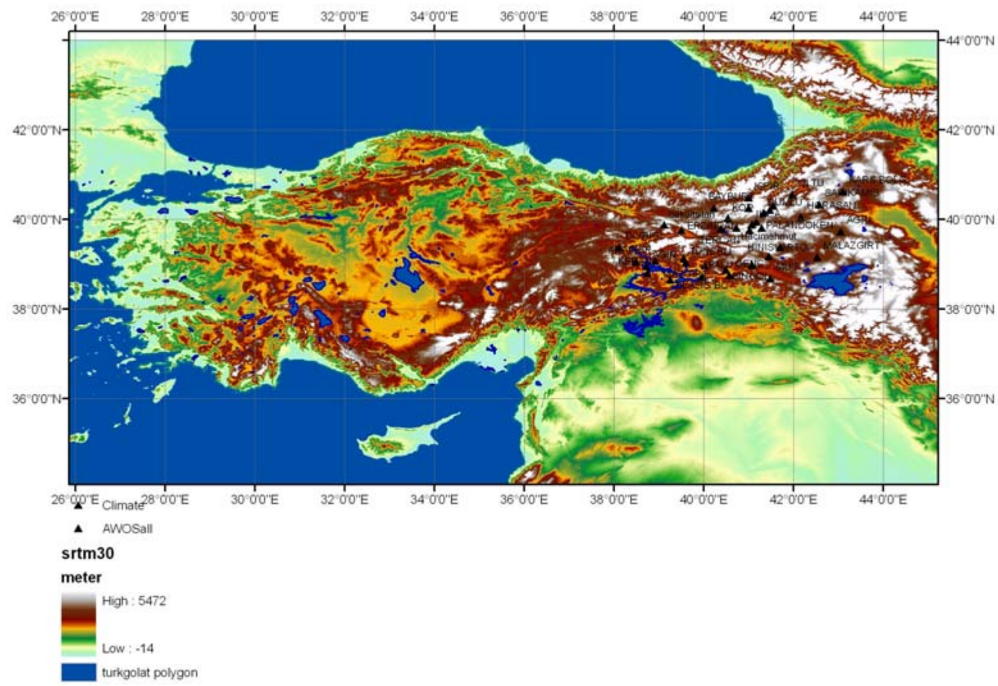


Figure 3.1. The DEM of Turkey and the location of the meteorological stations in the eastern part of Turkey

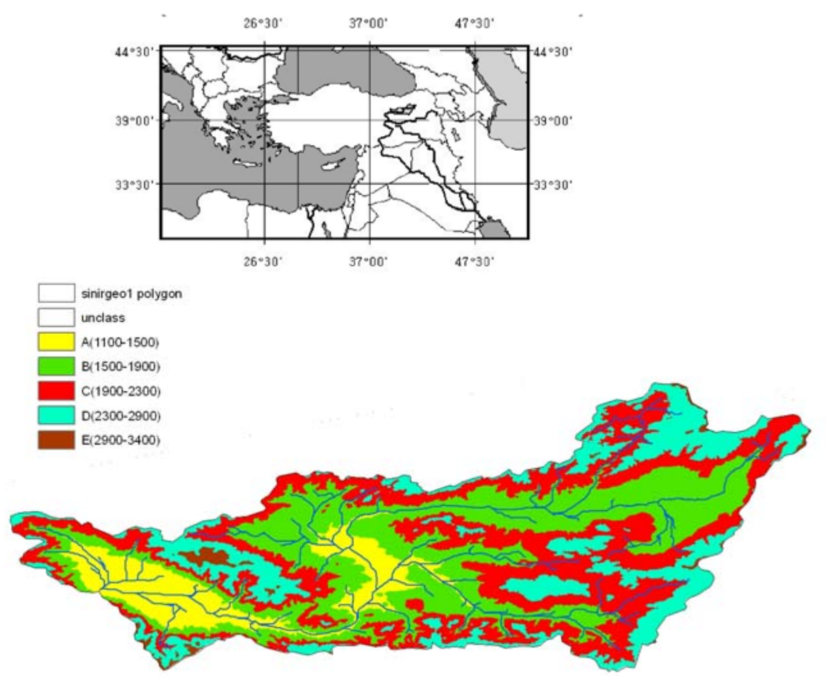


Figure 3.2. The elevation zones in the upper Euphrates basin

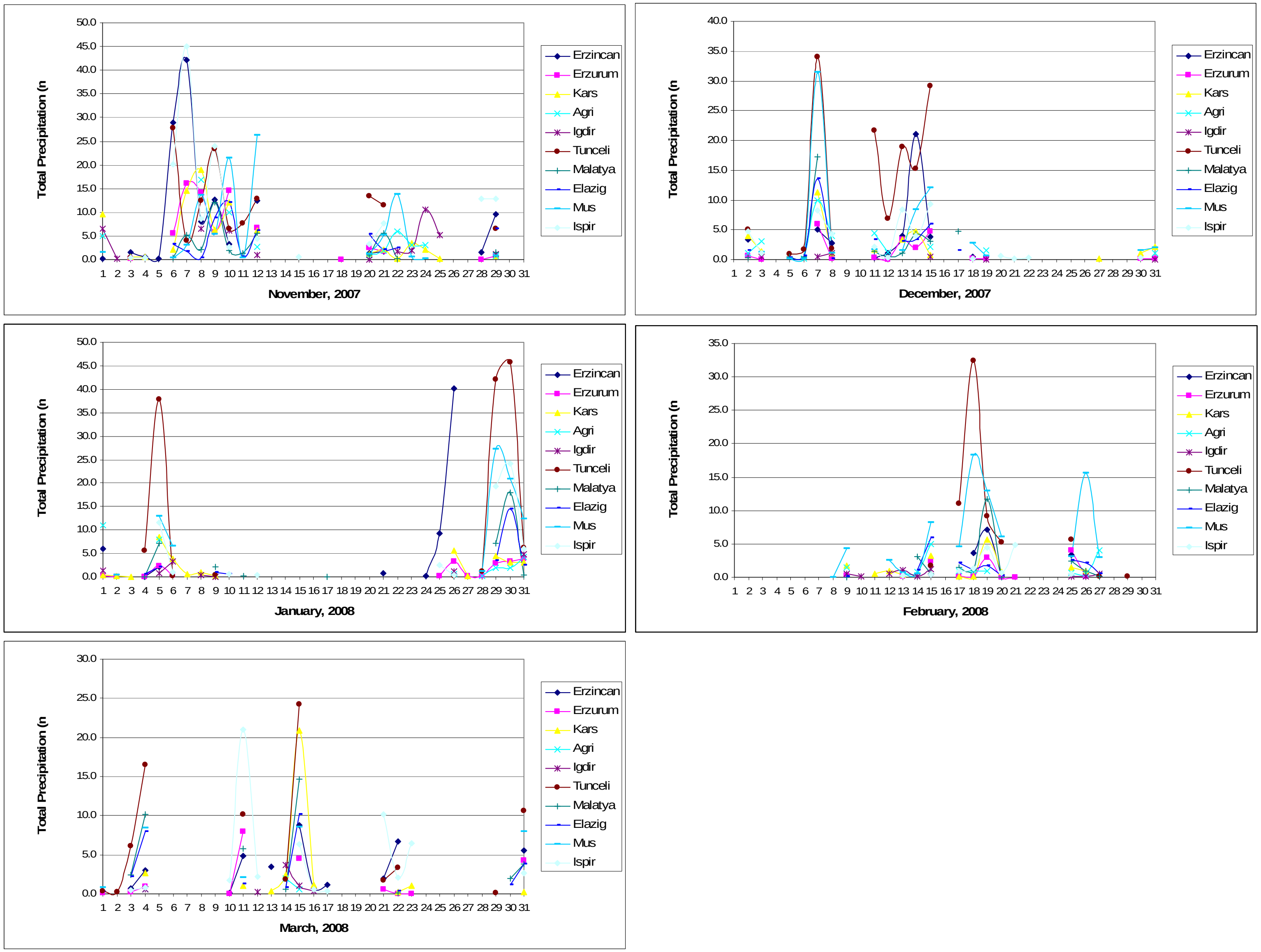
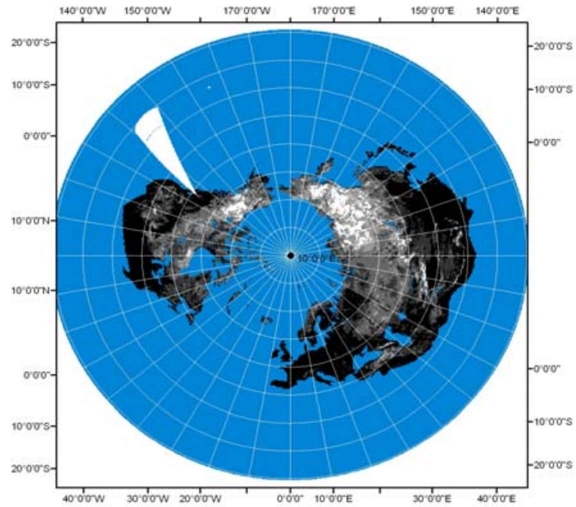
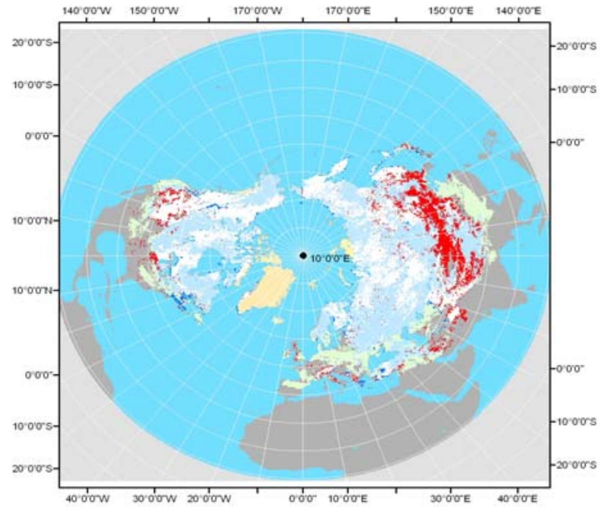
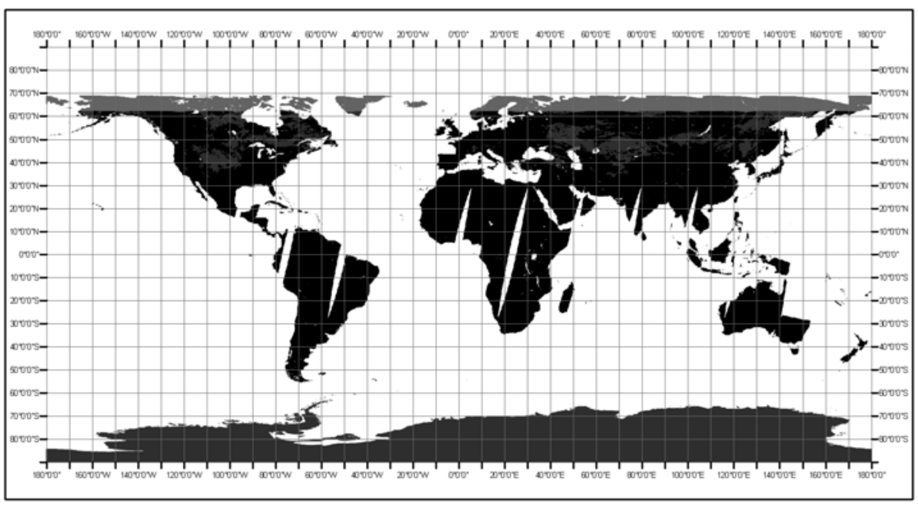


Figure 3.3. The daily precipitation observed at climate stations for November 2007 – March 2008





(a) (c)



(b)

Figure 3.4. Samples for AMSR-E (a), MOD10C1 (b) and ANSA (c) products for January 19, 2008.

3.2. Validation for Slovakia

In this study 62 stations are used in the validation of ANSA products for Slovakia. The validation was performed for January 2008. In Figure 3.5 the elevation variation in Slovakia and the locations of the stations used in the validation study are depicted. The number and the altitudes of the stations are also given in Table 3.2. The ANSA snow products for January 2008 were geocoded for Slovakia. Then the thematic values corresponding to the field observations were extracted from the products on daily basis.

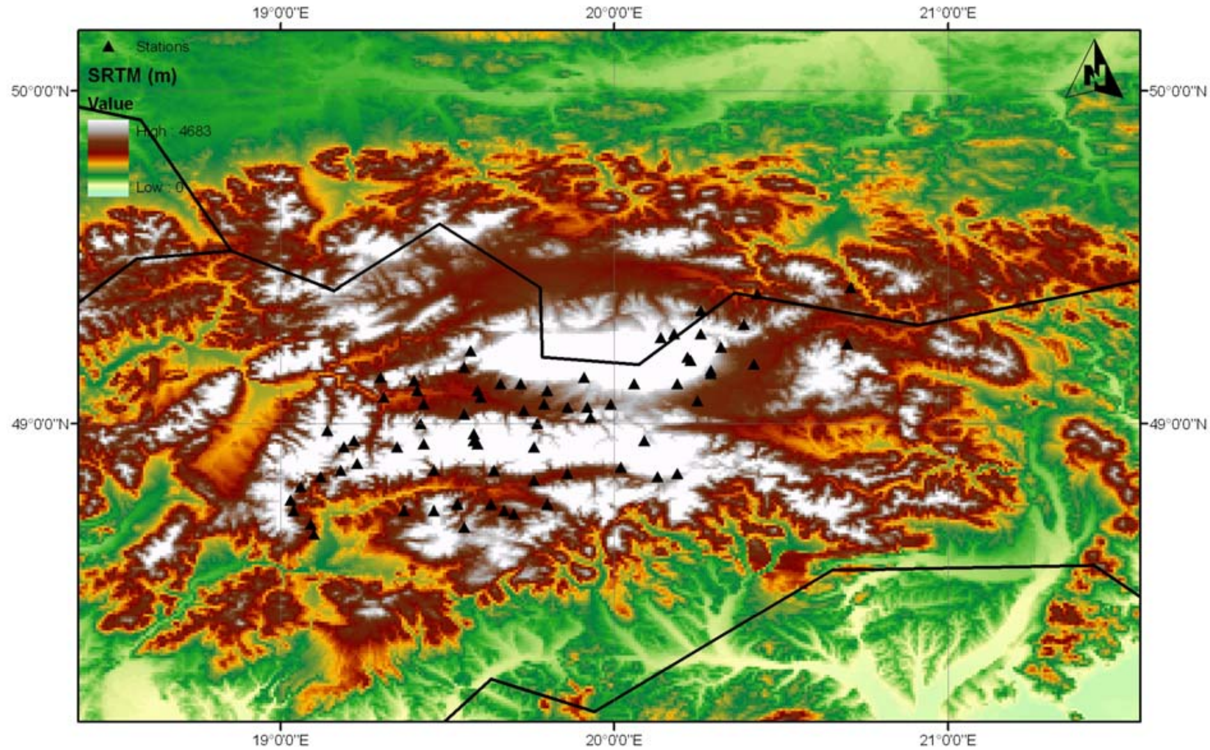


Figure 3.5. Location of stations on DEM of Slovakia

Table 3.2.The name and the altitude of the stations located in Slovakia

Station Number	Altitude (m)	Station Number	Altitude (m)	Station Number	Altitude (m)
11020	1007	21100	1661	34220	483
11040	910	21120	1196	34240	398
11060	680	21125	632	34255	362
11080	723	21130	569	34280	627
11100	520	21140	675	34285	814
11120	465	21180	795	34300	427
12020	829	21200	590	34310	623
12040	694	21240	1045	34320	460
12050	975	21270	705		
12090	808	21280	586		
12100	2635	21300	610		
12120	1778	21320	517		
12140	827	21340	685		
12160	665	21360	605		
12180	626	21380	810		
13020	760	21400	688		
13040	633	21420	471		
13060	905	21440	780		
13100	563	21460	445		
13120	680	33020	901		
13140	550	33040	887		
13160	535	33060	764		
13180	635	33120	586		
13200	515	33140	542		
13220	485	33160	618		
13240	425	33200	487		
20020	900	33217	570		
20040	730	33220	540		
20080	1322	33240	530		
20100	814	33245	715		
20120	750	33255	488		
20140	665	33258	590		
20160	930	34040	634		
20180	700	34070	540		
20200	710	34080	406		
20220	972	34090	1080		
20240	765	34100	477		
20260	640	34120	372		
21020	746	34140	459		
21040	747	34160	481		
21060	567	34170	992		
21080	2005	34180	688		

Chapter 4

Results and Discussion

4.1. Validation of ANSA having 25km resolution

i- Validation for Turkey

Results of snow extent comparison are presented in Figures 4.1 and 4.2. The comparison was performed on agreement and disagreement percentages on a daily basis (Figure 4.1). The relationship of the percent agreement of the ANSA blended product and the MODIS and AMSR-E input products alone for five months are given in Figure 4.2. It is observed that the ANSA blended snow products improve the mapping of snow cover extent relative to using either MODIS or AMSR-E products alone for the snow year 2007-08 in the east part of Turkey. The strength of the MODIS capturing the fresh snow on the ground is seen when the precipitation and the agreement percentages are compared (Figure 3.3). The agreement percentage is high for months January and February where the snow is thick and dry in these months, but as the snow gets shallow and wet, the agreement in the snow extent is decreased.

To make the comparison of the ANSA product among the months, metrics derived from the contingency table were used (Table 4.1). The Probability of detection (POD), hit rate (HR) and critical success index (CSI) were calculated as given in the equations 4.1-4.3. Table 4.2 presents the calculated metrics for the five months. The highest values were obtained for February where the maximum agreement was observed. The lowest values were obtained for March indicating the lowest performance of the ANSA product for this month. This is due to decrease in the snow depth and increase in the wetness of the snow.

The agreement of the ANSA blended products and the field observations was analyzed in the spatial distribution, and the higher disagreement percentages were seen for the stations (namely Keban, Arapkir, Malatya, Elazig, Palu), which are located near the reservoir lakes. This is due to the mix- pixel problem contributed from the smaller spatial resolution of AMSR-E product.

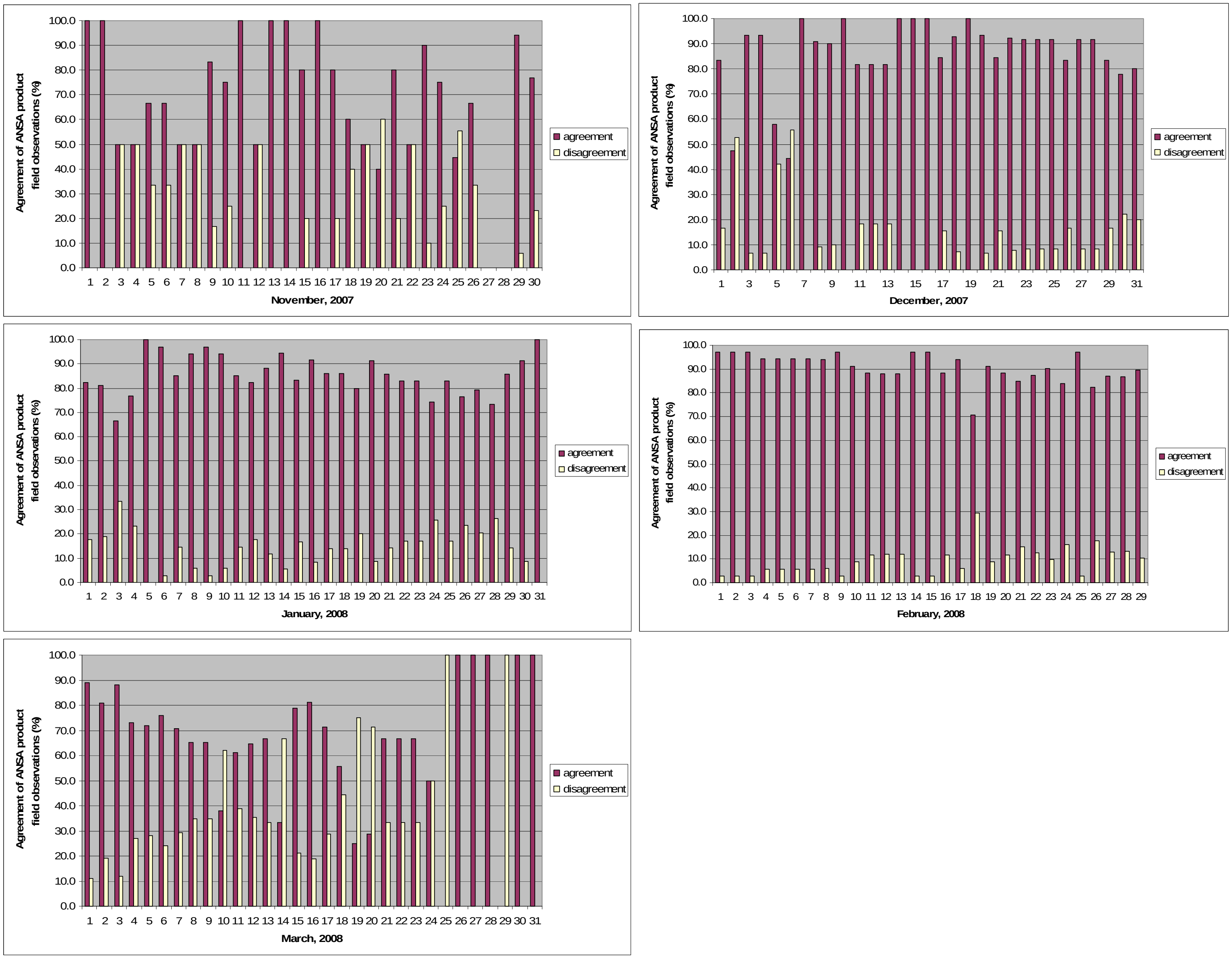


Figure 4.1. The percent of agreement and disagreement of ANSA product for November 2007 – March 2008.

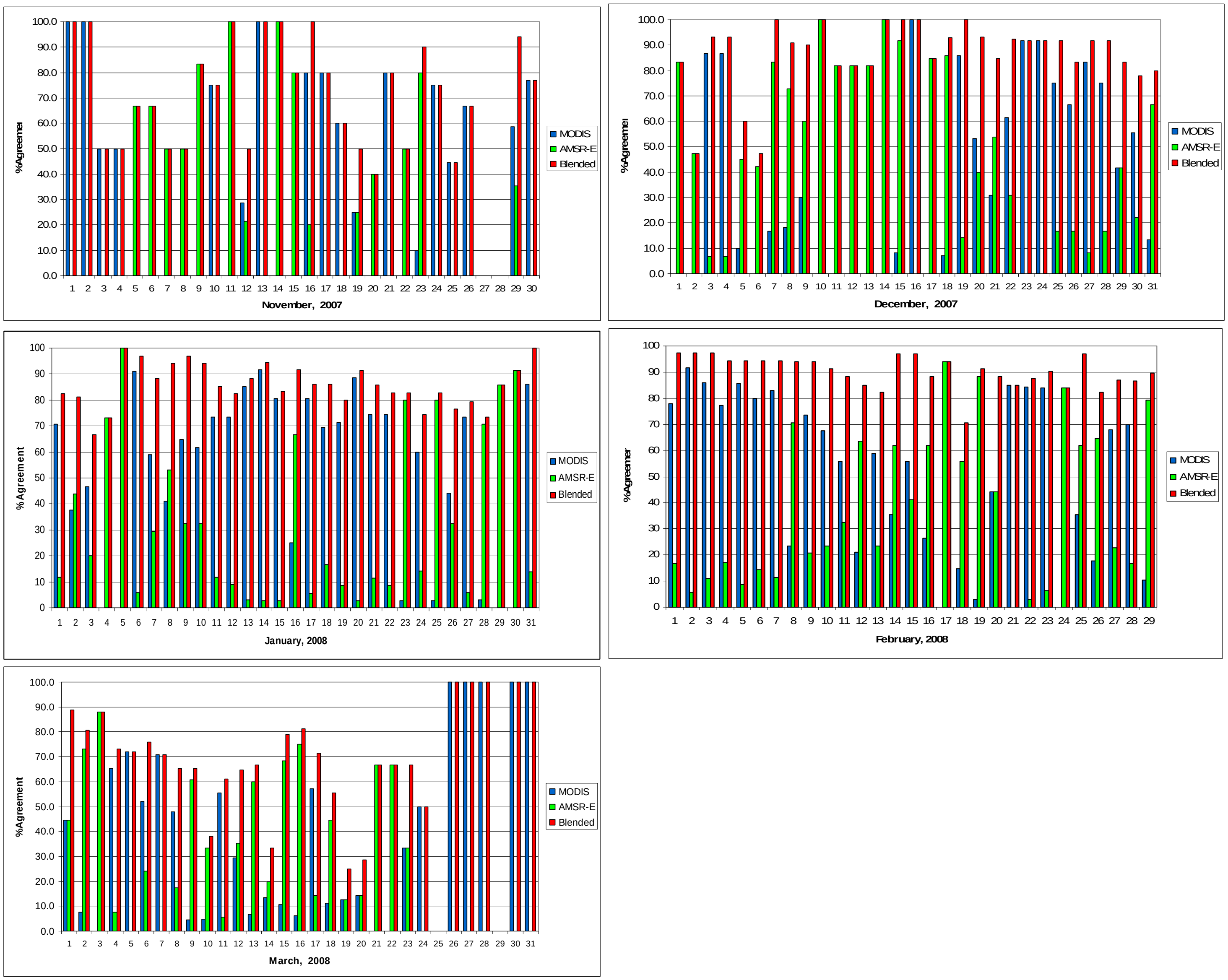


Figure 4.2.The percent of agreement of ANSA product, the MODIS and AMSR-E input products alone for November 2007 – March 2008.

Table 4.1. Contingency table for the snow cover product validation.

	Snow Cover Product		
In-situ Observation		Snow Presence	None
	Snow Presence	a	b
	None	c	d

POD = a / (a+b) (4.1)

HR = (a+d) / (a+b+c+d) (4.2)

CSI = a / (a+b+c) (4.3)

Table 4.2. The comparison of the validation in terms of POD, HR, and CSI

	Nov	Dec	Jan	Feb		Mar	
				ANSA-25km	ANSA-5km	ANSA-25km	ANSA-5km
POD (%)	80.00	90.33	93.57	97.44	98.78	81.97	88.59
HR (%)	73.78	84.44	86.13	90.75	93.31	68.37	74.27
CSI (%)	70.75	83.85	85.73	90.69	93.19	64.96	71.35

ii-Validation for Slovakia

Results of snow extent comparison are presented in Figures 4.3 and 4.4. The comparison was performed on agreement and disagreement percentages on a daily basis (Figure 4.3). The relationship of the percent agreement of the ANSA blended product and the MODIS and AMSR-E input products alone for January 2008 are given in Figure 4.4. It is observed that the ANSA blended snow products do not improve the mapping of snow cover extent relative to using either MODIS or AMSR-E products alone for January 2008 in Slovakia. The Probability of detection (POD), hit rate (HR) and critical success index (CSI) for January 2008 are presented in Table 4.3.

In the first five days in January 2008, the agreement of ANSA with field observations is around 80%. During this period blended snow products improve the snow mapping compared to MODIS and AMSR-E products alone. In the second and third weeks of January due to high cloud coverage, only contribution was observed from AMSR-E. The low spatial resolution of AMSR-E, and shallow snow cover decrease the agreement percentages. Increased snow extent comparison agreement was seen in the last five days of January. The difficulty of retrieving old snow fell on the forest area was seen in the validation of blended snow products.

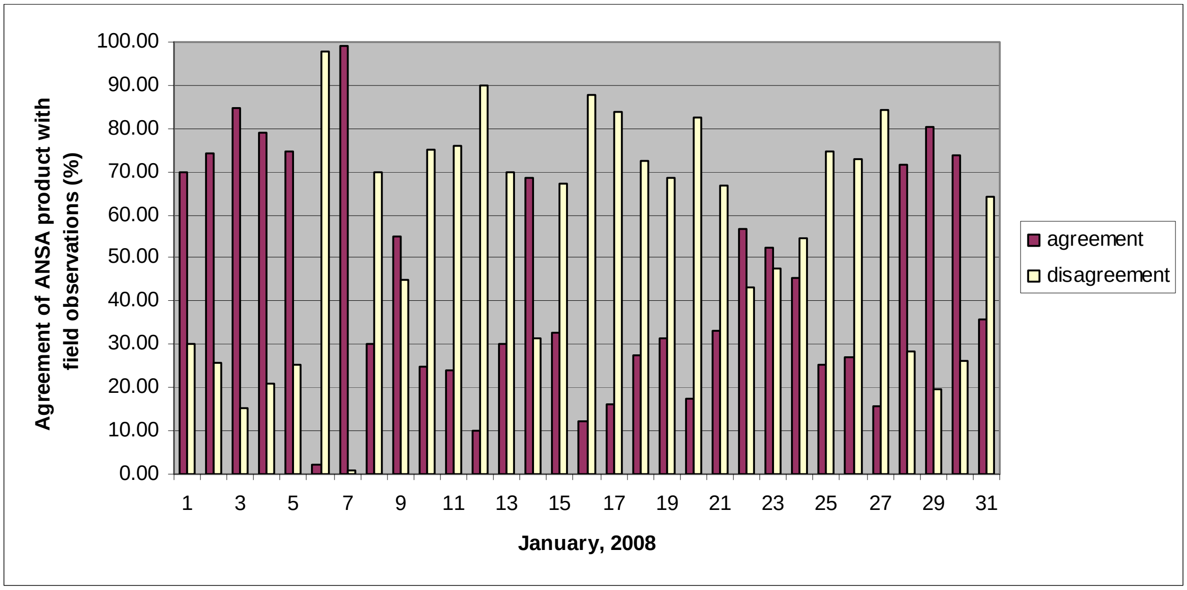


Figure 4.3. The percent of agreement and disagreement of ANSA product for January 2008 for Slovakia.

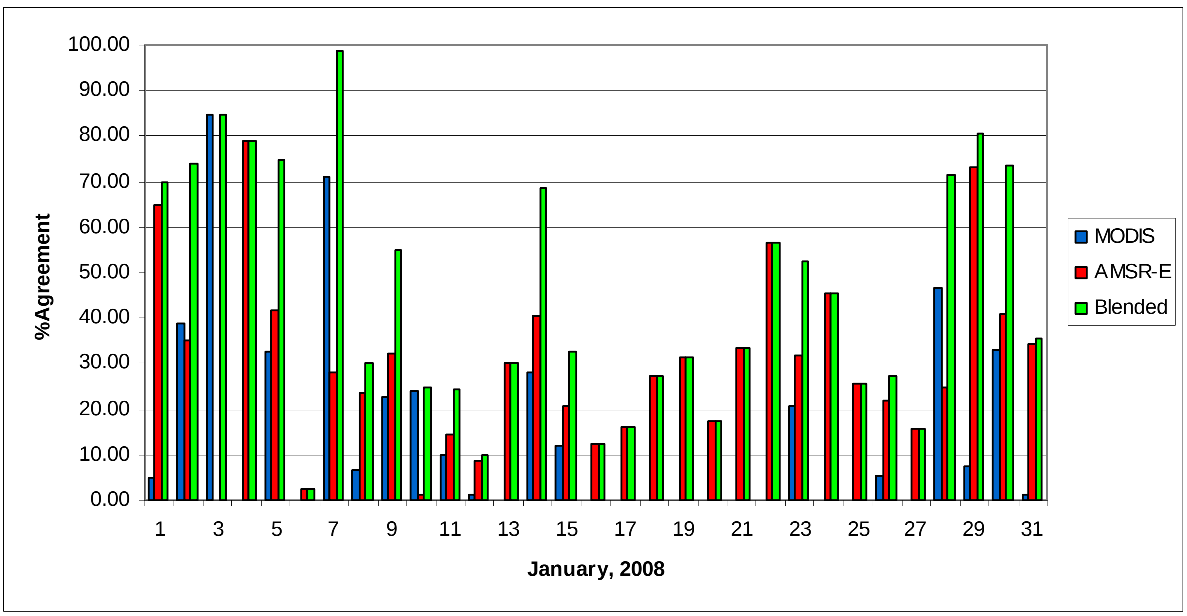


Figure 4.4. The percent of agreement of ANSA product, the MODIS and AMSR-E input products alone for January 2008 for Slovakia.

Table 4.3. The comparison of the validation in terms of POD, HR, and CSI for Slovakia data

	Jan
POD (%)	43.12
HR (%)	45.59
CSI (%)	41.29

4.2. Validation of ANSA having 5km resolution for February and March for the eastern part of Turkey

In order to see the effect of spatial resolution on snow mapping, ANSA-blended snow products having 5 km resolution were obtained for February and March 2008. Similar validation analysis performed for ANSA-25km product was performed for ANSA-5km product for February and March 2008. Figures 4.3 and 4.4 show the agreement, disagreement percentages for ANSA-5km product, MODIS and AMSR-E products alone for February and March.

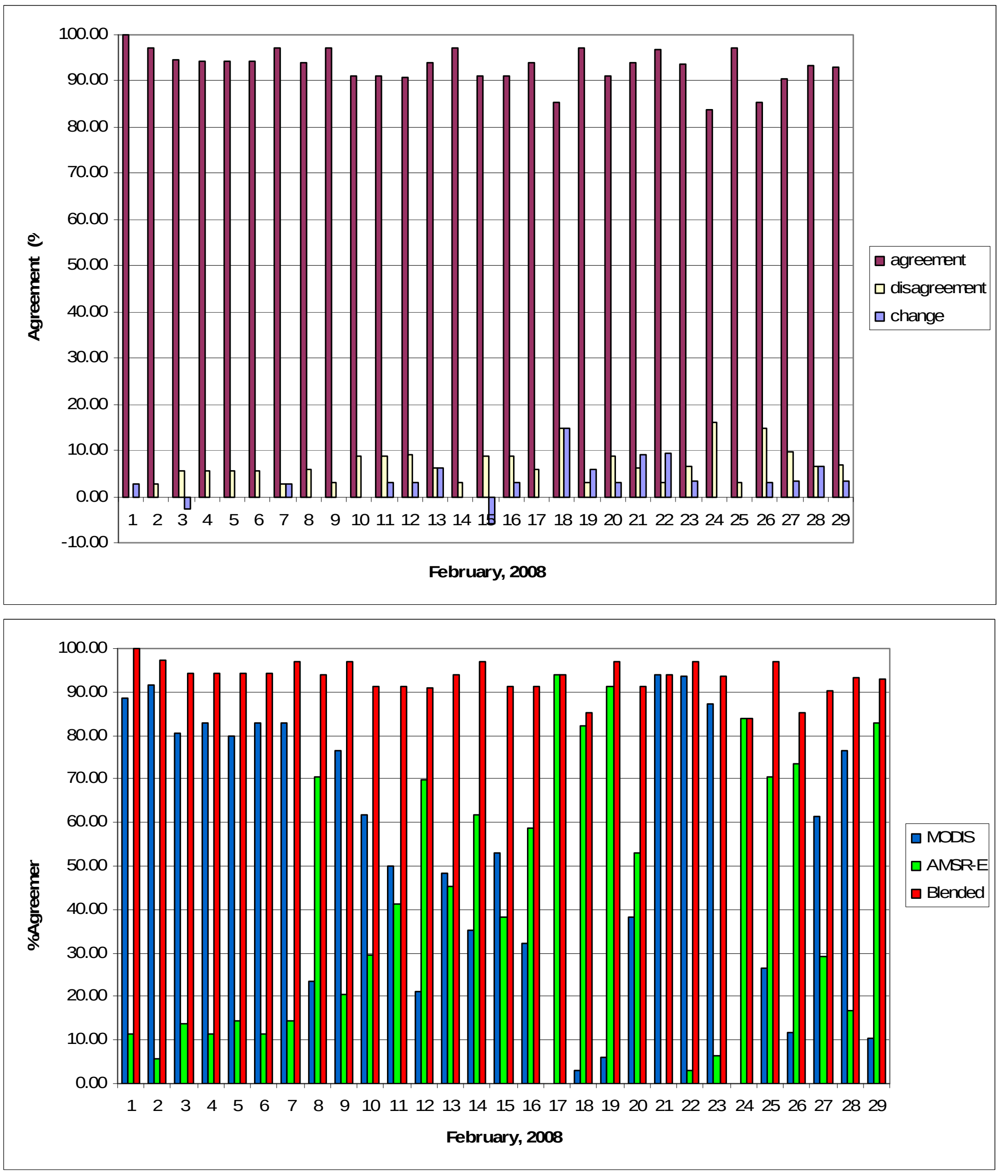
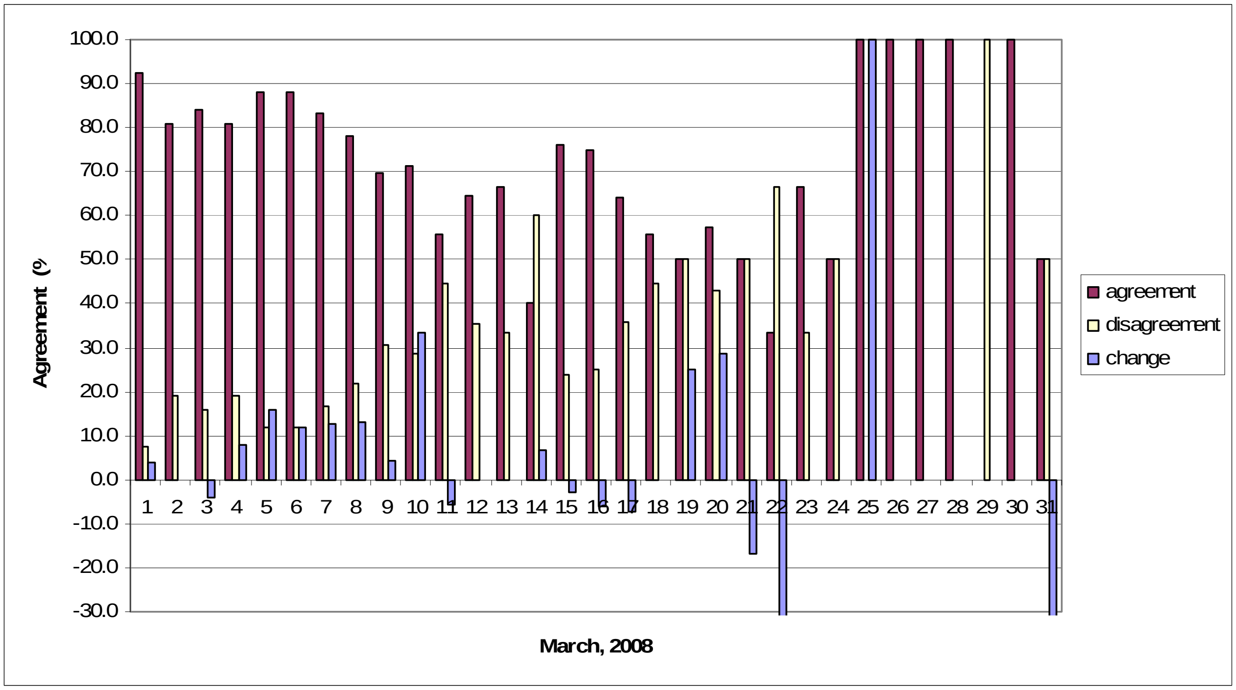
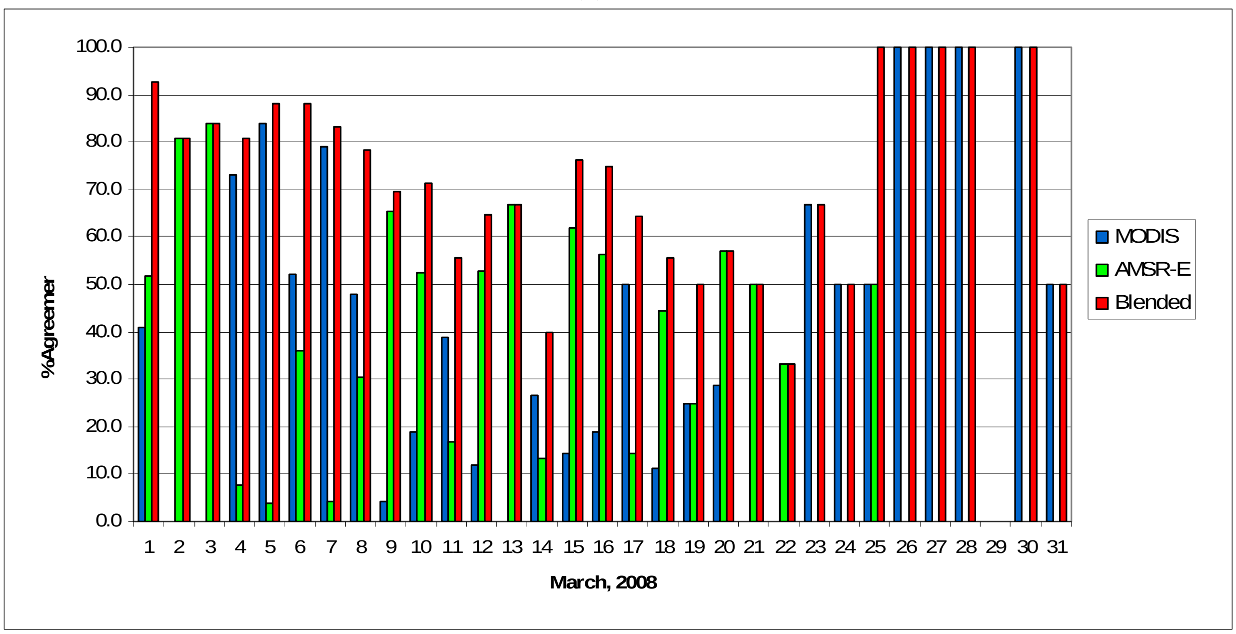


Figure 4.3. Agreement percentage of ANSA-5 product, the MODIS and AMSR-E input products alone for February- 2008.



(a)



(b)

Figure 4.4. Agreement percentage of ANSA-5 product (a), the MODIS and AMSR-E input products alone for February- 2008 (b).

With the ANSA-5km product the agreement percentages are increased for all the days except 3rd and 15th of February. In Figure 4.4a, the changes in the percentages are plotted with blue color. With ANSA-5km product, the no-snow cover observations at the site was started to be mapped better with the product.

In the spatial extent for three of the stations (Agin, Cemisgezek and Malatya) located nearby the reservoirs, the disagreement percentages are decreased. However for the other three stations (Keban, Palu, Genc) the same disagreement percentages are obtained. In terms of POD, HR and CSI metrics, all of them are increased for the 5km product (Table 4.2). Although 5km resolution product do not get additional information from AMSR-E SWE product, but MODIS snow cover product contribution is increased with a better spatial resolution.

4.3. SCA estimation from ANSA having 5km resolution for the upper Euphrates basin

Snow covered area depletion curves represent a key input for snow runoff melting models like the snowmelt runoff model (SRM). SRM is a degree-day-based model for daily runoff simulations and forecasts in mountainous areas in which snowmelt is the major runoff contributor (Martinec, 1975; Rango and Martinec, 1979). In order to see the utility of the ANSA product in obtaining the snow cover area depletion curves, ANSA having 5 km resolution images for March and April were used. The thematic maps were indicating the snow and no-snow classes were used to obtain snow covered area values for the upper Euphrates basin. Snow melting model SRM has been used for the area for ten years and the model parameters specific to the pilot basin have been already studied for the basin.

Since the model uses different elevation zones and accepts SCA depletion curves for these elevation zones, five elevation zones determined in previous studies were used to obtain corresponding SCA depletion curves. The elevation ranges for the proposed elevation zones are given in Figure 3.2. The SCA depletion curves for five elevation zones are given in Figure 4.5. The SCA values for the corresponding elevation zones were obtained from MOD10A1 and MOD10A2 snow products. The snow areas and the snow and cloud areas are considered separately in deriving the SCA depletion curves. These values are also plotted on the curves given in Figure 4.5. For lower elevations ANSA predicts more SCA compared to ones derived from MOD10A1 and MOD10A2, even the cloud and snow classes are considered as snow covered area, the values are lower than the ANSA predictions. On 21st of April precipitation was detected from the meteorological observations. At higher elevations the ANSA predictions are between the values derived from snow only class and cloud added to snow class. This indicates that ANSA finds snow under the clouds on the ground. With the MOD10A1 data if the clouds are not considered in the SCA values, they are underestimating the SCA, but if the clouds are considered in the SCA values, they are overestimating the SCA.

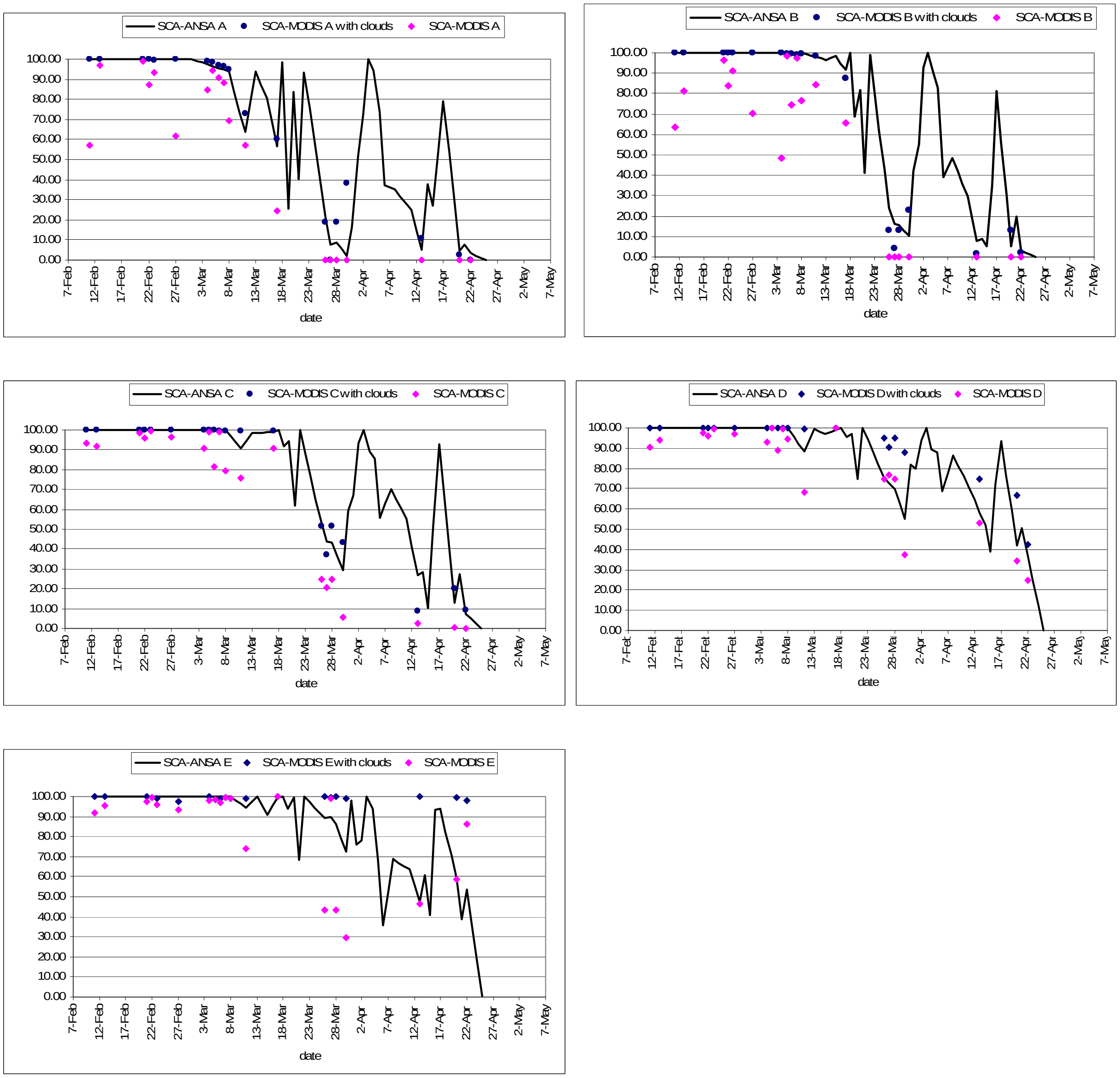
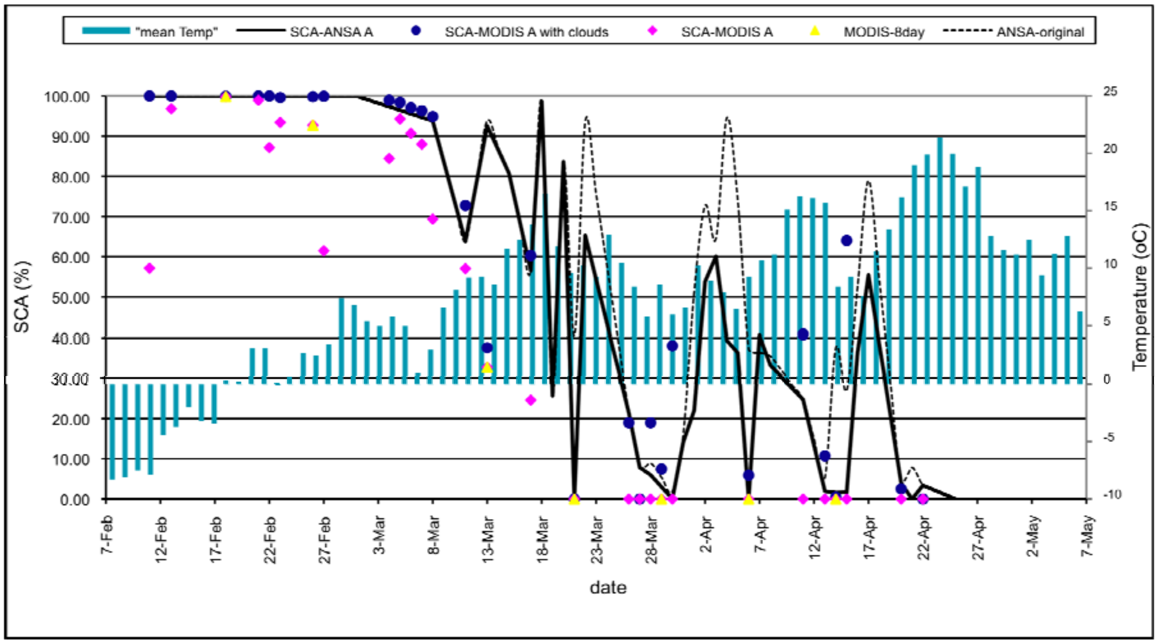


Figure 4.5. SCA depletion curves derived from ANSA and MOD10A1 products.

The ANSA product aims to detect the snow on the ground; therefore the thresholds used to classify the snow were set their minimum values. In SWE retrieval the snow determination is done if the SWE retrieval is between 2mm and 450 mm. This range is quiet large for modeling issues. Especially knowing the limitations of AMSR-E for shallow snow depth (SD =5cm, SWE= 15 mm), the lower limitation for snow detection was changed to 15mm in the SWE contribution of ANSA product. The snow cover depletion curves with this modification were obtained for five elevation zones and they are given in Figure 4.6 and 4.7. In these figures the SCA values obtained from MODIS 8 day (MOD10A2) snow products are also drawn. The mean temperatures distributed to the corresponding elevation zones were obtained and put on the figures to give information about the relationship between the temperature and accumulation, depletion parts in the SCA depletion curves.



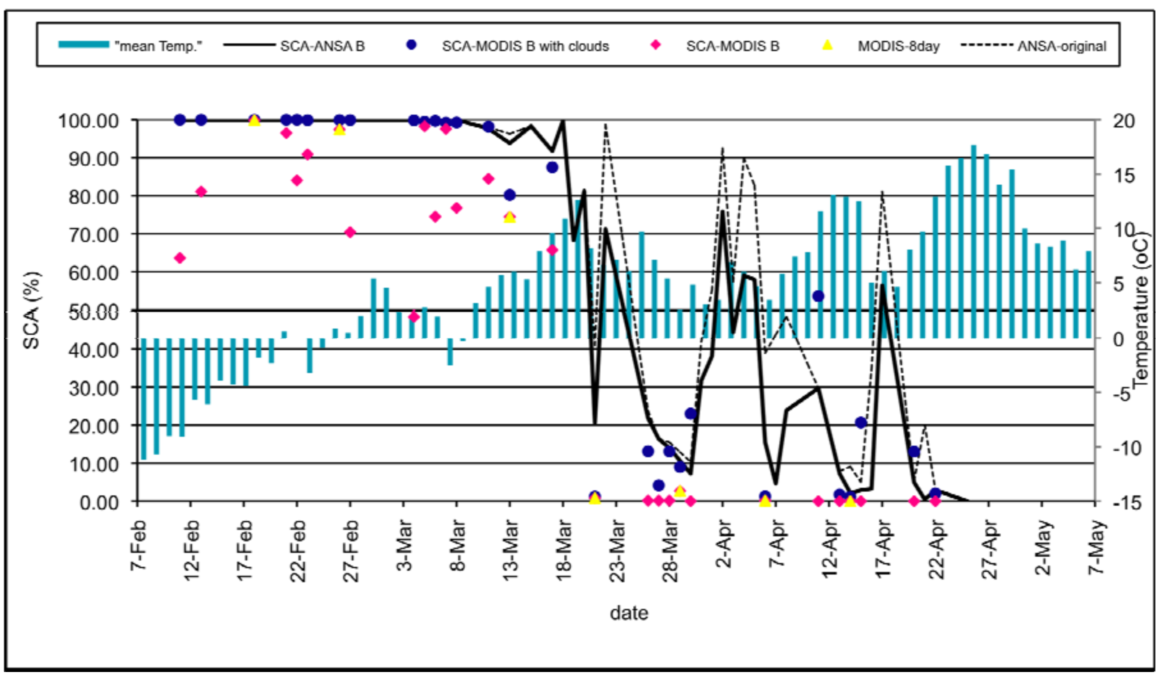


Figure 4.6. SCA depletion curves derived from modified ANSA and MOD10A1 products.

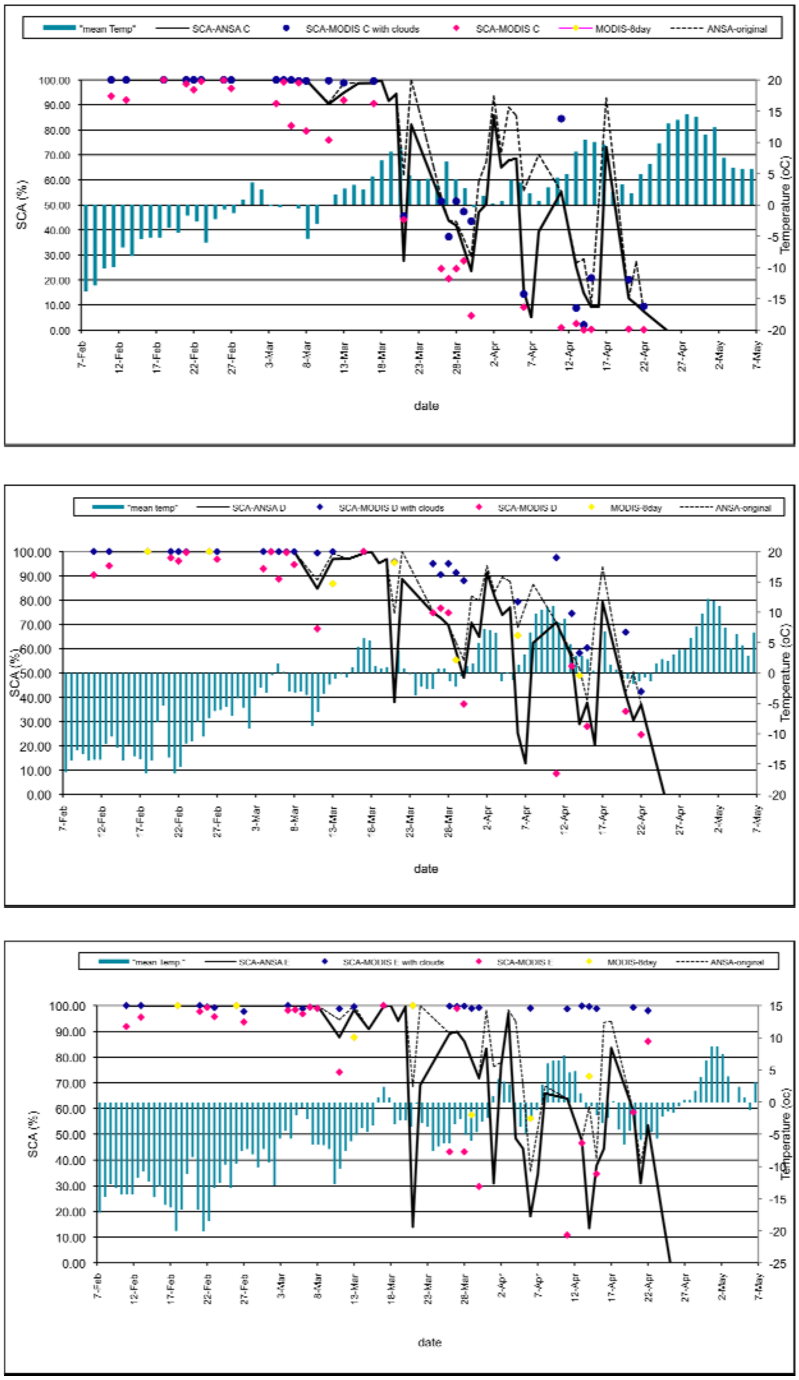


Figure 4.7. SCA depletion curves derived from modified ANSA and MOD10A1 products.

The major difference in SCA depletion curves derived from original and modified ANSA products was observed for April 4 and 5, 2008. A detailed spatial analysis was performed for these two dates. The spatial distribution of SWE values lower than 15mm was analyzed. In this spatial analysis larger areal extent of SWE values lower than 15mm were observed at lower elevation zones. Within the same elevation zone the areal distribution for the aspect classes were obtained. As it is given in Table 4.4 at zone A and B, larger areal coverage of SWE=< 15mm is seen on flat, southwest and southeast slopes. Due to solar illumination and shadowing the north-south difference in snow melt is expected. This analyses prove that snow on flat and south facing slopes are shallower compared to the snow on north faced slopes (Akyurek and Sorman, 2002). SCA depletion curves obtained from modified ANSA products still overestimate the snow cover extent obtained from MODIS snow products. This is due to the wet snow in month of April, which is a known AMSR-E snow mapping weakness.

Table 4.4. The spatial distribution (areal %) of SWE lower than 15mm according to the elevation and aspect classes.

A (1100-1500m)					
date	**F**	**NE**	**SE**	**SW**	**NW**
4.April	35.55	15.48	12.39	23.4	13.21
5.April	40.07	10.76	13.84	22.4	12.93

B(1500-1900m)					
date	**F**	**NE**	**SE**	**SW**	**NW**
4.April	11.8	19.43	26.92	22.91	18.94
5.April	12.41	15.9	29.13	24.65	17.92

C(1900-2300m)					
date	**F**	**NE**	**SE**	**SW**	**NW**
4.April	5.62	20.44	29.95	22.82	21.16
5.April	5.66	16.67	32.07	25.35	20.25

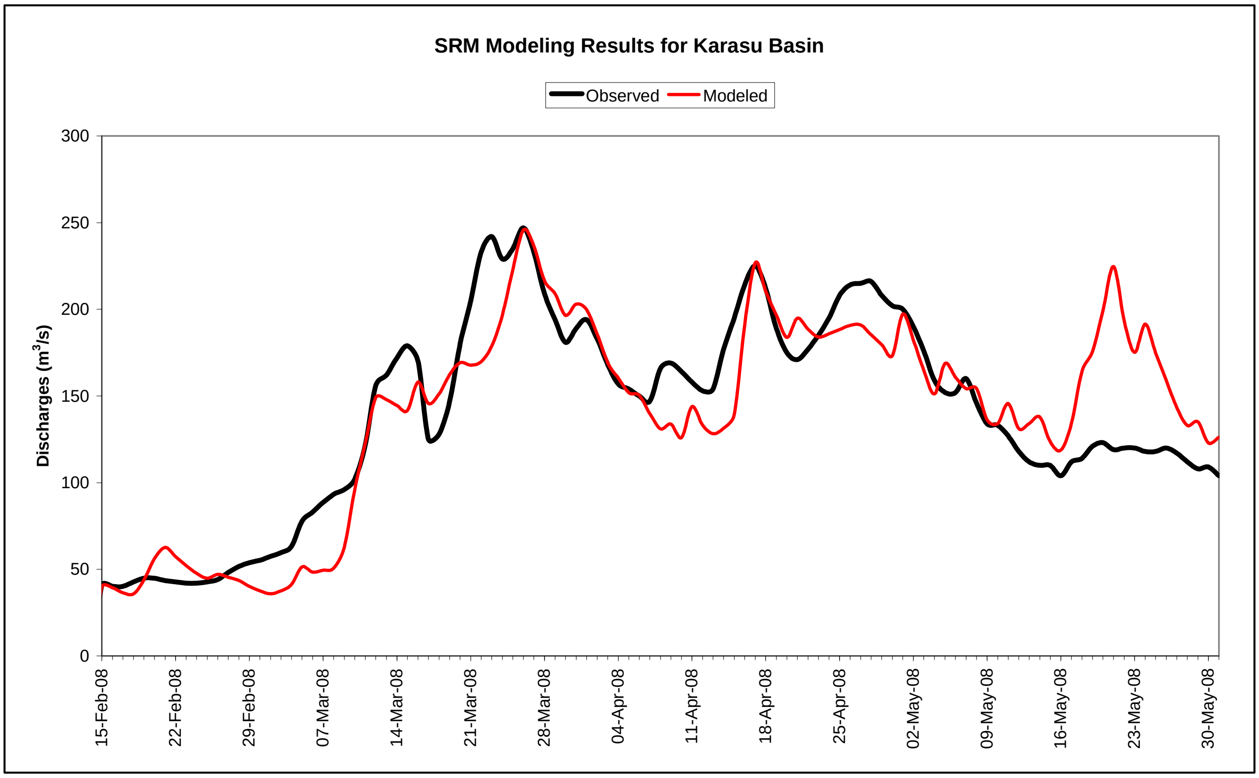
D(2300-2900m)					
date	**F**	**NE**	**SE**	**SW**	**NW**
4.April	5.13	25.00	25.21	18.56	26.10
5.April	4.03	20.82	29.06	21.73	24.36

4.4 Hydrological Impact of ANSA blended snow cover product compared to MODIS snow products

Impact assessment of different snow covered area products is done by using them as an input parameter to a hydrological model. Snow covered area of each elevation zone is defined as Snow Depletion Curve (SDC) to indicate the snow decrease/increase with time as continuous data input to the model SRM. One of the test sites, described in H-SAF project is used to test the impact of different snow covered area products. SDCs are derived on a daily basis for each of the five elevation zones of Karasu Basin (Upper Euphrates Basin) with a total approximate drainage area of 10 200 km^2. During the model application, different SDCs obtained using different products as MODIS daily and 8 day composite product, ANSA and modified ANSA products.

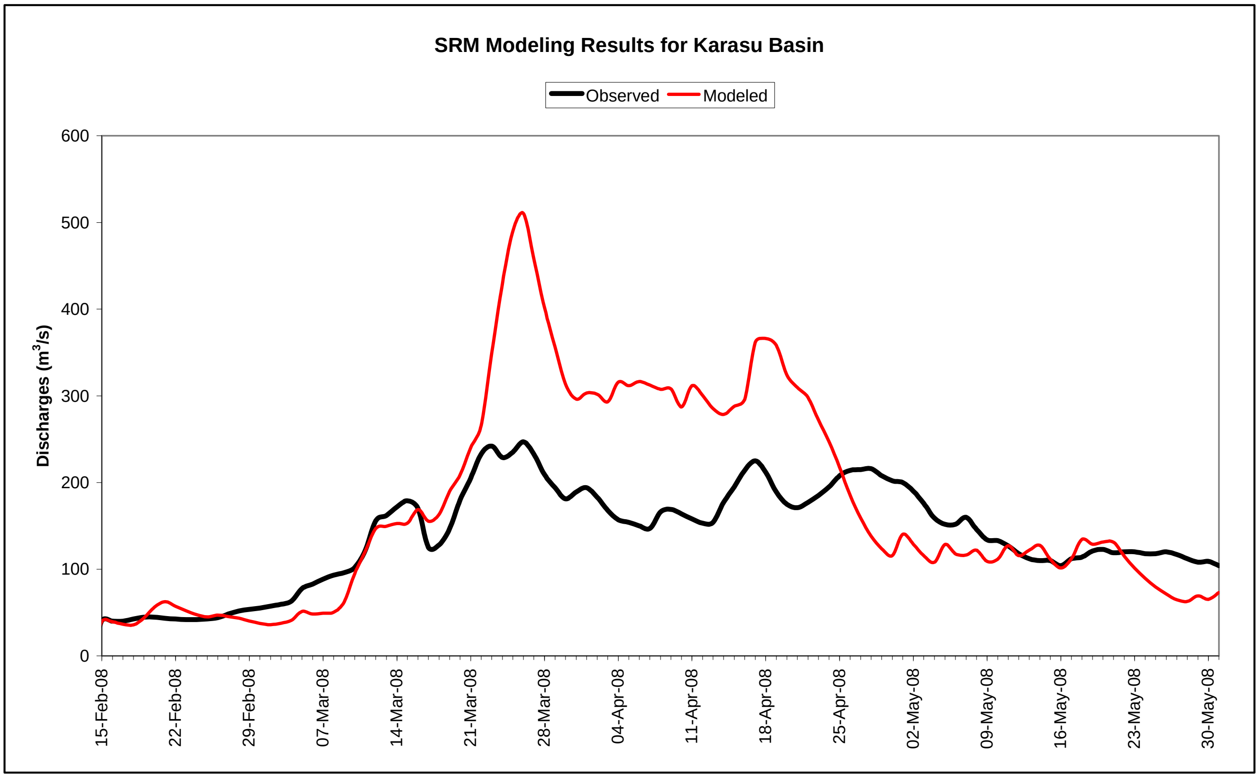
SCA values were obtained from ANSA and modified ANSA products for each day of February, March and April of the year 2008. MODIS snow covered area products (MOD10A1 and MOD10A2) were analyzed for relatively clear sky days when the cloud covered area is less than an average of 25% of whole basin. MODIS SCA products were evaluated from February to the end of May of the year 2008. Cloud coverage percentages are evaluated in two different approaches, firstly, all the cloud percentage of related zone is assumed to be snow for that zone, and secondly, all the cloud percentage of related zone is assumed to be apart from snow, thus snow covered area of the zone is assumed to be composed of snow pixels only. In order to derive a continuous SDC from the snow products, the unknown dates were simply interpolated from the known values of SCA for MODIS products.

Since the SDCs obtained from different snow products or from combination of these products are different, modeling is resulted in different visual and statistical evaluation of observed and modeled discharges at the outlet of the basin. The same model parameters were used for each simulation to concentrate on the impact of different SDCs on the hydrograph computation. However, model parameter modifications especially on snowmelt and rainfall runoff coefficient were done basically for the first case where MODIS daily and 8 day composite products were used together to derive SDC of Karasu Basin. The SRM model was applied only for the snowmelt season where the effect of SDC are obvious, therefore the model application period was defined as 15 Feb 08 – 31 May 2008 starting and terminating with fully snow covered and totally land covered areas, respectively. Model results are presented in Figures 4.8-4.10 with hydrograph comparison for the simulated and observed discharges and some statistical evaluation of the modeling results.



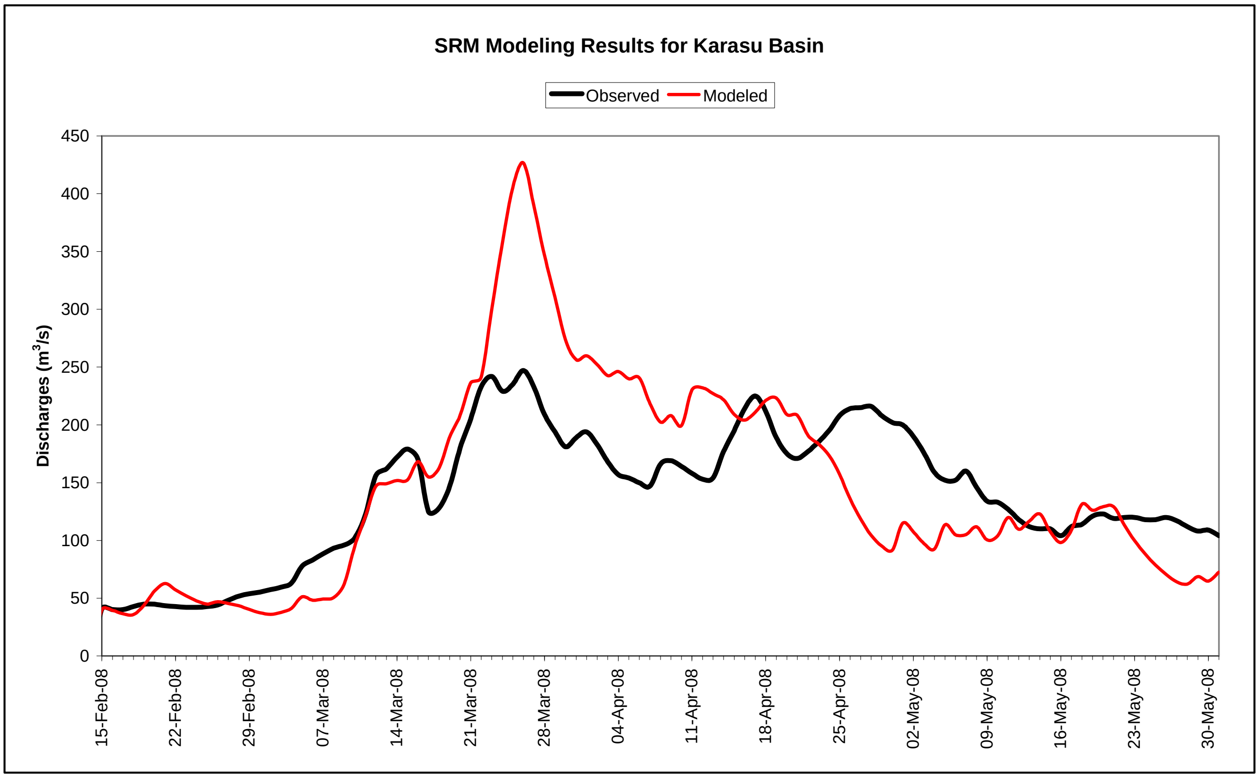
Measured Runoff Volume (10^6 m^3)	1286.57
Average Measured Runoff (m3/s)	139.17
Computed Runoff Volume (10^6 m^3)	1285.56
Average Computed Runoff (m^3/s)	139.06
Coefficient of Determination (R^2)	0.752
Volume Difference (%)	0.0781

Figure 4.8. Model application using SDC obtained from MODIS daily and 8 day composite products where clouds are classified as snow.



Measured Runoff Volume (10^6 m^3)	1286.57
Average Measured Runoff (m3/s)	139.17
Computed Runoff Volume (10^6 m^3)	1602.76
Average Computed Runoff (m^3/s)	173.37
Coefficient of Determination (R^2)	-1.3642
Volume Difference (%)	-24.5769

Figure 4.9. Model application using SDC obtained from ANSA original (5km) daily products



Measured Runoff Volume (10^6 m^3)	1286.57
Average Measured Runoff (m3/s)	139.17
Computed Runoff Volume (10^6 m^3)	1334.19
Average Computed Runoff (m^3/s)	144.32
Coefficient of Determination (R^2)	0.0221
Volume Difference (%)	-3.7016

Figure 4.10. Model application using SDC obtained from *modified* ANSA (5 km) daily products

As discussed in SDC evaluation, ANSA product by itself seem to overestimate the snow covered area compared to that of MODIS products during the early periods of melting. This situation is also observed in hydrograph simulation, the first and the biggest peak of the hydrograph reflects the overestimation in ANSA product. However, there is a significant improvement with the modification of the product as shown in the last simulation results. However, the new snowfall detection of ANSA during the later stages of melting is effective on the correct evaluation of snow depletion curves. Since the first peak is dominating the modeling results of the second and the third cases, the effect of new fallen fresh snow in the later stages could not be felt realistically.

Since ANSA products were not evaluated for the month May 2008 due to wet snow in this time of the year, the area was assumed to be snow free for the last two simulations above. The difference in the observed and simulated hydrographs during May can be disregarded for the product performance evaluation. SCA computations with ANSA during the last days of April resulted in an underestimation of SCA compared with that of MODIS most probably due to wet snow conditions and this lead to a sharp decrease in the hydrograph for the second and the third model simulations.

On the other hand, since optic satellite products are dependent on cloud cover, it is almost impossible to detect newly fallen snow with MODIS, but ANSA product can be helpful in this regard. In addition, the number of images with optical satellite data is limited due to cloud obscured problem, especially for the short melting period and it causes linear interpolation between two clear sky dates which could take prolong time periods. The strength of spatial resolution of MODIS daily snow products in mapping snow and the use of optical data in capturing the fresh snow can not be disregarded in snow melt modeling. The course resolution of AMSR-E contributes the course resolution in the blended snow product. Besides the spatial resolution limitations, the shallow depth and wet snow weaknesses of AMSR-E are still a problem in snow mapping and using snow products in snowmelt modeling. The blended snow products improvement by introducing improved spatial resolution and inclusion of the QuickSCAT scatterometer data (14GHz) in mapping areas of actively melting snow will improve the results of snow melting runoff simulations (Foster et al., 2008b).

The work done during the VS activity will be presented in AGU Fall Meeting in San Francisco between 15-19.December 2008 and in a national meeting in 3rd National Snow Conference, in Erzurum, between 17-19 February 2009. The abstracts submitted to these meetings are given in Appendix.

Chapter 5

Conclusions and Recommendations

5.1. Conclusions

The VS activity showed the utility of the blended-snow product in mapping snow covered area and in snowmelt modeling. We examine the ability of the preliminary ANSA blended-snow product to improve the mapping of snow-covered area on mountainous terrain relative to using either MODIS or AMSR-E products alone. The utility of the blended snow products in deriving snow cover depletion curves to be used in the snow modeling is also analyzed. Results demonstrate a strong improvement of snow-cover extent mapping as compared to using either optical data (e.g. MODIS) or microwave data (e.g. AMSR-E) alone. The strength of optical data in determining the fresh snow on the ground is observed. The contribution from microwave data during the cloud cover days is also seen. The results support the need of developing snow cover products based on multi-sensor data sources to provide continuous regional and global snow cover mapping for climate, hydrological and weather applications.

The accuracy of the blended snow cover products, namely ANSA, under development and verification by NASA-GSFC were tested for the first time in Turkey for the mountainous part of the country. Both 25 km and 5km resolution products were used during the accumulation and melting seasons of 2008. Not only for snow cover mapping the products were used in obtaining the snow cover depletion curves, which are the input parameters in snowmelt modeling. The snow cover area depletion curves were obtained from

i. MODIS (daily(MOD10A1) and 8 day (MOD10A2)) products with and without including the percentages of cloud coverages of the respective day

ii. With ANSA blended snow covered products with and without modification.

One of the weaknesses of the ANSA blended snow product is the course resolution based on the SWE product resolution. The course resolution problem leading the mix-pixel problem can be more important for hydrological studies on a regional basis. The main objective of the ANSA blended snow product is to map snow on the ground on a global basis. Therefore the snow/no-snow thresholds are set at minimum levels. In using the ANSA snow product in hydrological implementations the SWE thresholds were modified. In this preliminary modification, the limitation of the AMSR-E in retrieving shallow SWE is considered and 5cm snow depth threshold is used in the modified ANSA snow product. This modification helps to obtain more reasonable SCA depletion curves compared to SCA depletion curves obtained from MOD10A1 products. However the abrupt changes in the SCA depletion curves, which are not, recommended in the manual of snow melting model (SRM), lead overestimation in the runoff predictions. Considering 30% cloud cover in the snow classification from MODIS daily snow products produce comparatively reasonable runoff predictions in the preliminary modeling analysis. One another weakness of the ANSA blended snow cover product is the limitations of AMSR-E instrument in wet snow retrieval. This limitation affects the correctness of SCA depletion curves for the melting period.

5.2. Recommendations

The developed snow cover (SN_OBS3) and snow water equivalent (SN_OBS4) products within the HSAF project do not use the multi-sensor data. It is recommended to develop a blended snow cover product after producing the snow cover and snow water equivalent products in the future operational phases of HSAF project.

The other ongoing research and future activities of NASA-GSFC were also investigated during the visiting scientist activity and discussed at several meetings organized by the coordinator Dr. K. D.Hall with other research scientists Dr James Foster from Hydrologic Sciences Branch and Dr. Kim Edward from Hydrospheric and Biospheric Sciences Branch at NASA-GSFC. It is recommended to introduce scatterometer data for determination of wet snow in the blended snow product. It has been also recommended by the GSFC scientists that for every MW frequency there is always a certain threshold value after which an increase in SWE does not result any further changes in brightness temperature and the traditional algorithms of single pack snow gets saturated at certain snow depth (around 60cm). The present snow products of AMSR-E to determine SWE are less accurate for those areas with vegetation cover than in areas having medium snow depth and less complex topography. The modeling of snow using MW radiance approach for multi-layer snowpacks is also advised by using radiative transfer model for layered snow and predicting and quantyfing model accuracy and sensitivity depending on layering scheme. But this layering approach requires additional data, those should be collected from intensive field survey.

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Appendix

Abstract submitted to AGU 2008:

Evaluating the utility of the ANSA Blended Snow Cover Product In Obtaining Snow Cover Area Depletion Curves

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Snow covered area depletion curves represent a key input for snow runoff melting models like the snowmelt runoff model (SRM). SRM is a degree-day-based model for daily runoff simulations and forecasts in mountainous areas in which snowmelt is the major runoff contributor. Satellite images and aerial photographs are valuable sources for retrieving snow covered areas on non-cloudy days. The accuracy of the snow cover mapping studies in the optical wavebands mostly depends on the algorithm's ability to detect clouds. On very cloudy days it is not possible to make accurate snow cover mapping using only optical sensors. Microwave sensors can be used to obtain snow information on cloudy days. The snow-water equivalent (SWE) of a dry snowpack can be estimated with passive-microwave sensors such as Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Scanning Radiometer for EOS (AMSR-E). Development of snow cover products based on multi-sensor data sources is needed for continuous regional and global snow cover mapping for climate, hydrological and weather applications. A preliminary blended snow product has been developed jointly by the U.S. Air Force Weather Agency (AFWA) and NASA / Goddard Space Flight Center. The AFWA – NASA or ANSA blended snow product is an all-weather product that utilizes both visible and near-IR (MODIS) and microwave (AMSR-E) data. In this study the validation of the ANSA blended snow cover product, having 25 and 5 km resolution, respectively, was performed for the eastern part of Turkey for five months in the winter of 2007-2008. This is the first time that the blended snow cover product has been evaluated in a mountainous area, where the elevation ranges between 850 and 3000 m. Daily snow data collected at 36 meteorological stations were used in the analysis. The ANSA blended snow products improve the mapping of snow cover extent relative to using either MODIS or AMSR-E products, alone, for the 2007-08 winter in the eastern part of Turkey. 5 km resolution ANSA prototype ANSA maps from February and March 2008 were used to derive snow cover depletion curves for the upper Euphrates basin located in the eastern part of Turkey. The results are compared with the curves obtained from MODIS daily snow products, and found to provide an improvement over using MODIS daily maps alone. This is because of cloud obscuration on the MODIS maps.

Keywords: Snow Cover Area, Depletion Curve, Blended, MODIS, AMSR-E

Abstract submitted to *3rd National Snow Congress*:

3rd National Snow Congress-Erzurum Turkey (III. Ulusal Kar Kongresi-Erzurum)
17-19.February.2009 (17-19.Subat.2009)

Evaluation of the ANSA Blended Snow Cover Product over the Eastern part of Turkey

ANSA HARMANLANMİS KAR-KAPLİ URUNUNUN TURKİYE'NİN DOGU BOLGESİNDE DEGERLENDİRİLMESİ

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Amerika Hava Kuvvetleri Hava Dairesi (AFWA) ve NASA-Goddard Space Flight Center'da yer alan Hidrosfer ve Biosfer Labarotuvari elemanlari tarafindan yeni bir harmanlanmis kar urunu gelistirilmistir. AFWA-NASA ANSA olarak anilmakta olan bu urun MODIS'in 5-km mekansal cozunurlugune sahip standart gunluk kar-kapli urunu ile Advance Microwave Scanning Radiometer (AMSR-E)'nin 25 km mekansal cozunurlugune sahip standart gunluk kar-su esdegeri (SWE) urununu kullanmaktadir. Bu calismada 2007-2008 kar sezonu ele alinarak ANSA urunu uretilmis ve Turkiye'nin dogu bolgesinde yer alan DMI tarafindan isletilen klima/sinoptik ve Karasu havzasinda yer alan otomatik istasyonlardan elde edilen gunluk kar kalinlik degerleri dikkate alinarak ANSA urununun dogrulama calismasi yapilmistir. Ocak 2008 yili icin ANSA urun ile yer gozlem degerleri arasinda %85 uzerinde tutarlik gozlenmistir. Elde edilen sonuclar yeni urunun kar kapli alanin haritalanmasinda sadece MODIS veya sadece AMSR-E urunlerinin kullanilmasina gore daha basarili sonuclar verdigini gostermektedir. Ayrica calismada ANSA harmanlanmis kar kapli urununun hidrolojik modelleme calismalarinda kullanimi tartisilmaktadir.