NOAA NESDIS global multisensor automated satellite-based snow mapping system and products

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ABSTRACT

Accurate, timely and spatially detailed information on the snow cover distribution and on the snow pack properties is needed in various research and practical applications including numerical weather prediction, climate modeling, river runoff estimates and flood forecasts. Owing to the wide area coverage, high spatial resolution and short repeat cycle of observations satellites present one of the key components of the global snow and ice cover monitoring system. The Global Multisensor Automated Snow and Ice Mapping System (GMASI) has been developed at the request of NOAA National Weather Service (NWS) and NOAA National Ice Center (NIC) to facilitate NOAA operational monitoring of snow and ice cover and to provide information on snow and ice for use in NWP models. Since 2006 the system has been routinely generating daily snow and ice cover maps using combined observations in the visible/infrared and in the microwave from operational meteorological satellites. The output product provides continuous (gap free) characterization of the global snow and ice cover distribution at 4 km spatial resolution. The paper presents a basic description of the snow and ice mapping algorithms incorporated in the system as well as of the product generated with GMASI. It explains the approach used to validate the derived snow and ice maps and provides the results of their accuracy assessment.

Keywords: Automated snow and ice maps, satellites, monitoring

1. INTRODUCTION

Monitoring of the Earth's cryosphere and in particular of its snow and ice cover is one of the primary applications of satellite data. Mapping of snow and ice cover from satellite observations is performed using various techniques, both interactive and automated[1]. To identify snow and ice in the satellite imagery these techniques make use of specific spectral features of snow and ice which are different from other natural Earth's surface cover types (e.g., soil, vegetation) and from the spectral response of various atmospheric phenomena (clouds, fog, smoke, precipitation, etc.). Providing routine satellite-based monitoring of the terrestrial snow and ice along with a large number of other environmental parameters is within the scope of primary responsibilities of the National Environmental Satellite Data and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA).

Since 1972 at NOAA NESDIS snow and ice in the Northern Hemisphere has been routinely mapped using interactive visual analysis and interpretation of satellite imagery. In 1999, a computer-based Interactive Multisensor Snow and Ice Mapping System (IMS) was implemented to facilitate the satellite image analysis[2]. This allowed for improving the spatial and the temporal resolution of snow and ice maps correspondingly from 180 km to 24 km and from weekly to daily updates. In 2004, the spatial resolution of IMS snow and ice products was further increased to 4 km [3]. Since 2014 IMS maps are generated at 1 km spatial resolution and are updated twice a day.

Although the interactive approach to the snow and ice map generation has proved to be accurate and robust, it is labor intensive and is affected by subjectivity of satellite image interpretation by individual human analysts. Interactively generated snow and ice maps are difficult to reprocess. This fact complicates generation of consistent time series of the product for climatological analyses. Therefore a wider interest is attracted to automated algorithms for mapping snow and ice cover from satellite observations. In contrast to interactive snow and ice mapping techniques (similar to IMS), automated algorithms are objective, they can better utilize the advantages of available satellite observations, including high spatial resolution, multispectral sampling, and a frequent repeat observation cycle.

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This paper presents the Global Automated Snow and Ice Mapping System (GMASI) operated by NOAA NESDIS. The principal intent behind the development of this system was to generate spatially continuous daily global maps of snow and ice cover distribution at high spatial resolution that could be used in NOAA numerical weather prediction, climate and hydrological models as well as in other operational applications. To achieve the spatial continuity in the mapped snow and ice cover the system acquires and combines observations from visible/infrared and microwave sensors onboard multiple operational meteorological satellites.

2. GMASI SNOW AND ICE MAPPING TECHNIQUE

The two principal satellite snow and ice remote sensing techniques utilize passive observations in the visible/infrared and in the microwave spectral bands. Both techniques are actively used to map snow and ice with current weather and environmental satellites and both have their own advantages and weaknesses [4,5,6,7]. Observations in the visible/infrared provide spatially detailed characterization of the snow and ice but are inefficient at night and in cloudy conditions. Observations from microwave sensors are practically unaffected by clouds, do not require daylight and hence are often considered as all-weather observations, however they have a much coarser spatial resolution and typically provide less accurate retrieval results due to specific physical limitations of the technique. The latter includes in particular poor sensitivity to shallow and wet snow as well as to the melt-water-covered ice and frequent confusion of snow with frozen rocks and soil. A number of algorithms have been proposed where satellite observations in the visible/infrared and in the microwave are combined to achieve spatially continuous and more accurate characterization of the snow and ice cover [8,9,10,11]. This multisensor approach is utilized in the NOAA NESDIS Global Automated Snow and Ice Mapping System (GMASI).

The primary intent of the developed technique is to generate a spatially continuous distribution of the global snow and ice cover on a daily basis by making maximum use of advantages of the two techniques, visible/infrared and microwave and compensating for their limitations. The algorithm implemented in the GMASI system first performs snow and ice retrievals using satellite observations in the visible/infrared and microwave bands. In addition to the image classification algorithms used to identify snow and ice in the satellite imagery we apply a number of consistency tests to the results of the image classification which retain only the most reliable retrievals. Observations from multiple sensors of the same type are acquired and processed to improve the maps. This concerns observations in the microwave spectral bands which are available from several operational meteorological satellites.

At the next stage daily snow and ice maps derived from visible/infrared and from microwave sensors data are combined in an optimal way. When mapping snow cover the priority is given to snow retrievals from observations in the visible and infrared due to their better spatial resolution and better accuracy than microwave data. Ice cover in the open ocean is primarily mapped with microwave sensor data, whereas when mapping ice cover over small inland water bodies in midlatitudes we rely mostly on observations in the visible and infrared. At the final stage of the data processing, to ensure full spatial continuity of the maps a recurrent gap-filling algorithm is used where grid cells in the current day snow and ice that remained undetermined for any reason are filled in with the previous day snow and ice map data. The data flow chart of the system is presented in Figure 1.

The first version of the GMASI system was developed and implemented in 2006. A number of modifications to the algorithm have been made in the course of the last ten years to improve its performance and to incorporate data from replacement and newer satellites and sensors. The current version of the system uses observations from the Advanced Very High Resolution Radiometer (AVHRR) onboard MetOP satellites as well as from Special Sensor Microwave Imager/Sounder (SSMIS) sensors on all active Defense Meteorological Satellite Program (DMSP) satellites (currently, F-16,-17,-18 and -19). Prior to 2011 AVHRR observations from NOAA polar orbiting satellites were used rather than MetOP. Earlier version of the system also incorporated observations in the visible and infrared from geostationary satellites (GOES-East, GOES-West and Meteosat), however benefits of having these data were found insufficient to justify substantial additional efforts needed to routinely calibrate and cross calibrate visible sensors onbard all platforms. In the paper we give a basic description of the algorithms, techniques and sensors currently incorporated in the GMASI and provide examples of products illustrating the system performance. GMASI products are compared with the snow and ice maps generated by IMS analysts and with information on the snow cover available from conventional in situ snow cover observations.

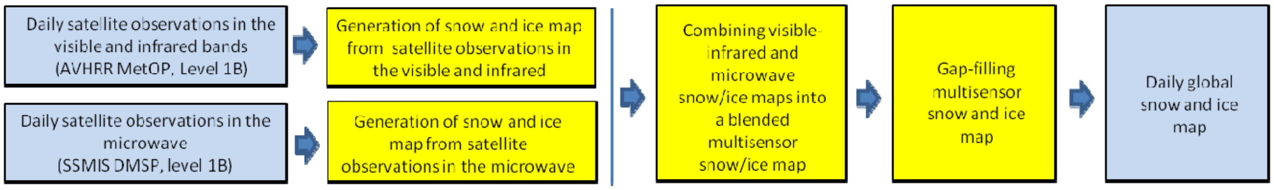


Figure 1.High level flow chart of the Global Multisensor Snow and Ice Mapping System (GMASI).

Within the system blended gap-filled daily snow and ice maps over the Northern and Southern Hemisphere are generated separately and are then combined to achieve the full global coverage. There is a number of regional peculiarities in the snow and ice mapping algorithms. Some areas are assumed either permanently snow free (e.g., low elevation equatorial regions) or permanently snow covered (e.g., Antarctica) and thus no snow cover retrievals are performed there. Ice cover retrievals are limited only to the high and midlaltitude regions of the globe. The primary output of the system is a global continuous daily map of snow and ice cover distribution generated on a latitude-longitude grid with 0.04 degree grid cell size (or approximately at 4 km spatial resolution). Every land grid cell of the map is labeled as “snow-free land” or “snow cover” and every map grid cell over water surface is labeled as “clear water” or “ice cover”. The system is set to collect incoming satellite observations continuously throughout the day. For a daily snow and ice map satellite observations acquired within a 24-hour period (0000-2359UTC) are used. The final processing of satellite observations and snow/ice map generation is conducted in the beginning of the next day. The output daily snow and ice map typically becomes available at 1100-1200 UTC on the next day. A full detailed description of the technique is available in the GMASI Algorithm Theoretical Basis Document (ATBD)[12].

The primary output product of the system is the global daily snow and ice map generated on a latitude-longitude grid at about 4 km spatial resolution. The map is continuous, i.e. it does not have gaps due to unavailability of data or inability to perform retrievals. An example of the daily blended snow and ice map is shown in Figure 2. Daily snow and ice map images can be viewed at http://www.star.nesdis.noaa.gov/smcd/emb/snow/HTML/multisensor_global_snow_ice.html. Binary snow and ice maps generated since 2006 can be downloaded from ftp://www.star.nesdis.noaa.gov/pub/smcd/emb/snow/binary/multisensor/global.

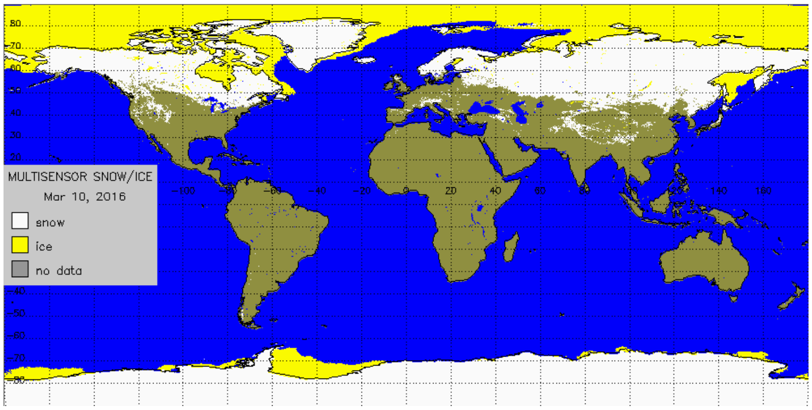
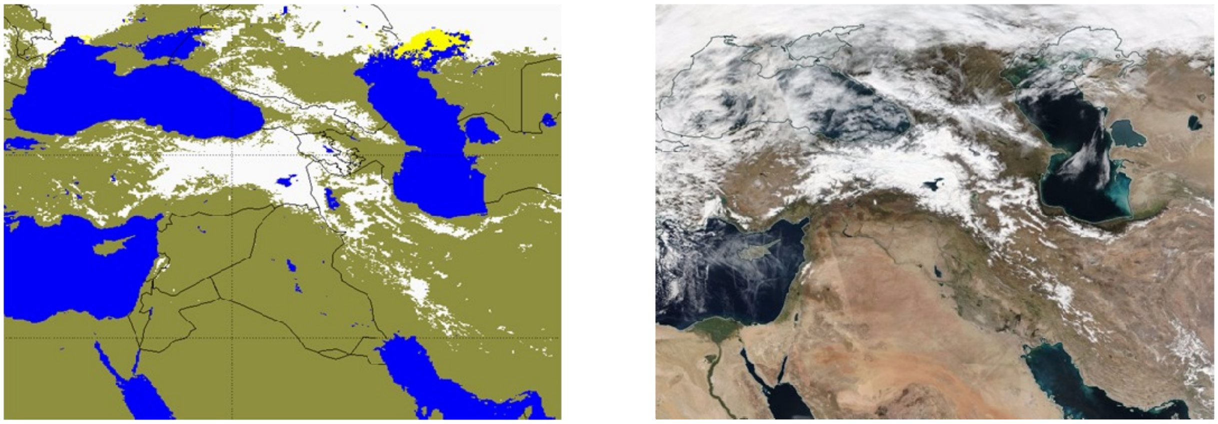


Figure 2. Example of GMASI daily global snow and ice map. The map is produced on a latitude-longitude grid at 4 km spatial resolution.

3. EVALUATION OF SNOW AND ICE MAPS

The GMASI system was implemented into operations at NOAA NESDIS in 2006 and thus has been used for more than 10 years. Both qualitative and quantitative examination of the maps has shown that the product realistically characterizes the global distribution of snow and ice cover and adequately reproduces seasonal changes of these cryosphere parameters. Qualitative evaluation includes the visual inspection of the maps and their comparison with available satellite false-color and true-color imagery. As an example Figure 3 presents a daily snow and ice map and a corresponding true color image over Middle East. Similar spectral features of snow and clouds in the visible part of spectrum certainly makes difficult discriminating between clouds and snow in parts of the true color image, however in the clear sky portions of the image, particularly in its center and in the bottom right portion an obviously close agreement between the snow cover patterns is seen in the true color image and in the automated product.

A more spatially detailed assessment of the automated snow and ice product involves its comparison with information on the snow cover provided by ground-based stations and with the snow and ice cover mapped interactively within the NOAA IMS system. Comparison with both datasets is fully automated and is conducted on a daily basis. Since only few ground-based stations in the Southern Hemisphere occasionally provide reports on the snow depth and since IMS system does not cover areas south of the equator, detailed quantitative evaluation of snow and ice maps is performed only over the Northern Hemisphere.



(a) (b)

Figure 3. GMASI daily snow and ice map over Middle East on February 4, 2016 and corresponding true color image from MODIS Terra. In the GMASI snow and ice map snow is shown in white and ice is shown in yellow. MODIS Terra true color image was acquired from NASA Worldview at https://worldview.earthdata.nasa.gov.

3.1 Comparison with in situ data

Daily comparison of GMASI snow cover maps with the snow cover observed at ground-based meteorological stations typically incorporates reports from several thousand meteorological stations over the globe operating under the auspices of WMO. Additional information on the snow depth may be available from regional in situ observing networks. In the United States snow depth is routinely observed at several thousand stations within the US Cooperative Network and within the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS). Information on the snow water equivalent (SWE) can also be obtained from Snow Telemetry (SNOTEL) stations, however the latter are mostly confined to the Western US and Alaska.

It is important that WMO stations do not explicitly report “zero” snow depth when there is no snow on the ground but rather report a missing snow depth observation. Therefore these reports can be used only to evaluate and assess snow misses in the automated snow maps (or “true positive” accuracy), but not false snow identifications. Stations of the US Cooperative Network do report “zero” snow depth when there is no snow on the ground and thus can be used to calculate all components of the satellite-based snow product error matrix, i.e., true and false positives as well as true and false negatives.

A large number of daily in situ snow depth observations performed over the territory of Conterminous US (CONUS) allows for a spatially detailed assessment and quantitative evaluation of the snow extent estimated from satellite data. In the peak of the winter season reports from over 2000 stations may be available and used for validation of the snow maps. The map in Figure 4 gives an idea of the daily number, the spatial distribution of snow depth measurements over CONUS and on the general agreement between the station data and the snow cover mapped with the automated algorithm. Within the system maps of snow cover with station data overlaid, similar to the one in Figure 4, are generated daily once the station data become available. The results presented in Figure 4 show a good correspondence of the snow cover distribution mapped by the automated algorithm to in situ data. A small number of “snow misses” by the automated map in the southern part of the CONUS area (lower half of the map) may be associated with shallow snow cover that was not identified from satellite data. It also can be due to the snow pack which melted during the time period between surface observations, which typically occur early in the morning, and the time of the first valid satellite-based snow cover retrieval on the same day.

The quantitative comparison of the satellite snow product with station data is performed by matching in situ observation data with the classification status of corresponding grid cells in the snow cover map. The results of the comparison are compiled on a daily basis to estimate the total agreement between the two products. Time series of daily snow map vs surface observations match-up statistics in Figure 5 illustrate a typical seasonal change of the agreement between the two datasets in the CONUS region. As it is seen from the graphs in late spring, summer, and early fall when the CONUS area is mostly snow free the agreement between the two dataset reaches 100%. In middle of the winter season when approximately half of the CONUS area is affected by seasonal snow the rate of agreement decreases to 75-85%. Most of the disagreement between surface and satellite snow observations in the middle of winter is due to the snow cover which was reported by ground-based observers, but was not identified from satellite data.

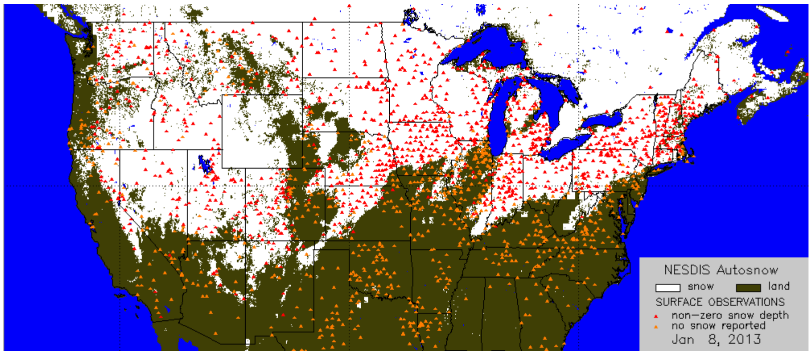


Figure 4. Example of GMASI snow cover over Conterminous US (CONUS) with surface observations data overlaid. Locations with some snow on the ground are marked with red; Stations which reported no snow on the ground are shown in yellow.

Besides the time difference between satellite and surface observations and possible errors in the snow cover identification in satellite imagery, there are at least two factors that affect the correspondence between the two datasets. First, errors in the characterization of the snow cover by the satellite product may occur due to certain inertia of the GMASI snow maps. None of the techniques, visible/infrared or microwave allows for accurate retrieval of snow cover properties beneath precipitating clouds. Therefore in most cases a fresh-fallen snow is identified and mapped on the second or, sometimes, on the third day after the event. Second, the station data used for comparison are not quality controlled. We expect that about 1-2% of all snow depth reports may be erroneous. The most typical error consists in reporting no snow on the ground in the presence of the snow cover. Therefore the true yearly mean accuracy of the automated snow maps may be somewhat better than 93.8% as it is shown in Figure 5.

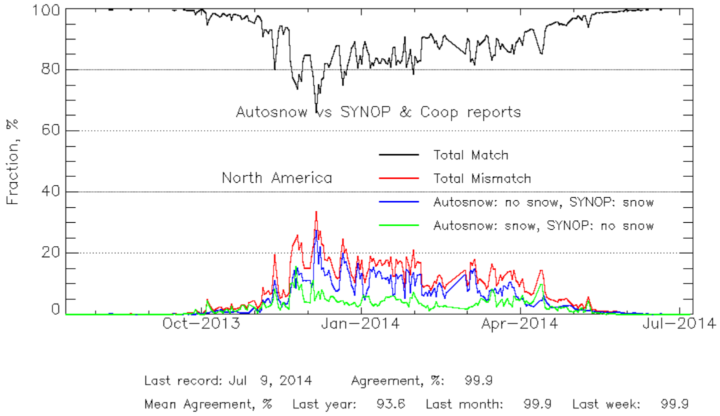


Figure 5. Time series of daily estimates of the percent of correct snow identifications ("Total Match") and errors in the GMASI product in the winter season of 2013-2014.

3.2 Comparison with IMS interactive snow charts

Interactive charts of snow and ice generated at NOAA within IMS system present the primary snow cover product used in most operational numerical weather prediction models of NOAA National Weather service (NWS). Similarly to GMASI, IMS snow charts are mostly based on the analysis of satellite imagery and therefore cannot be considered fully independent of GMASI. Still, a completely different approach to the snow mapping used by IMS and an implicit quality assurance of the maps resulting from the involvement of human analysts in the product generation justifies its use as "truth" in the comparison and accuracy assessment of GMASI. For the accuracy assessment of GMASI we use IMS snow maps generated at 4 km spatial resolution and match the two datasets pixel by pixel. Grid cells where the two products disagree on the type of the surface (land or water) are excluded from the statistics. Because of the limited area coverage of the IMS the comparison of IMS with the GMASI snow maps is conducted only over the Northern Hemisphere.

The comparison of the two products has shown that their yearly mean rate of agreement in the Northern Hemisphere ranges within 94-96%. The difference in the agreement in Eurasia and North America is rather small and typically does not exceed 1%. Figure 6 illustrates typical seasonal variations of the daily percent of agreement between GMASI and IMS. The rate of agreement between the two products increases in summer, when most of the area in Eurasia and North America (except Greenland) is snow-free and increases to 6-8% in October and in the middle of April. Larger disagreement in the fall and in the spring can be caused by fast changes of the snow cover distribution during his time. These fast changes make challenging the proper reproduction of the snow cover distribution not only for the automated system but also for human analysts working on interactive snow maps.

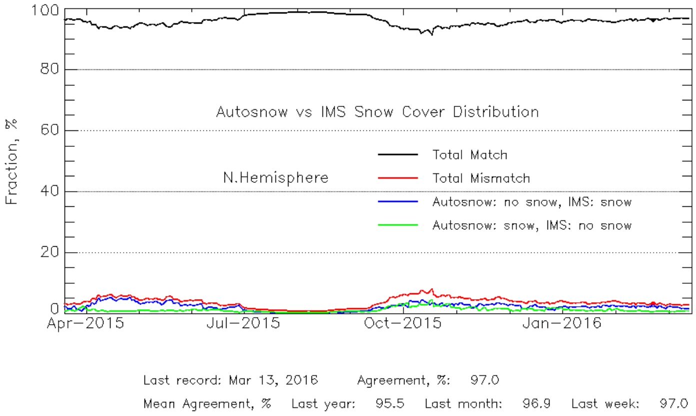


Figure 6. Time series of the rate of correct snow classifications (“Total match”) and errors (“Total mismatch”) in the GMASI snow cover as compared to IMS during the 2014-2105 winter season in the Northern Hemisphere

Large rates of agreement of GMASI and IMS snow maps are partially explained by the fact that in the estimates we used all grid cells located in the Northern Hemisphere independently of the snow cover climatology. Excluding from the statistics grid cells where snow cover has never been observed or has always been observed on a given date appears a more adequate way to assess the agreement between the dataset. The agreement rate estimated within this latter approach the agreement will certainly be smaller than when the comparison is performed over the whole land area of the Northern Hemisphere.

3.3 Validation of GMASI ice retrievals

IMS charts are also used to evaluate the accuracy of GMASI ice retrievals. The comparison of the two products have shown that their agreement rate in the Northern Hemisphere typically varies within 97 to 99%. The high rate of the agreement is partially explained by the fact that similar to the snow cover, all grid cells in the Northern Hemisphere corresponding to the ocean and inland water bodies were included in the comparison. Limiting the comparison to areas affected by seasonal ice cover will reduce the estimated rate of agreement. The automated snow and ice maps tend to mostly underestimate the ice extent as compared to IMS. This underestimation ranges mostly within 2-5% of the total ice extent and peaks in the end of summer – beginning of fall, i.e., at the time of the minimum seasonal ice cover in the Northern Hemisphere. One of the reasons for the underestimation of the ice extent in the GMASI system in summer consists in a reduced efficiency of identification of ice covered with melt water by microwave sensors. Another possible reason for the difference consists in the fact that IMS analysts are instructed to map all ice they see in the imagery including small ice concentrations. In GMASI the ice cover over the open ocean is primarily mapped from satellite observations in the microwave. The microwave ice algorithm implemented in the system is more conservative and is tuned to identify ice of larger concentrations of about 50% and above.

4. CONCLUSION

Synergy of satellite observations in the visible/infrared and in the microwave presents a powerful approach to improve characterization and monitoring of the global snow and ice cover from satellites. This approach has been implemented in the NOAA NESDIS Global Automated Multisensor Snow and Ice Mapping System. In the algorithm we combined retrievals made from visible/infrared and from microwave data in an optimal way trying to reduce the effect of physical limitation of the two types of observations and to make maximum use of their advantages. The system has been run operationally for the last 10 years. It has demonstrated robust performance throughout all seasons providing daily global spatially-continuous maps of snow and ice cover at the spatial resolution of about 4 km

Validation study has shown that the agreement of GMASI daily snow maps to the surface snow depth observations ranges within 75 to 85% in the middle of the winter season and averages to about 96% over the year. The agreement to IMS interactive maps averages to about 97% over the year. It reaches minimum of about 90% in October and in the middle of April, when changes in the snow cover distribution are largest due to seasonal snow advance or retreat. Because of unavailability of in situ and IMS data in the Southern Hemisphere, validation studies were limited to Eurasia and North America, however there is no strong reason to assume large differences in the product accuracy in the two hemispheres.

The ice cover distribution derived within GMASI closely corresponds to the one produced interactively by NOAA analysts. Differences of 2-5% in the mapped ice distribution are mostly due to underestimation of the ice extent by the automated algorithm. The latter may be due to a reduced efficiency of ice identification in the microwave bands which is typically caused by unresolved thin or low concentration ice types and surface melt effects.

Although the primary application of the GMASI products is within operational applications, the system can be contribute to the climate studies. The existing satellite-based snow cover climatology developed at SnowLab of Rutgers University is based on NOAA historical interactive weekly snow cover charts. It is defined on a very coarse grid of around 200km and is limited to the Northern Hemisphere only. Availability of both AVHRR and SSMI observations since the middle of 1980s allows for extending the time series of automated daily snow maps backwards and generating a 30-years climate-grade record of the global snow cover. This work will contribute substantially to establishing more reliable, fully consistent snow cover climatology at much higher spatial and temporal resolution.

REFERENCES

[1] Romanov, P., “Snow cover,” In: Satellite-based applications to climate change. Qu J.J., Powell A., Sivakumar M.V.K., Eds., Springer, New York, 217-224 (2013)

[2] Ramsay B., “The interactive multisensor snow and ice mapping system,” Hydrological Processes 12, 1537–1546 (1998)

[3] Helfrich S.R., McNamara, D., Ramsay, B. H., Baldwin T. and Kasheta T., “Enhancements to, and forthcoming developments in the Interactive Multisensor Snow and Ice Mapping System (IMS),” Hydrological Processes, 21, 1576-1586 (2006)

[4] de Wildt M, Seiz, G., and Gruen, A., “Operational snow mapping using multitemporal Meteosat SEVIRI imagery,” Remote Sensing of Environment, 109, 29-41 (2007)

[5] Grody N.C. and Basist, A.N., “Global identification of snowcover using SSM/I measurements,” IEEE Transactions on Geoscience and Remote Sensing, 34, 237–249 (1996).

[6] Hall, D. K., and Riggs G.A., “Accuracy assessment of the MODIS snow products, Hydrological Processes,” 21, 1534 – 1547 (2007).

[7] Zhao H. and Fernandes R., “Daily snow cover estimation from Advanced Very High Resolution Radiometer Polar Pathfinder data over Northern Hemisphere land surfaces during 1982–2004,” Journal of Geophysical Research, 114, D05113 (2009)

[8] Solberg, R., Rudjord, O., Salberg, A. B. and Killie M.A., “A multi-sensor multitemporal algorithm for snow cover extent retrieval from optical and passive microwave data,” 7th EARSeL workshop on Land Ice and Snow. 3–6 February 2014, Bern, Switzerland. (2014)

[9] Romanov P., Gutman G. and Csiszar I., “Automated monitoring of snow cover over North America with multispectral satellite data,” Journal of Applied Meteorology, 39, 1866-1880 (1999).

[10] Foster J.L., Hall, D. K., Eylander, J.B., Riggs, G. A., Nghiem, S.V., Tedesco, M., Kim, E., Montesano, P. M., Kelly, R. E. J., Casey, K. A. and Choudhury B., “A blended global snow product using visible, passive microwave and scatterometer satellite data,” International Journal of Remote Sensing, 32, 1371-1395 (2011).

[11] Gao Y., Xie, H., Lu, N., Yao T. and Liang T., ”Toward advanced daily cloud-free snow cover and snow water equivalent products from Terra–Aqua MODIS and Aqua AMSR-E measurements,” Journal of Hydrology, 385, 23–35 (2010).

[12] Romanov P., “Global 4km Multisensor Automated Snow/Ice Map (GMASI): Algorithm Theoretical Basis Document,” http://www.star.nesdis.noaa.gov/smcd/emb/snow/documents/Global_Auto_Snow-Ice_4km_ATBD.pdf