Snow Cover Monitoring over the Hindu Kush Himalayan Region Using Cloud Removal MODIS Snow Cover Data

Nishu Bhardwaj[1], Bhaskar R. Nikam[2], S.K.S. Yadav[1], Manaruchi Mohapatra[2], Sudhakar Shukla[1], Joyeeta Poddar[1]

[1]Remote Sensing Applications Centre Uttar Pradesh, Lucknow 226021, India
[2]Indian Institute Of Remote Sensing Dehradun 248001, India

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Abstract - *In the High Mountain Asia region the presence of snow is the has greater importance because of availability of freshwater which directly affects not only the ecosystem of the globe but also affects the 240 million people who live in the High Mountain Asia region. The HMA region is fed by the melt water of Snow and Glaciers. Regular monitoring and mapping of snow is utmost importance for various Hydrological Models. The tradition approach of snow cover mapping is very tedious and time consuming. That's why an appropriate tool for monitoring of snow cover and determination of snow cover parameters is satellite based remote sensing that allows investigation over the large and inaccessible areas. Snow cover data from Moderate Resolution Spectroradiometer has been widely used for snow cover mapping in hydrological models for model calibration and updation. But the presence of cloud cover in the available satellite imagery is a major problem that hindered its applicability; hence a methodology to remove or mitigate the present cloud covered pixels in the data is required. In this study we use MODIS snow products of Aqua and Terra for the time range of 2008-2018. These products are freely downloaded from NSIDC and are available at spatial resolution of 500m. For mapping and monitoring of snow cover in the HMA region we use MOD10A2 of "MODIS-Terra" and MYD10A2 of "MODIS-Aqua". The cloud pixels have been addressed and mitigated by applying three spatio-temporal filters such as combination of Terra/Aqua satellite images, Short term temporal filter and Neighborhood spatial filter. A total 99.862% cloud cover is removed after applying a series of filters. The Combination of Terra Aqua, Short-Term Temporal filter and Nearest Neighborhood filter removes cloud cover of 50.852%, 37.153%, 12.528% respectively. The final images have 0.138% cloud cover. This mitigated MODIS snow products has been validated against the snow cover area (SCA) maps generated from the Landsat-7 and Landsat-8 optical multispectral data. This process showed the higher percentage of hit pixels this means have the strongest agreement with the MODIS snow cover imageries. Total 506 images were taken for the observation and found that the minimum snow cover area is recorded as 0.239775 million sq. km on 28 July 2013 while the maximum snow cover is recorded as 1.09435 million sq. km on 02/02/2008. It is also found that the snow cover area is decease after 2013.Our study estimates the SCA with the 8-Day MODIS snow cover product 2008 to 2018 and found that the average snow-covered area is equal to 0.652 million Km² which is 15.52% of the total geographical area of the HKH region*

***Key Words*: HMA, MODIS-Aqua, MODIS-Terra, NSIDC, RSLE, SCA**

1. INTRODUCTION

From a hydrological point of view, snow cover is a predominant factor for ecosystem supply like water supply, food, energy. Regular snow cover mapping and monitoring of permanent snow cover are essential because they provide approximately 70% freshwater on the earth's surface(Rodda, et al. 2014). On the geo-ecologist asset, the Hindu Kush Himalayan region is the origin of major 10 river basin that covers the 8 major countries in Asia. The HKH includes Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan. Optical satellites like Landsat-7, Landsat-8 & MODIS are generally utilized for snow cover mapping. An appropriate tool for mapping of snow is remote sensing because they provides regular monitoring of snow in all seasons. The tradition mappi8ng techniques of snow is very tedious and time take process.

The previous studies show that there are different approaches to for mapping the snow cover on a regional scale. The previous approaches include interpolation of ground-based snow depth measurements done by Dutra et al., 2019; López-Moreno & Nogués-Bravo, 2006; Juraj Parajka et al., 2007), application of remote sensing techniques done by (Maskey et al., 2011; Scherer et al., 2005) and a combination of these done by (Huang et al., 2011; Notarnicola et al., 2013; J Parajka et al., 2006)). Various sensors like GOES, SPOT, AWiFS, Landsat MSS (Multispectral Scanner System), TM (Thematic Mapper) have been used for the analysis of snow cover area estimation but these sensors have few limitations related to small swath, temporal and spectral resolutions(Kulkarni et al. , 2006; Xiao et al., 2002). For snow cover mapping of the entire High Mountain Asia (HMA), the MODIS satellite sensors are very helpful due to their temporal resolution (8 day or a day) and relatively coarser as well as the finer spatial resolution of respectively 0.05° (Approximately 5 Kilometer) and 500 m. Also, there are two independent sensors respectively Terra and Aqua in which Terra is in descending node and provides snow cover imagery at 10:30 AM local time and Aqua is in ascending node who provides snow cover imagery at 01:30 PM local time. These snow products provide global coverage and could be used in a complementary way for mapping. Currently the Moderate Resolution Imaging Spectroradiometer (MODIS) snow products are downloaded from the National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center (NSIDC-DAAC). Sets of daily and 8-day composite products are available on the NSIDC website whose provide the global coverage. The algorithm of snow map for MODIS datasets are automated which describe that consistent datasets are required for snow cover information (Hall & Riggs, 2011). In the present study, the main aim is to remove cloud cover using cloud removal mitigation filters given by Gafurov & Bárdossy, (2009) from available snow cover products. Subsequently, this cloud-free data is used for the estimation of snow cover area and to map the snow cover.

The paper is organized as follow: firstly we describe the study area and the MODIS data products used in the present study. After that we present methodology and the cloud mitigation approach. In the result we give the total snow cover area and evaluate their accuracy against Landsat data. Finally we present the snow cover map for the entire area. We conclude the paper with a discussion regarding the result and present some future applications of snow cover product.

2. STUDY AREA

The geographical boundary of the HKH region includes the Karakorum, the Pamir, the Himalaya and other neighboring ranges. The Hindu Kush Himalayan (HKH) region extends 3,500 km over all or part of eight countries from Afghanistan in the west to Myanmar in the east. It is the source of 10 major Asian river systems (Amu Darya, Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtse, Yellow River and Tarim) who provides ecosystem services and the basis for livelihoods to a population of around 240 million people in the region. The basins of these rivers provide water to 1.9 billion people, a fourth of the world's population. A total of 54,000 individual glaciers were identified, with an overall area of 60,000 km2 and estimated glaciers were identified, with an overall area of 60,000 km2 and an estimated 6000 km3 of ice reserves(Williams, 2013). A report of The International Centre for Integrated Mountain Development (ICIMOD) shows that the snow cover area during winter varies between 951,000 $Km^2$and 1,390,000Km^2 but during summer, its ranges are decreases and vary between 388,000Km^2 and 481,000 Km^2. The total glacier area can extend up to 87,340 Km^2. The study area is shown in figure-1.

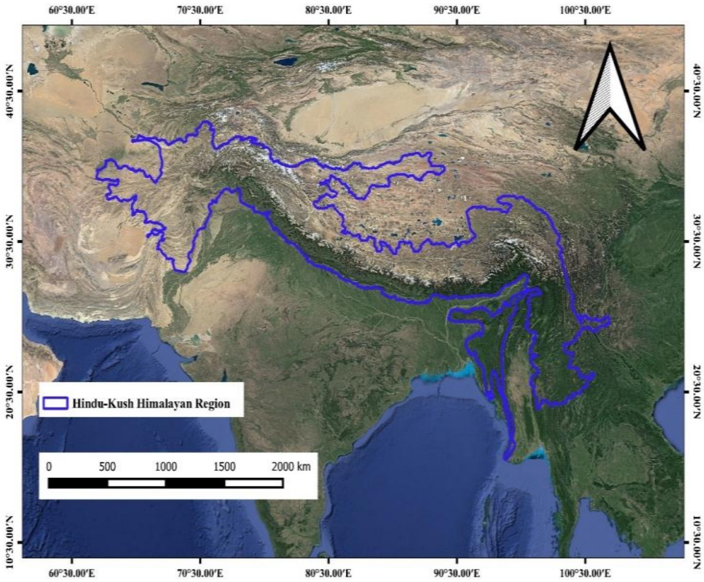

Figure 1. The Hindu-Kush Himalaya Region

3. DATA USED

MODIS stands for Moderate Imaging Spectroradiometer MODIS is an imaging sensor consists of two sun-synchronous, near polar circular orbit satellites, namely Terra and Aqua in which Terra (EOS-AM1) is in descending node and Aqua (EOS-PM1) is in ascending node. MODIS snow cover data are widely used to analyze and monitor snow cover variations in terms of real-time analyses due to global coverage (Gunnarsson et al. 2019). MODIS is a set of individual detectors viewing the entire globe who provides the imagery of earth's surface and clouds in 36 spectral bands or group of wavelengths from 0.405 μm to 14.385 μm. MOD10A2 (Terra) and MYD10A2 (Aqua) images are used in this study are downloaded from the NASA Earth Observation system website. Wolfe et al.(1998), George Riggs and J. Parajka et al., (2008) describe that the geolocation accuracy of Terra satellite is about 45m and that of the Aqua satellite is about 60m. The snow cover mapping process was based on the NDSI(Normalized Difference Snow Index) band ratio technique (Hall & Riggs, 2011; Li & Williams, 2008; Salomonson & Appel, 2006). For NDSI calculations, band 4 (0.55μm) and band 7 (2.1) m) of Aqua are used while band 4 (0.55 μm) and band 6 (1.6μm) of Terra are used. The detailed description of MODIS snow cover is presented in user guide provided by Riggs & Hall, (2015)

4. METHODOLOGY

The methodology adopted for snow cover mapping over the whole region is shown in a flow chart. For mapping the snow cover, the 8 day MODIS Collection 6 snow cover data MOD10A2 (Terra) and MYD10A2 (Aqua) data was obtained from National Snow and Ice Data Center (NSIDC) for the time period from 2008 to 2018..From the 8 day snow cover dataset, two sub-datasets *Day_CMG_Snow_Cover* (index: 0) and *Daily_CMG_Cloud_Obscured* (index: 2) were extracted in raster format for the entire HKH region. The extracted data was reclassified into three classes, namely snow, cloud and land. For a pixel, if snow cover percentage was greater than 50% then the pixel was declared as Snow. Else if sum of snow and cloud fraction was smaller than 50% then the pixel was declared as Land. Rest of the pixels were declared as Cloud (Tran et al., 2019). The null data present inside the study area was considered as cloud pixels which ground states would also be estimated in the further steps. In the resulting reclassified dataset; snow, land, cloud and null pixels were assigned the value 1, 2, 3 and 0 respectively. For the mitigation of clouds, Cloud cover mitigation filters are used. Cloud mitigation steps as stated by (Gafurov & Bárdossy, 2009) was followed in order to reduce the cloud pixels to mitigate cloud obstruction. The flow chart of methodology is given in figure 2.

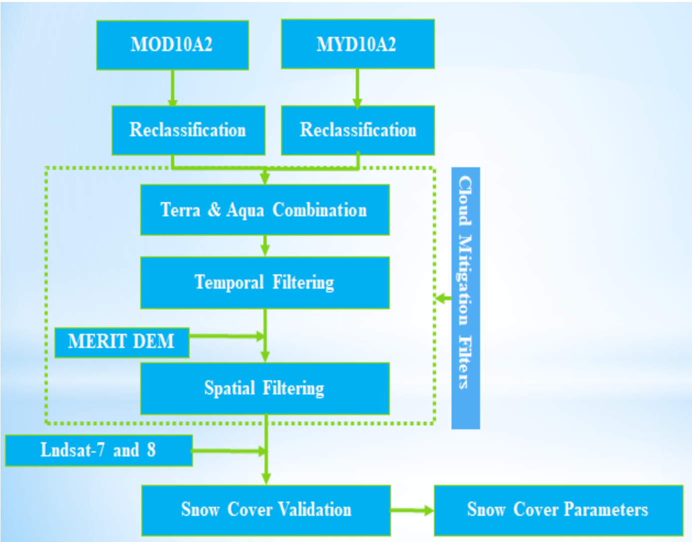

Figure 2. METHODOLGY

The first spatio-temporal cloud mitigation filter is the combination of Terra and Aqua images. This filter was based on the assumption that in between the snow cover observations of the two sensors on the same day, no snow melt or snowfall occurs. A pixel will be assigned as snow if the pixel shows snow in any of the sensor observations. Similarly, a pixel will be assigned as land if the pixel shows land in any of the sensor observations.

The second spatio-temporal cloud mitigation filter, short term temporal filter was based on the temporal combination of cloud covered pixels. Eight day forward and backward data was used to estimate actual ground status of a cloud covered pixel. In other words, for a cloud covered pixel if the observed value for the pixel was snow for both the preceding and the succeeding days, then the cloud covered pixel would be assigned to be snow. Similarly, if the observed value for the pixel was land for both the preceding and the succeeding days, then the cloud covered pixel would be assigned to be land.

The third spatio-temporal cloud mitigation step, neighborhood spatial filter is based on the spatial properties of the neighboring pixels in terms of ground status and elevation. This step combines the two spatial filters given by Gafurov & Bárdossy (2009).

In the first step, if three out of the four direct side-bordering pixels of the cloud covered pixel shows snow, the cloud pixel was declared to be snow covered. Similarly, if three of the side-bordering pixels of the cloud covered pixel shows land, the cloud pixel was declared to be land covered. In the second step, all the 8 neighboring pixels were considered around a cloud covered pixel called as center pixel. From the neighboring pixels, if any pixel had (a) lower elevation than the elevation of center pixel and (b) shows snow, the center pixel was declared as snow covered. This step was based on the fact that as elevation increases, the temperature required for snowmelt decreases. So the pixels at higher elevation would melt later as compared to the pixels located at lower elevation. After applying the filters the cloud is removed from the MODIS imagery. For the accuracy assessments these imageries are compared with the Landsat images. After that snow cover maps are generated, which can be further used to study the climatology and cryospheric studies.

5. RESULT

This study generated a combined Terra and Aqua 8 day snow cover map for the time range of 2008 to 2018. We use the existing algorithm for cloud mitigation. The aim of this study is to test the approaches for cloud removal on the MODIS 8 day snow products. Our motivation was to enable an accurate map of snow cover with a minimum percentage of the cloud. For this we tested the cloud mitigation approach. The first step (Terra and Aqua Combination) removes approximately *50.852%* of the total existing cloud. The second step (short term temporal filter) removes approximately *37.153%* clouds. 88.005% of clouds are removed by these two filters. For removing the remaining clouds we use the nearest neighborhood filter which removes approximately *12.528%* of clouds. The combination of terra and aqua was an effective filter for cloud mitigation. On average, approximately 0.138% of clouds are remaining in the final product. For accuracy assessment, we compare these MODIS cloud removed images with the Landsat imagery which shows a good percentage of a hit with an accuracy of 92.56%. The minimum snow cover area is recorded as 0.239775 million sq. km on 28 July 2013 while the maximum snow cover is recorded as 1.09435 million sq. km on 02/02/2008. It is also found that the snow cover area is decease after 2013. Our potential applications will be used for runoff forecasting, hydrological modeling, data assimilations. The percentage cloud remaining after the sequential application of spatio-temporal filters, snow cover probability maps generated using the cloud mitigated snow cover data and the time series SCA variation for the time period of 2008-2018 are shown in figure 3, 4 and 5 respectively.

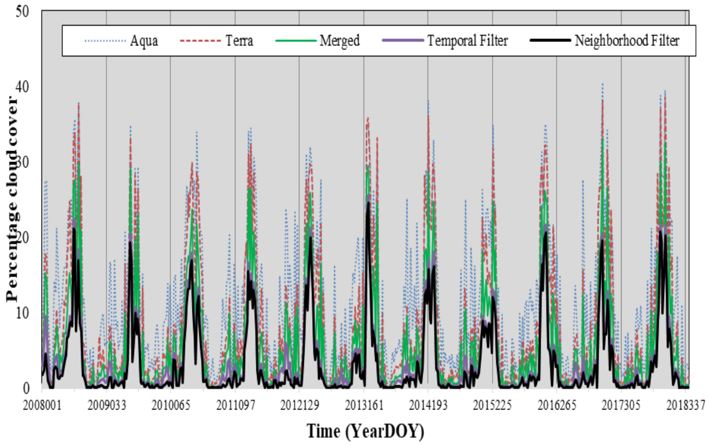

Figure-3: Remaining percentage cloud cover after the sequential application of spatio-temporal cloud mitigation steps

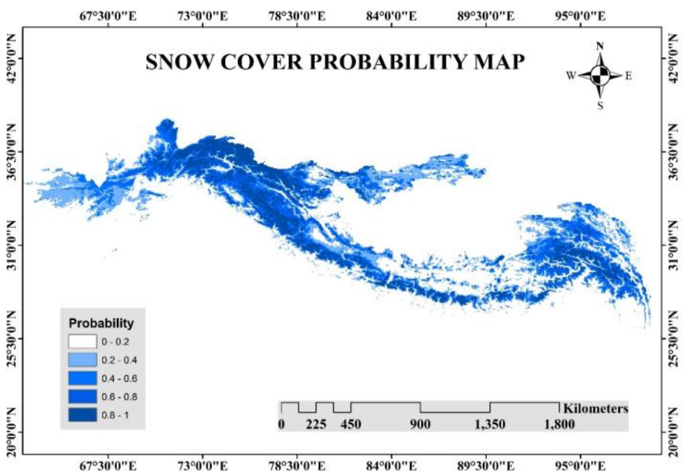

Figure-4: Snow cover probability map generated using the cloud mitigated snow cover dataset in the time period 2008-2018

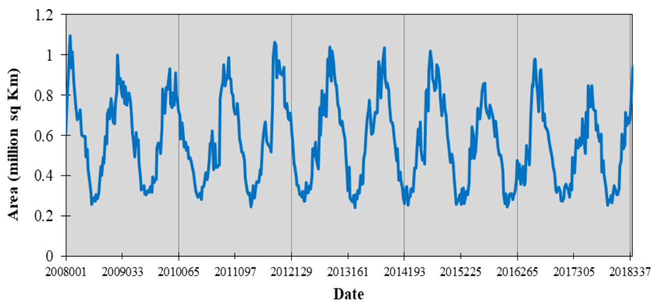

Figure-5: Time series SCA variation over HKH region

6. DISCUSSION AND CONCLUSION

Snow is an essential component of the cryosphere. Estimation of snow cover area in the High Mountain Asia region is very tedious and time-consuming due to high variabilities, complex topography, and different climatic conditions. Snow cover area monitoring is necessary because snow cover monitoring is an indicator of climate change and it may be used for estimation of glacier mass balance and study of various hydrological models. For this purpose, we use the MODIS 8 day snow products. The present study computes the snow cover area and discusses the probability of snow cover using MODIS data products in the entire region of the High Mountain Asia region. The present study shows that the snow cover varies during the period of ablation and accumulation period and the indicator for the earth-atmosphere system. This MODIS snow cover data over the region can be further used to study climatology and cryospheric properties of the High Mountain Asia.

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REFERENCES

1. Dutra, E., Boussetta, S., Arduini, G., Balsamo, G., & de Rosnay, P. (2019). Data assimilation of in-situ snow depth and its impact on river discharge. Geophysical Research Abstracts, 21.
2. Gafurov, A., & Bárdossy, A. (2009). Cloud removal methodology from MODIS snow cover product. Hydrology and Earth System Sciences, 13(7), 1361–1373. https://doi.org/10.5194/hess-13-1361-2009
3. Gunnarsson, A., Gar\dharsson, S. M., & Sveinsson, Ó. G. B. (2019). Icelandic snow cover characteristics derived from a gap-filled MODIS daily snow cover product. Hydrology and Earth System Sciences, 23(7), 3021–3036.
4. Hall, D. K., & Riggs, G. A. (2011). Normalized-difference snow index (NDSI). Encyclopedia of Snow, Ice and Glaciers, 779–780.
5. Huang, X., Liang, T., Zhang, X., & Guo, Z. (2011). Validation of MODIS snow cover products using landsat and ground measurements during the 2001-2005 snow seasons over northern Xinjiang, China. International Journal of Remote Sensing, 32(1), 133–152. https://doi.org/10.1080/01431160903439924
6. Kulkarni, A. V, Singh, S. K., Mathur, P., & Mishra, V. D. (2006). Algorithm to monitor snow cover using

AWiFS data of RESOURCESAT-1 for the Himalayan region. International Journal of Remote Sensing, 27(12), 2449–2457. https://doi.org/10.1080/01431160500497820

7. Li, X., & Williams, M. W. (2008). Snowmelt runoff modelling in an arid mountain watershed, Tarim Basin, China. Hydrological Processes, 22(19), 3931–3940.
8. López-Moreno, J. I., & Nogués-Bravo, D. (2006). Interpolating local snow depth data: an evaluation of methods. Hydrological Processes: An International Journal, 20(10), 2217–2232.
9. Maskey, S., Uhlenbrook, S., & Ojha, S. (2011). An analysis of snow cover changes in the Himalayan region using MODIS snow products and in-situ temperature data. 391–400. https://doi.org/10.1007/s10584-011-0181-y
10. Notarnicola, C., Duguay, M., Moelg, N., Schellenberger, T., Tetzlaff, A., Monsorno, R., … Zebisch, M. (2013). Snow cover maps from MODIS images at 250 m resolution, part 2: Validation. Remote Sensing, 5(4), 1568–1587. https://doi.org/10.3390/rs5041568
11. Parajka, J, & Blo, G. (2008). Spatio-temporal combination of MODIS images – potential for snow cover mapping. 44, 1–13. https://doi.org/10.1029/2007WR006204
12. Parajka, J, Blöschl, G., Parajka, J., & Validation, G. B. (2006). Validation of MODIS snow cover images over Austria To cite this version : HAL Id : hal-00305018 Validation of MODIS snow cover images over Austria. 10(5), 679–689.
13. Parajka, Juraj, Merz, R., & Blöschl, G. (2007). Uncertainty and multiple objective calibration in regional water balance modelling: case study in 320 Austrian catchments. Hydrological Processes: An International Journal, 21(4), 435–446.
14. Riggs, G., & Hall, D. (2015). MODIS Snow Products Collection 6 User Guide. Digital Media, 6(December), 1–80.
15. Rodda, J. C. (n.d.). World Water Resources at the Beginning of the Twenty-First Century Edited by.
16. Salomonson, V. V, & Appel, I. (2006). Development of the Aqua MODIS NDSI fractional snow cover algorithm and validation results. IEEE Transactions on Geoscience and Remote Sensing, 44(7), 1747–1756.
17. Scherer, D., Hall, D. K., Hochschild, V., König, M., Winther, J. G., Duguay, C. R., … Walker, A. E. (2005). Remote sensing of snow cover. In Geophysical Monograph Series (Vol. 163, pp. 7–38). https://doi.org/10.1029/163GM03
18. Tran, H., Nguyen, P., Ombadi, M., Hsu, K. L., Sorooshian, S., & Qing, X. (2019). A cloud-free modis snow cover dataset for the contiguous United States from 2000 to 2017. Scientific Data, 6, 1–13. https://doi.org/10.1038/sdata.2018.300
19. Williams, M. W. (2013). The Status of Glaciers in the Hindu Kush–Himalayan Region. Mountain Research and Development, 33(1), 114–115. Retrieved from http://dx.doi.org/10.1659/mrd.mm113
20. Wolfe, R. E., Roy, D. P., & Vermote, E. (1998). MODIS Land Data Storage , Gridding , and Compositing Methodology : Level 2 Grid. 36(4), 1324–1338.
21. Xiao, X., Moore, B., Qin, X., Shen, Z., & Boles, S. (2002). Large-scale observations of alpine snow and ice cover in Asia: Using multi-temporal VEGETATION sensor data. International Journal of Remote Sensing - INT J REMOTE SENS, 23, 2213–2228. https://doi.org/10.1080/01431160110076180

BIOGRAPHY:

Nishu Bhardwaj received Bachelor degree in Civil Engineering in 2015. After that works as a Assistant Professor from 2015 to 2018. Currently, Pursuing M.Tech in Remote Sensing and GIS from Remote Sensing Applications Centre Uttar Pradesh, Lucknow India. The area of research is related to water resources. This work is done at Indian Institute of Remote Sensing Dehradun.